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TOWARDS A SUSTAINABLE OPTIMIZATION OF PAVEMENT MAINTENANCE PROGRAMS UNDER BUDGETARY RESTRICTIONS

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ABSTRACT

Transport sector constitutes the second largest source of global greenhouse gas (GHG) emissions, being the road transportation the main contributor of these emissions. Efforts in the road sector have traditionally focused on vehicle emissions and infrastructure is typically not included in the emissions account. Road environmental impact is estimated to increase by 10% if the stages of road design, construction, and operation were considered. Previous literature has widely study sustainable practices in pavement design and construction, with little attention paid to maintenance. Current state of practice reveals that pavement managers barely consider environmental performance and their evaluations solely rely on technical and economic criteria. This situation creates the need to incorporate, in an integrated manner, technical, economic, and environmental aspects in the design of maintenance programs. The main objective of this research is to develop a tool for the optimal design of sustainable maintenance programs. Given a maintenance budget, the tool aims to maximize the long-term effectiveness of the network while minimizing GHG emissions derived from the application of maintenance treatments. The capability of the proposed tool is analyzed in a case study dealing with an urban pavement network. In comparison to the traditional maintenance policy, the proposed tool designs maintenance programs that increase the average network condition by up to 22% and reduces GHG emissions by 12%. This application also analyzes the effect of different budgetary scenarios in the technical and environmental performance of the network. This application helps pavement managers in the trade-off between budget and network performance.

Keywords: greenhouse gas emissions; long-term effectiveness; optimization; sustainability; pavement management; sensitivity analysis.

1. INTRODUCTION

Funds available for pavement maintenance are often limited, leading to a rapid deterioration of the road network (ASCE, 2013). In this study, maintenance refers to all the different types of treatments that can be applied over the pavement life cycle. Maintenance treatments may be grouped in three categories: preservation, maintenance and rehabilitation. These categories differ on the severity level and magnitude of pavement distresses they are able to address. Preservation treatments are applied when the pavement condition is still good, extending pavement service life without increasing its structural capacity (FHWA, 2005). Maintenance treatments delay future deterioration and maintain or improve the functional condition of pavements without significantly increasing their structural capacity (FHWA, 2005). Finally, rehabilitation treatments extend the service life and/or improve the structural capacity of pavements in poor condition (FHWA, 2005).

Neglecting the need for preservation and delaying pavement maintenance implies higher costs and risk of structural failure. Compared to early maintenance based on preservation, late maintenance is estimated to triple agency and user costs (CSCE et al., 2012; de Solminihac et al., 2007; Schliesser and Bull, 1992). The design of maintenance programs is therefore crucial for pavement managers. This study covers two aspects in the design of pavement maintenance programs: the sustainable evaluation of maintenance alternatives and the optimal allocation of available funds.

1.1. Sustainable Evaluation of Maintenance Alternatives

The evaluation of pavement maintenance alternatives has traditionally focused on economic and technical terms, neglecting the importance of environmental impacts (Pellicer et al., 2016; Torres-Machi et al., 2014a). In environmental terms, the transport sector constitutes the second largest source of global greenhouse gas (GHG) emissions (Ang and Marchal, 2013). In global terms, the transportation sector accounted for 23% of world carbon dioxide (CO_2) emissions from fossil fuel combustion (IEA, 2016). In the absence of new policies, it is estimated that these emissions will double between 2010 and 2050, reaching around 12 GtCO2eq/yr by 2050 (Ang and Marchal, 2013; Sims et al., 2014). Within transportation, the road sector plays a significant role, as it accounts for three quarters of transport emissions (IEA, 2016).

In the road sector, efforts have traditionally focused on reducing vehicle emissions. Infrastructure is indeed typically not included in the sector's account, so the impact of the road sector is even higher (Reger et al. 2015; Revi et al 2014). Previous studies have estimated that the stages of road design, construction, and operation would increase by 10% the environmental impact of roads (Chester and Horvath, 2009). Existing literature has widely studied sustainable practices applied to pavement design, construction and material selection, whereas little attention has been applied to maintenance (Araújo et al., 2014; AzariJafari et al. 2016; Santero et al. 2011). Despite transportation agencies are becoming more aware of the significance of environmental sustainability, a survey developed by Tighe and Gransberg (2011) in the USA and Canada found that only 4% of respondent agencies were using environmental performance to select maintenance practices. There is therefore a need to include environmental aspects in the evaluation of maintenance alternatives.

In the pavement field, recent efforts have quantified the environmental impact of maintenance activities (Giani et al., 2015; Huang et al., 2009; Nathman et al., 2009; Turk et al., 2016). However, current models lack of an integrated evaluation of technical, economic, and environmental aspects (Torres-Machi et al., 2014a). This limitation creates the need to develop an evaluation of the sustainability of maintenance alternatives that consider, in an integrated manner, the three aforementioned aspects over the pavement life cycle. Having detected this gap, this study addresses the sustainable design of maintenance programs subject to budgetary restrictions. As it would be explained in the following sections, the study is focused on pavement infrastructure and the environmental impact is assessed in terms of the GHG emissions derived from the application of maintenance treatments.

1.2. Optimal Allocation of Maintenance Budget

Once maintenance alternatives have been evaluated, pavement managers need to optimize the allocation of available budget. This poses a combinatorial optimization problem with a solution that is not straightforward. There are S^{TxN} possible solutions in a network with N pavement sections and S possible treatments over a planning horizon of T years (Golroo and Tighe, 2012). Previous studies have considered different optimization methods to address this problem (Chamorro, 2012; Chamorro and Tighe, 2009; Torres-Machi et al., 2014b; Wu et al. 2012). Pavement management systems mainly rely on mathematical programming and near-optimization methods (Chamorro and Tighe, 2015; Torres-Machi et al., 2014b). The efficiency of mathematical programing methods is commonly limited to small networks, because the objective functions must accomplish a set of conditions regarding their continuity and ability to be differentiated.

Regarding near-optimization methods, little attention has been paid to heuristic algorithms, which have mainly been applied to solve the problem at the project level (Chou and Le, 2011; Tsunokawa et al., 2006). These applications optimize the maintenance treatment applied to a pavement section to maximize the net benefit (Tsunokawa et al., 2006), and to maximize reliability by minimizing maintenance costs (Chou and Le, 2011), respectively. These approaches optimize the maintenance program at the section level. Once the maintenance strategy has been optimized for each section, the system selects the sections that will receive treatment based on the available budget. The main limitation of this approach is that it ignores the effect on the network as a whole: the optimal maintenance strategy at the section level may not be the optimal solution at the network level, when all the sections and available budget are simultaneously taken into account. In addition, these applications only consider one maintenance alternative (asphaltic overlay), failing to consider a wider set of maintenance alternatives. Therefore, these applications do not account for the benefits gained from applying preservation treatments or recycling alternatives.

A recent application developed by Yepes et al. (2016) overcomes these limitations by proposing a heuristic algorithm that optimizes the design of maintenance programs at the network level given an available budget. The algorithm proposed by Yepes et al. (2016), based on a hybrid greedy randomized adaptive search procedure algorithm (hybrid GRASP), consider a wider set of maintenance alternatives. However, this application focuses on technical and economic aspects, thus failing to account for the environmental impact derived from maintenance activities. Indeed, optimization applications in infrastructure management are mainly focused on one objective, ignoring the complex and multi-objective nature of the real problem (Wu and Flintsch, 2009; Wu et al., 2012).

1.3. Incorporating Sustainability in the Optimal Design of Maintenance Programs

Given the limitations identified in the previous sections, a heuristic multi-objective optimization tool considering a sustainable evaluation of maintenance alternatives should be developed. This tool is aimed to improve the current allocation of maintenance resources. Thus, the objectives of this research are to develop just such a tool and to analyze its capability in a case study analyzing an urban pavement network in Chile. The case study employs real data collected in the urban network (Videla et al., 2010), a condition indicator named UPCI (Urban Performance Condition Index) (Osorio et al., 2014), and performance models (Osorio, 2015; Osorio et al., 2015). This data and models were developed within the context of a four-year research project for the sustainable management of urban pavement networks, Fondef Project D09I1018. More details regarding these data are provided later on in the text.

To achieve the main goal of the study, the paper is structured as follows: Section 2 describes the optimization tool proposed to enhance the sustainable maintenance of pavement networks; this proposal includes a description of the proposed tool, the sustainable evaluation of maintenance alternatives, and the optimization algorithm. Section 3 examines the application of the proposed tool in a real case study consisting of the management of an urban pavement network in Chile. The final section derives conclusions from this application, in addition to defining practical implications and opportunities for improvement in future research.

2. OPTIMIZATION TOOL FOR ENHANCING THE SUSTAINABLE MAINTENANCE OF PAVEMENT NETWORKS

Based on the limitations identified in the current state of the art and practice, this section proposes a tool that aims to maximize the long-term effectiveness of pavement networks and reduce GHG emissions derived from the application of maintenance treatments.

2.1. Framework of the Optimization Tool

The proposed optimization tool consists of four components: parameters, evaluation module, optimization process, and results. The relations between these components are depicted in Fig. 1. This framework has been developed considering other pavement management systems that have been successfully developed and applied in rural pavement networks (Chamorro, 2012; Chamorro and Tighe, 2009). At this point it is worth mentioning that the optimization tool proposed in this study is a generic tool that could be applied to different pavement networks. In order to explain better the capabilities of this tool, a real case study dealing with the management of an urban pavement network is presented in section 3. Other networks could similarly be analyzed as far as all the input data needed by the tool is available.

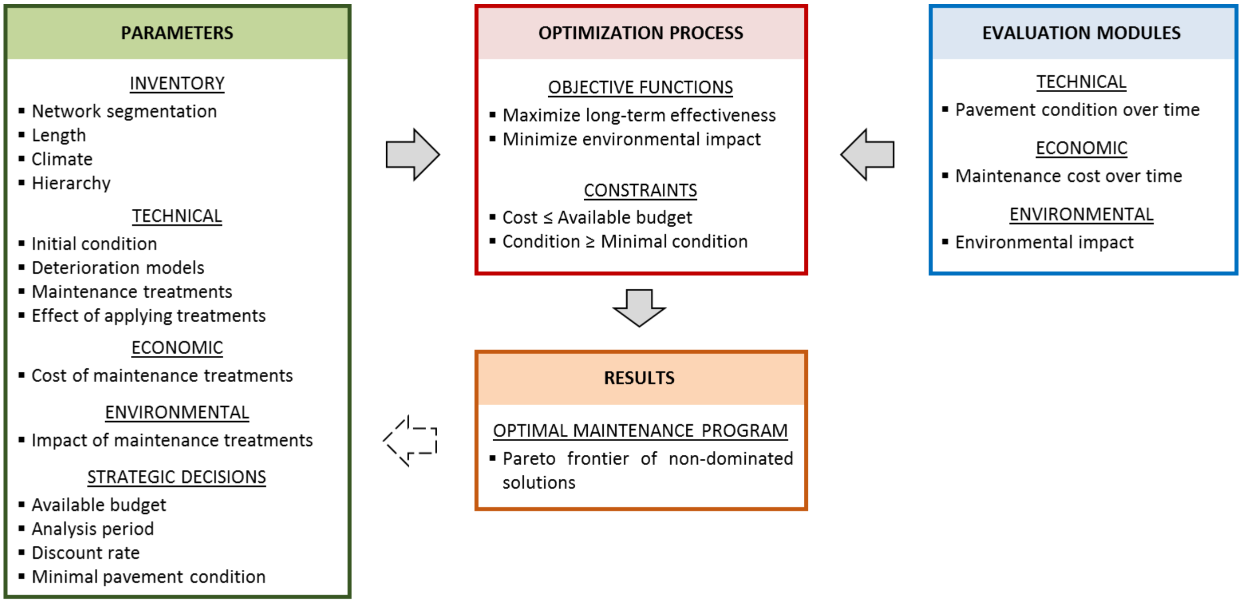

Fig. 1. Framework of the proposed optimization tool.

The first component is related to the parameters of the optimization problem. Parameters comprise all input data needed to undertake the optimization process. Parameters may be expressed by a single measure (such as the length of each pavement section) or by a set of measures (such as the effect on condition derived from the application of the available maintenance treatments). For illustrative purposes, an example of each of these parameters is included in the application of the proposed tool in the case study.

Parameters include information of the network in terms of the inventory, such as number of sections in the network, length of the sections, hierarchy, etc. They also include technical information regarding pavement initial condition, expected deterioration trend (also called deterioration models), set of maintenance treatments that may be applied to improve pavement condition and the effect on condition derived from the application of each of these treatments. Pavement condition may be assessed using different overall condition indices that account for pavement distress over time, such as the Urban Pavement Condition Index (UPCI) (Osorio et al., 2014); the Pavement Condition Index (PCI) (Shahin, 2005); or the Pavement Quality Index (PQI) (Karan et al., 1983). The proposed tool could use different condition indices as far as all the technical parameters are referred to the same index.

Economic and environmental parameters refer to the unitary cost and environmental impact derived from the application of each maintenance treatment. As parameters, they are an input data of the optimization tool and their value is obtained from historic agency data or other data source chosen by the user. In the case study presented in this paper, environmental impact is assessed in terms of GHG emissions because they are the main driving force of climate change (IPCC, 2007). However, the methodology presented in the proposed framework could similarly consider other environmental indicators. As the optimization tool is designed to minimize environmental impact (assessed in terms of GHG emissions), when using indicators aimed to be maximized (for example the use of recycled materials), the objective function should be adapted. This process is simple, as maximization objective functions can easily be adapted into minimization ones because $\min \mathrm{f}(\boldsymbol{x}) = \max(-\mathrm{f}(\boldsymbol{x}))$.

Finally, strategic decisions parameters are related to the agency objectives, goals and maintenance policy. They include required minimal pavement condition, available maintenance budget, analysis period and discount rate. Strategic decision parameters include technical and economic information. However, they are not included in these categories because their value is determined in upper management levels based on political or administrative decisions. A variation in strategic decision parameters would indeed reflect different maintenance policies.

The second component corresponds to the evaluation module. This component assesses maintenance programs in terms of their technical, economic, and environmental impact. Given a maintenance program, the technical module estimates pavement condition over time (depicted by the pavement performance curve) and long-term effectiveness (LTE). As depicted in Fig. 2, LTE is assessed for each section of the network in terms of the area bounded by the pavement performance curve and a condition threshold. The total LTE of a maintenance program is obtained by adding the LTE of all the section in the network. LTE is largely applied in the pavement field as a surrogate for overall user benefits because a well-maintained pavement, thus having a larger area bounded by the performance curve, provides greater social benefits than a poorly maintained infrastructure (Khurshid et al., 2009; Torres-Machi et al., 2014a). Some studies consider the LTE together with costs, hence using a cost-effectiveness evaluation (Chamorro and Tighe, 2015; Torres-Machi et al., 2014a). Given that this study is seeking the optimal allocation of maintenance funds, costs and LTE are considered separately: the aim is to maximize LTE and minimize GHG emissions while ensuring that maintenance costs do not exceed the budget available. Therefore, the economic module quantifies the annual cost of the maintenance program and compares it to the available budget. Finally, the environmental module evaluates the environmental impact of the maintenance program in terms of the total GHG emissions derived from the application of maintenance treatments.

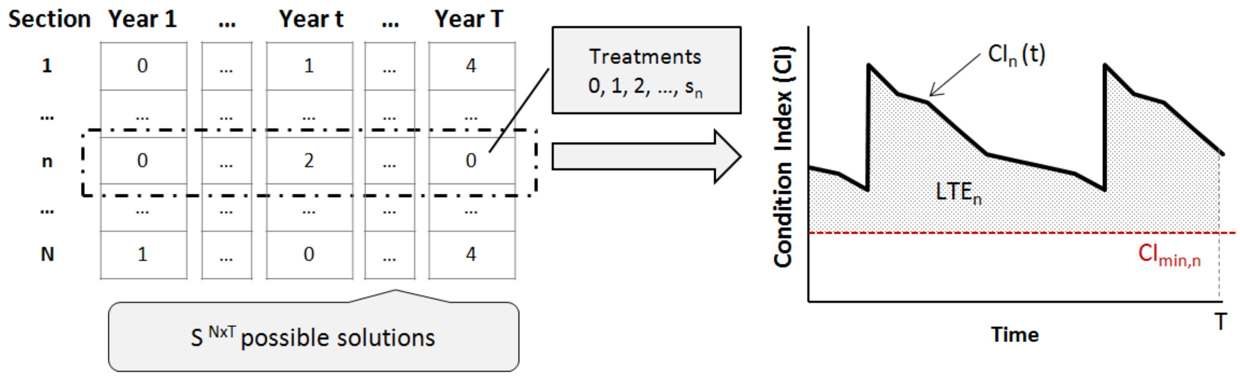

Fig. 2. Technical evaluation of maintenance program for section n.

The main component of the proposed tool undertakes the optimization process by considering two objectives simultaneously: maximizing LTE (Equation (1)) and minimizing GHG emissions (Equation (2)).

$$\max f_1(\boldsymbol{x}) = \max LTE = max \sum_{n=1}^{N} \int_{t=0}^{T} (CI_n(t) - CI_{min,n})\, dt \tag{1}$$

$$min\, f_2(\boldsymbol{x}) = min \sum_{n=1}^{N} (GHG)_n \tag{2}$$

where *LTE* is the long-term effectiveness of the maintenance program, $CI_n(t)$ is the condition index of section n in year t, $CI_{min,n}$ is the minimal condition index of section n, GHG_n is the environmental impact of the maintenance program considered for section n, t is the year of analysis (with $t \leq T$, being T the analysis period), and n is the section being analyzed (with $n \leq N$, being the total number of sections in the network).

In the optimization process, both budgetary and technical constraints are considered. The budgetary constraint ensures that present annual cost does not exceed available budget (Equation (3)). In technical terms, a minimal condition for all the sections in the network is required (Equation (4)).

$$g_1(\boldsymbol{x}) = \sum_{n=1}^{N} cost(x_n) \cdot \frac{1}{(1+i)^t} \leq B(t)\,;\ \forall\, t \tag{3}$$

$$g_2(\boldsymbol{x}) = CI_n(t) \geq CI_{min,n};\ \forall\, t \text{ and } \forall\, n \tag{4}$$

where *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 the discount rate i in year t, $B(t)$ is the present value of the budget available in year t, $CI_n(t)$ is the condition index of section n in year t, and $CI_{min,n}$ is the minimal condition index of section n.

As a result of this process, an optimal maintenance programs at the network level is defined. Given that two objective functions are considered simultaneously, there is not a unique optimal solution and a Pareto set of non-dominated solutions is defined. A solution is called non-dominated (also known as Pareto optimal) if none of the objective functions can be improved in value without degrading some of the other objective values (Marler and Arora, 2004). The results derived from the optimization process should retrofit the system to guarantee feedback between the optimization results and the strategic parameters (dashed arrow in Fig. 1).

2.2. Integration of Technical and Environmental Evaluation of Maintenance Alternatives

In order to integrate technical and environmental evaluations, this study proposes to penalize the LTE of those alternatives that are less respectful of the environment. Penalization is assessed for each maintenance alternative (s_n) in terms of an environmental coefficient ($\beta_{env,sn}$) ranging from 0 to 1, being 0 the corresponding value for the worst environmental evaluation. This study proposes thus a new environmental coefficient ($\beta_{env,sn}$) aimed to enhance the application of treatments that are more respectful toward the environment. By using the proposed environmental coefficient, maintenance alternatives producing lower GHG emissions should receive better evaluations (and thus lower penalizations) than those alternatives producing higher emissions. The environmental coefficient of a maintenance alternative is obtained based on Equation (5). This evaluation considers: GHG emissions produced by the treatment under evaluation (GHG_{sn}); the minimum and maximum GHG emissions of the maintenance alternatives that could be applied to the section n under evaluation (GHG_{min} and GHG_{max}, respectively); and an environmental parameter (w_{env}), ranging from 0 to 1, that accounts for the importance of the environmental evaluation.

The value of w_{env} can be set either before or after the optimization process. In the former case, decision makers set the relative importance among objectives before the optimization process is undertaken. In this case, the optimization tool will provide a unique solution which accounts for the decision makers preferences. Another approach consists of analyzing the set of optimized solutions obtained with different values of $w_{env.}$ This approach allows to explore the solution space and define the Pareto set of solutions. The main advantage of this approach is that it allows decision makers to define the preference between objectives after the optimization process. This study proposes to explore the solution space by varying the value of w_{env} through a grid of values from 0 to 1 in incremental steps of 0.05. This approach is one of those most commonly used in the infrastructure management field to define the Pareto set of solutions (Meneses and Ferreira, 2015; Wu and Flintsch, 2009; Wu et al., 2012).

$$\beta_{env,sn} = (1 - w_{env}) \cdot \frac{GHG_{sn} - GHG_{min}}{GHG_{max} - GHG_{min}} + \frac{GHG_{max} - GHG_{sn}}{GHG_{max} - GHG_{min}}; \text{ with } w_{env} \in [0,1] \tag{5}$$

2.3. Heuristic Multi-Objective Optimization Algorithm

This study proposes a heuristic multi-objective optimization algorithm based on a hybrid Greedy Randomized Adaptive Search Procedure (GRASP). Compared to other heuristic algorithms based on a local search, such as those proposed by Tsunokawa et al. (2006) and Chou and Le (2011), GRASP enables efficient exploration of the solution space when the alternatives considered are not continuous or generate significant changes in the starting solution (Yepes and Medina, 2006). The proposed optimization process is developed in two phases explained in the following subsections.

2.3.1. Construction of Feasible Solutions

One of the problems of heuristic algorithms in the design of maintenance programs is the difficulty of obtaining solutions that satisfy both technical and economic constraints (Equations (3) and (4)). Given this issue, the proposed algorithm constructs initial feasible solutions using a hybrid GRASP. GRASP (Feo and Resende, 1989) follows an iterative process in which all the possible alternatives are analyzed and ranked based on a greedy function. The greedy function assesses the benefits derived from including an alternative in the solution. All the possible maintenance treatments are evaluated and ranked using the greedy function. The alternatives to be included in the final solution are selected based on a probabilistic function that combines quality and variability.

The proposed optimization algorithm includes a greedy function that considers: the environmental coefficient (Equation (5)); the increase in LTE derived from the application of the maintenance treatment; and a term that prioritizes those sections that will fail before the end of the analysis period if no treatment is applied. This greedy function is an adaptation of that proposed by Yepes et al. (2016), which has the advantage of incorporating environmental aspects in the evaluation of maintenance alternatives. Thus:

$$GF_{n,sn} = \beta_{env,sn} \cdot \left(LTE_{n,sn} - LTE_{n,0}\right) + \lambda \cdot \left(T - t_{failure,0}\right) \cdot I(\boldsymbol{x}) \tag{6}$$

Where $GF_{n,sn}$ is the value of the greedy function when maintenance alternative s_n is applied in section n, $\beta_{env,sn}$ is the environmental coefficient defined in Equation (5), $(LTE_{n,sn} - LTE_{n,0})$ is the increase in long-term effectiveness gained if the treatment s_n is applied compared to the alternative if no treatment is applied, λ is a parameter controlling the prioritization of those sections that will fail before the end of the period of analysis, T is the period of analysis, $t_{failure,0}$ is the year of failure if no treatment is applied, and $I(\boldsymbol{x})$ is a dichotomic function the value of which equals 1 if $t_{failure,0} \leq T$ and 0 otherwise.

2.3.2. Improvement of Constructed Solutions

In this second phase, constructed solutions are improved based on a local search heuristic. Specifically, a greedy first best (GFB) algorithm is developed. This algorithm starts from the initial constructed solution and explores the solution inference space seeking better solutions. In this exploration, alternative solutions are generated by slightly modifying the maintenance program of the initial constructed solution. Slight modifications, implying that the value of the alternative solution is close to the initial one, are necessary to guarantee the efficiency of the local search. The objective function considered in this improvement phase (Equation (7)) incorporates the sustainable approach proposed in section 3.2 in terms of the environmental coefficient:

$$\max f(\boldsymbol{x}) = \max \sum_{n=1}^{N} \beta_{env} \cdot LTE_n \tag{7}$$

where β_{env} is the environmental coefficient defined in Equation (5) and LTE_n is the long-term effectiveness of the maintenance program applied to section *n*.

3. CASE STUDY: THE MANAGEMENT OF AN URBAN PAVEMENT NETWORK IN CHILE

The proposed optimization tool is applied to a real case study addressing the management of a real urban pavement network in Chile.

3.1. Network Characteristics

The network considered in this application is located in Santiago (Chile), which is characterized by a mild Mediterranean climate (Osorio et al., 2014). The urban network in Santiago comprises a total length of 810 km (MINVU, 2008). In this case study, a portion of this network is analyzed, namely 20 sections of a total length of 10 km (Table 1). This network includes asphalt and concrete pavements belonging to the different hierarchies in the network (MINVU, 2008): primary network (with an average capacity lower than 600 veh/hour) and secondary network (with an average capacity ranging from 600 to more than 4,000 veh/hour).

In this case study, pavement condition is assessed in terms of an overall condition index named the Urban Pavement Condition Index (UPCI). This index, proposed by Osorio et al. (2014), assesses pavement condition based on objective measures of pavement distresses by using a scale of 1 to 10, being 10 the best condition possible. The initial condition of the network ($UPCI_{initial}$) was established based on data collected in the field in June 2012 (Table 1). The performance models considered in this case study were specifically developed for the management of Chilean urban pavements in the Mediterranean climate (Osorio, 2015; Osorio et al., 2015). These models employ data collected in field evaluations using transition probability matrices and Monte Carlo simulations (Osorio, 2015; Osorio et al., 2015).

Table 1. Inventory characteristics of the network considered in the case study

ID	Network	Structure	Length [m]	Width [m]	UPCI $_{initial}$
1	Primary	Asphalt	718	3.5	5.5
2	Primary	Asphalt	850	3.6	5.2
3	Secondary	Asphalt	118	4.0	6.6
4	Primary	Asphalt	600	3.4	6.6
5	Primary	Asphalt	502	3.0	8.0
6	Primary	Asphalt	98	3.0	7.1
7	Primary	Asphalt	273	3.6	8.3
8	Primary	Asphalt	503	3.0	9.4
9	Secondary	Asphalt	533	3.6	10.0
10	Primary	Asphalt	393	3.4	9.9
11	Primary	Concrete	547	3.5	7.7
12	Primary	Concrete	836	3.1	7.7
13	Primary	Concrete	562	3.0	9.0
14	Secondary	Concrete	355	3.5	8.2
15	Primary	Concrete	1.190	3.0	8.1
16	Primary	Concrete	366	3.5	9.5
17	Secondary	Concrete	175	4.0	9.3
18	Primary	Concrete	336	3.5	9.1
19	Secondary	Concrete	170	3.0	9.3
20	Primary	Concrete	511	3.3	9.2

Source: Fondef Project (Videla et al., 2010)

Taking into consideration the various definitions and characteristics of maintenance treatments available from the state of the art and the practice (Osorio, 2015; TAC, 2013), a set of maintenance treatments were defined for the purpose of this study, which are presented in Tables 2 and 3. For asphalts, preservation treatments mainly rely on seals that can be applied when the pavement condition is still good; while maintenance treatments consists of placing new wearing surfaces using in-place recycling or structural overlays. With respect to concrete, preservation treatments consider functional overlays and reducing irregularities by diamond grinding. Maintenance treatments include structural overlays and full depth repair, which consists of removing the loose material from the concrete pavement and pouring a new concrete layer on top of the cleaned surface.

Most of the treatments reflect current practices in Chile, based on meetings with professionals in charge of the network developed within the framework of the Fondef Project (Videla et al., 2010). Treatments not currently applied in Chile were extracted from the international literature and included in the analysis to broaden the scope and future application of this study in other countries. This is the case of treatments such as cold and hot in-place recycling, not currently applied to urban pavements in Chile but included because they reduce the use of raw material. It is important to note that to consider the different management of pavements in the primary and secondary networks, the set of maintenance treatments included for each network are different. As these networks differ in terms of the structural design and traffic loading, the set of available maintenance treatments also differ on their quality and structural capacity.

The sets of treatments vary in terms of the distresses that they are able to address. This is why each treatment may be grouped within a maintenance category (preservation, maintenance or rehabilitation) and should be applied within a range of pavement condition (expressed in terms of UPCI). These values have been defined based on the decision trees used by Chilean and international administrations for the selection of optimal maintenance treatments (Hicks et al., 2000; MOP, 2012a, 2012b; Peshkin et al., 2004).

The application of maintenance treatment produces an increase in pavement condition ($\Delta UPCI$) and therefore an increase in pavement service life (ΔSL). Tables 2 and 3 show the increase in service life for each maintenance treatment. These values have been calibrated based on previous studies (Chan et al., 2011; Gransberg, 2010; Gransberg and James, 2005; Hicks et al., 2000; Peshkin et al., 2004; TAC, 2013; Wu et al., 2010). These studies allow calibration of the effect of treatments in terms of the UPCI and make it possible to determine the maximal increase in pavement condition derived from the application of each maintenance treatment ($UPCI_{max}$).

The application costs of each maintenance treatment are also included in Tables 2 and 3. These values are defined based on maintenance contracts in the city of Santiago and on information from the Ministry of Public Works of Chile (Ilustre Municipalidad de Santiago and Pehuenche, 2012; MOP, 2012c). For treatments not currently applied in Chilean urban areas, such as microsurfacing and in-place recycling, costs were estimated from international studies (Chan and Tighe, 2010a; Hicks et al., 2000). In these cases, a corrective coefficient was applied to account for the difference between Chilean and international costs. This corrective coefficient was calculated, when both Chilean and international cost data was available, as the average cost difference between them.

Environmental impact derived from the application of each maintenance treatment is also included in Tables 2 and 3. Values considered in the case study were mainly obtained from the PaLATE worksheet, which consists of a life-cycle assessment tool that considers construction materials and processes in terms of an inventory of emissions and hazardous material outputs over the life cycle of the pavement (Nathman et al., 2009). Values proposed by PaLATE were compared to those obtained by other studies in order to check the consistency of results. In these cases, values of GHG emissions were averaged and then included in the analysis. A detailed description of the sources used to determine GHG emissions are included in Tables 2 and 3. It is important to note that existing studies may differ in the considerations taken in the evaluation. This is, indeed, a major limitation in pavement life cycle assessment, as existing studies lack of consensus upon the assumptions considered in the evaluation (Santero et al., 2011; AzariJafari et al., 2016). Previous studies differ thus in aspects such as the functional unit, the time horizon and the data sources considered in pavement life cycle assessment (Table 4).

At this point it is worth mentioning that the present study aims to introduce a tool aimed to design optimal maintenance programs by simultaneously considering technical and environmental aspects. The goal of this research is to identify the difference between maintenance treatments, not an absolute value of their environmental or technical impact. Given this assumption, future work could address a sensitivity analysis analyzing the effect of the value of GHG emissions in the maintenance programs designed with the optimization tool proposed in this paper. The environmental evaluation considered in this case study could also be enhanced by including traffic and vehicle operation emissions derived from pavement condition. However, most of the existing models relating GHG emissions and pavement condition are based on fuel consumption, which is mainly driven by pavement roughness (normally assessed through the International Roughness Index [IRI]) and vehicle speed (Santos et al., 2015). These models could be considered in applications in which IRI is a suitable indicator of pavement condition. However, this is not the case for urban pavements (Shafizadeh and Mannering, 2003).

Given that the development of a specific life cycle assessment tool exceeds the scope of this research, this case study relies on existing environmental evaluations and considers GHG emissions derived from the application of maintenance treatments. This approach, already considered in previous studies (Giustozzi et al., 2012; Gosse et al., 2013), aims to recognize maintenance alternatives enhancing environmental sustainability.

Table 2. Characteristics of maintenance treatments considered for asphalt pavements

Treatment	Maintenance category	Application threshold [UPCI]		Service life increase (ΔSL) [years]		UPCI$_{max}$		Cost [US\$/m^2]		GHG emissions [kg CO_2/m^2]		GHG emissions source
		PN	SN	PN	SN	PN	SN	PN	SN	PN	SN	
Fog seal	Preservation	≥ 8.5	-	1	-	9.50	-	2.19	-	0.04	-	[1]
Slurry seal	Preservation	≥ 7.5	-	2	-	9.75	-	4.69	-	0.32	-	[1]–[3]
Chip seal	Preservation	≥ 7.5	-	2	-	9.75	-	4.90	-	0.43	-	[1]–[3]
Microsurfacing	Preservation	≥ 7.0	-	3	-	9.75	-	7.76	-	1.51	-	[2]–[6]
Milling and functional overlay	Preservation	≥ 6.5	≥ 5.5	4	3	10.00	9.50	25.90	15.86	6.75	6.68	[1]–[3], [7]
Hot in-place recycling	Maintenance	≥ 5.5	-	5	-	10.00	-	53.54	-	6.70	-	[1], [2], [4], [5], [8], [9]
Cold in-place recycling	Maintenance	≥ 5.5	-	6	-	10.00	-	54.65	-	5.49	-	[2], [7]–[9]
Milling and structural overlay	Maintenance	≥ 4.5	≥ 3.5	8	7	10.00	10.00	63.79	34.19	13.11	7.66	[1], [2], [8]
Reconstruction	Rehabilitation	≥ 1	≥ 1	15	15	10.00	10.00	143.59	81.64	27.36	13.78	[2], [8]

Table 3. Characteristics of maintenance treatments considered for concrete pavements

Treatment	Maintenance category	Application threshold [UPCI]		Service life increase (ΔSL) [years]		UPCI$_{max}$		Cost [US\$/m^2]		GHG emissions [kg CO_2/m^2]		GHG emissions source
		PN	SN	PN	SN	PN	SN	PN	SN	PN	SN	
Diamond grinding	Preservation	≥ 7.0	-	3	-	9.75	-	14.71	-	0.02	-	[1]–[3], [10], [11]
Milling and functional overlay	Preservation	≥ 7.0	-	5	-	9.75	-	32.29	-	6.67	-	[1]–[3], [7], [10], [11]
Full depth repair	Maintenance	≥ 4.5	≥ 3.5	6	5	10.00	9.50	49.06	19.28	9.62	4.81	[2]
Milling and asphalt structural overlay	Maintenance	≥ 4.5	≥ 3.5	7	6	10.00	10.00	55.35	28.90	22.56	13.16	[2], [10], [11]
Milling and concrete structural overlay	Maintenance	≥ 4.5	≥ 3.5	8	7	10.00	10.00	74.27	43.32	13.60	7.93	[1], [2], [10], [11]
Reconstruction	Rehabilitation	≥ 1	≥ 1	20	20	10.00	10.00	203.69	158.44	40.63	24.38	[2]

Notes: PN denotes the primary network; SN is the secondary network

Source: Various (detailed in the text). Sources for GHG emissions are detailed following the following code: [1] Chehovits and Galehouse (2010); [2] Nathman et al. (2009); [3] Robinette and Epps (2010); [4] Chan et al. (2011); [5] Giustozzi et al. (2012); [6] Gransberg (2010); [7] Chan and Tighe (2010b); [8] Cerea (2010); [9] Schvallinger (2011); [10] Santero et al. (2013); [11] Wang et al. (2014).

Table 4. Environmental database and analysis period considered in reviewed studies

	Sources considered for GHG emissions										
Environmental database	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
Eurobitume (1999)	x		x	x	x	x	x	x			
Athena (2006)	x		x	x	x	x	x	x			x
IVL (Stripple, 2001)	x		x	x	x	x	x	x			x
PaLATE (Nathman, 2009)		x		x			x				
EcoInvent (2011)					x						x
AsPECT (TRL Limited, 2009)					x			x	x		
GaBi (PE International, 2011)										x	
USLCI (National Renewable Energy Laboratory, 2011)											x
PCA (Marceau et al., 2006)											x
Analysis period (years)	30	N.A.	40	30	50	30	30	50	N.A.	40	5 and 10

Sources for GHG emissions are detailed according to this code: [1] Chehovits and Galehouse (2010); [2] Nathman et al. (2009); [3] Robinette and Epps (2010); [4] Chan et al. (2011); [5] Giustozzi et al. (2012); [6] Gransberg (2010); [7] Chan and Tighe (2010b); [8] Cerea (2010); [9] Schvallinger (2011); [10] Santero et al. (2013); [11] Wang et al. (2014).

Regarding strategic decisions, this study considers a period of analysis (*T*) of 25 years. This period was chosen to account for a complete pavement life cycle. The discount rate (*i*) applied to discount maintenance costs over the period of analysis is 6%. This value is that proposed by the Chilean Ministry for the evaluation of social projects (Ministerio de Desarrollo Social, 2014). To guarantee a minimal network condition, it is required that none of the sections need to be rehabilitated. In terms of UPCI, this condition translates into a minimal pavement condition ($UPCI_{min}$) of 4.5 for the primary network and 3.5 for the secondary network.

The budgetary restriction was estimated by simulating current maintenance practices in Chile. Currently, pavements are maintained under a reactive policy in which asphalt overlays are applied to pavements showing high levels of deterioration. This scenario, called "base case", intends to simulate the expenses derived from the current maintenance policy. This budget does not reflect the current maintenance budget of the network, or the optimal budget to maintain it. Rather, it simulates the current maintenance costs derived from the reactive maintenance policy. Considering these assumptions, the equivalent annual maintenance budget is US$ 210,750.

3.2. Results

As stated before, this study explores the solution space of the bi-objective optimization problem by varying the value of w_{env} through a grid of values from 0 to 1 in incremental steps of 0.05. For each value of the environmental coefficient (w_{env}), a set of 25 maintenance programs were optimized, leading to a total of 525 potential solutions (Fig. 3). Among these 525 potential solutions, only 5% of them accomplished both economic and technical restrictions. The difficulty of finding feasible maintenance programs highlights that economic and technical restrictions set in this case study are very demanding.

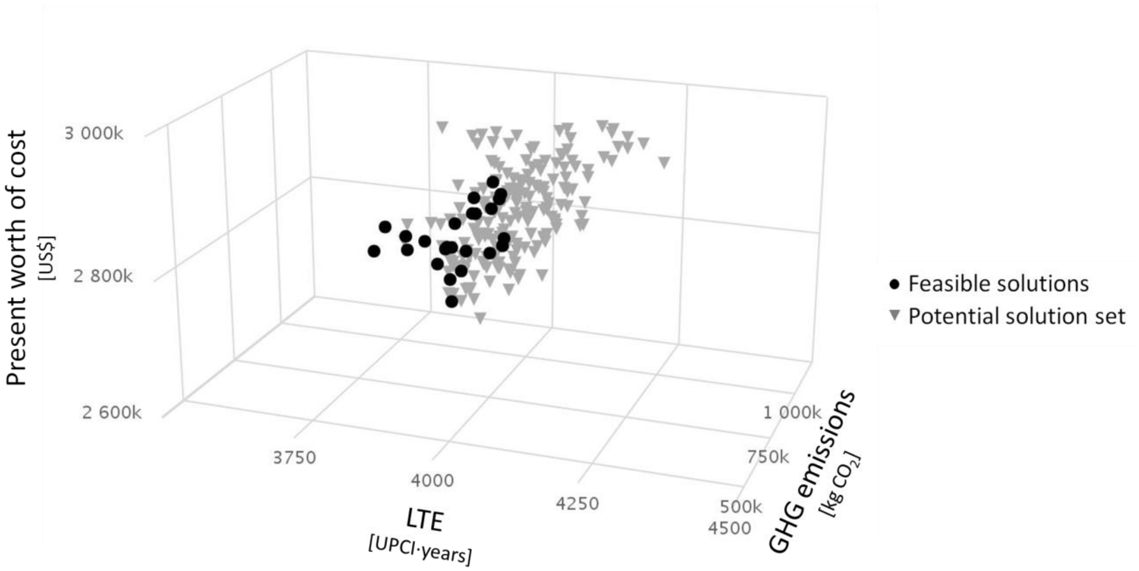

Fig. 3. Set of solutions obtained in the bi-objective optimization problem

To provide a better understanding of the solutions defined in the bi-objective optimization, three of the non-dominated solutions are analyzed in detail: the solution with the highest long-term effectiveness (LTE_{max}), the solution with the lowest GHG emissions (GHG_{min}), and a compromise solution (N_{min}) defined as the one with the shortest normalized Euclidean distance to the "ideal point". In multi-objective optimization problems, the "ideal point" corresponds to a theoretical solution that contains the best values for each objective function. In this case study, the "ideal point" would correspond to a theoretical maintenance program having the maximum long-term effectiveness (LTE_{max}) and minimal GHG emissions (GHG_{min}). Given that the "ideal point" is generally unattainable, the next best thing would be a solution as close as possible to the "ideal point" (Marler and Arora, 2004). This is the reason why this case study analyzes a compromise solution, called N_{min}, which has the shortest Euclidean distance to the "ideal point". Note that if the relative importance of the objectives changes (expressed in terms of the environmental coefficient w_{env}), a different compromise solution may be chosen. This choice depends on the goals and objectives of the administration in charge of the network.

Table 5. Characteristics of the optimal solutions obtained in the bi-objective optimization

	Base case	**LTE_{max}**	**N_{min}**	**GHG_{min}**
Present worth of cost [US$]	2,855,720	2,797,610	2,800,450	2,774,540
LTE [UPCI·years]	1,045	3,988	3,984	3,934
GHG emisisons [kg CO_2]	823,638	877,399	809,855	725,464
Environmental coefficient (w_{env})	NA	0.2	0.3	0.7

Table 5 shows the characteristics of optimal solutions (LTE_{max}, GHG_{min}, and N_{min}) in terms of cost, long-term effectiveness and GHG emissions. These values correspond to measures for the whole network in the whole analysis period. Base case solution is also included in Table 5 for comparison purposes. Results in Table 5 also show the effect of w_{env} in the search of optimal solutions. Optimal solutions having a lower environmental impact are obtained when considering values of w_{env} closer to 1. That is, when the environmental impact is given more importance than technical impact.

Results in Table 5 allow concluding that the two objectives are in conflict: it is difficult to improve one of them without a deleterious effect on the other one. Indeed, the solution showing the highest LTE (LTE_{max}) corresponds to that with the highest GHG emissions. On the other hand, the most environmentally friendly solution (GHG_{min}) corresponds to the solution with the lowest LTE and therefore the lowest network condition. In environmental terms, the solution showing lower GHG emissions (GHG_{min}) reduces environmental impact by 12% compared to the base case scenario (Table 5). Indeed, when the GHG_{min} solution is compared to that with the highest LTE (LTE_{max}), the emission reduction is 21%.

In technical terms, optimal solutions present a LTE nearly four times higher than the one obtained in the base case (Table 5). Given that LTE is correlated with pavement condition over time, average network condition, expressed in terms of UPCI, is analyzed here because its value may be easier to understand than LTE. In terms of network condition, optimal solutions present similar values (Fig. 4). Indeed, the three optimized solutions present an average network condition in the 25 years period similar to the initial condition ($UPCI$ = 7.9). In terms of average UPCI, optimal solutions increase network condition obtained in the base case by 22% (Fig. 4).

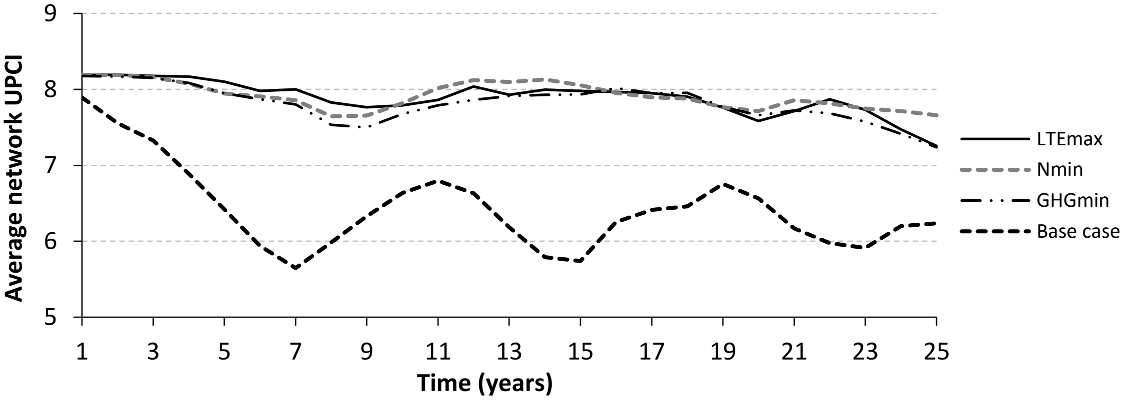

Fig. 4. Average network condition in optimal and base case scenarios.

To derive practical recommendations for the design of maintenance programs, treatments considered in the optimal solutions will now be analyzed in detail. This analysis allows us to conclude that rehabilitation treatments are not sustainable (both in terms of LTE and GHG emissions), as they are not included in any optimal maintenance program (Fig. 5). Fig. 5 also shows that the optimal programs are based on a proactive maintenance policy, in which preservation treatments are applied when pavements are still in good condition. In the following paragraphs, a more detailed analysis of treatments applied in optimal maintenance programs is developed. For this purpose, Fig. 6, 7 and 8 show the application rate of each treatment in optimal programs. The application rate accounts for the number of times one treatment was applied in optimal programs. For example, when seeking to maximize LTE (LTEmax in Fig. 6), the preferred preservation treatments are slurry and fog seals, which accounted for 93% of the interventions in optimal programs.

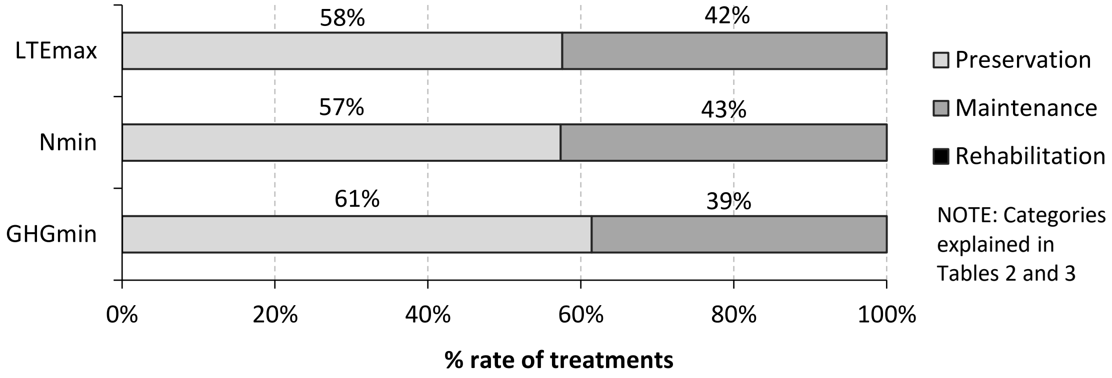

Fig. 5. Types of treatment considered in optimal maintenance programs.

Data in Fig. 6 allows us to conclude that preservation treatments mainly applied to asphalt pavements are slurry and fog seals. Fog seals are indeed highly recommended in the design of environmentally friendly maintenance programs (*GHG*$_{min}$ in Fig. 6). In this regard, it is worth mentioning that fog and slurry seals are the less intensive preservation treatments considered in this study, as they can only address pavement distresses with low severity and extent. This is the reason why the threshold values for the application of these treatments are especially high (*UPCI* ≥ 8.5 for fog seal and *UPCI* ≥ 7.5 for slurry seal, Table 2). These results support the conclusion derived previously: optimal maintenance programs are based on a proactive maintenance policy. From this analysis, it can also be concluded that pavement preservation with chip seal is not competitive in technical, economic, and environmental terms, barely being applied in optimal programs (Fig. 6).

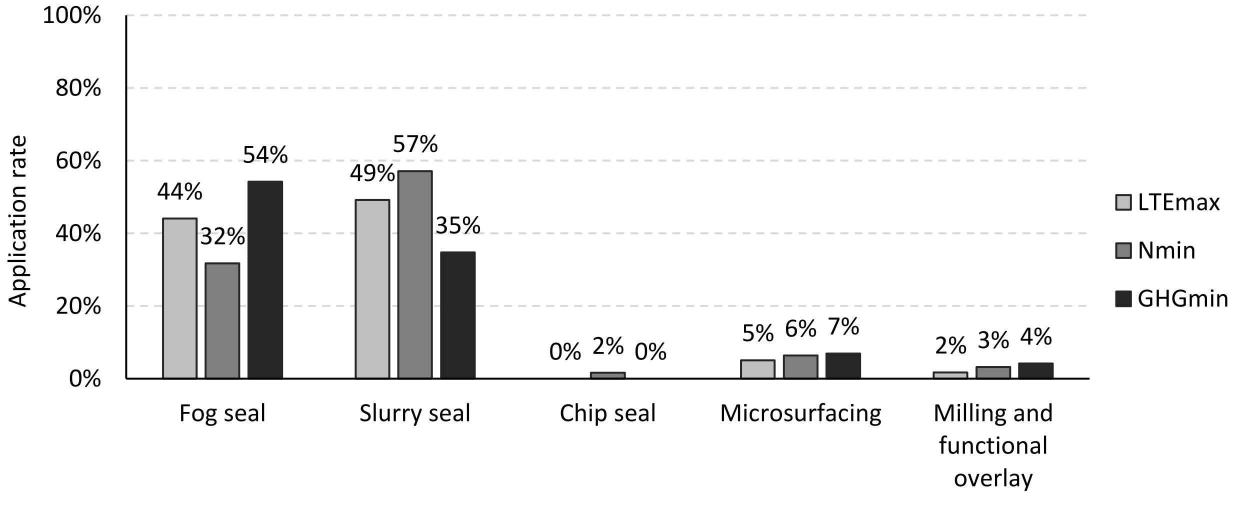

Fig. 6. Optimal preservation treatments for asphalt pavements.

Regarding maintenance treatments for asphalt pavements, Fig. 7 shows that optimal programs mainly apply structural overlays. Treatments using recycling techniques are only included when environmental aspects are considered (*N*$_{min}$ and *GHG*$_{min}$ in Fig. 7).

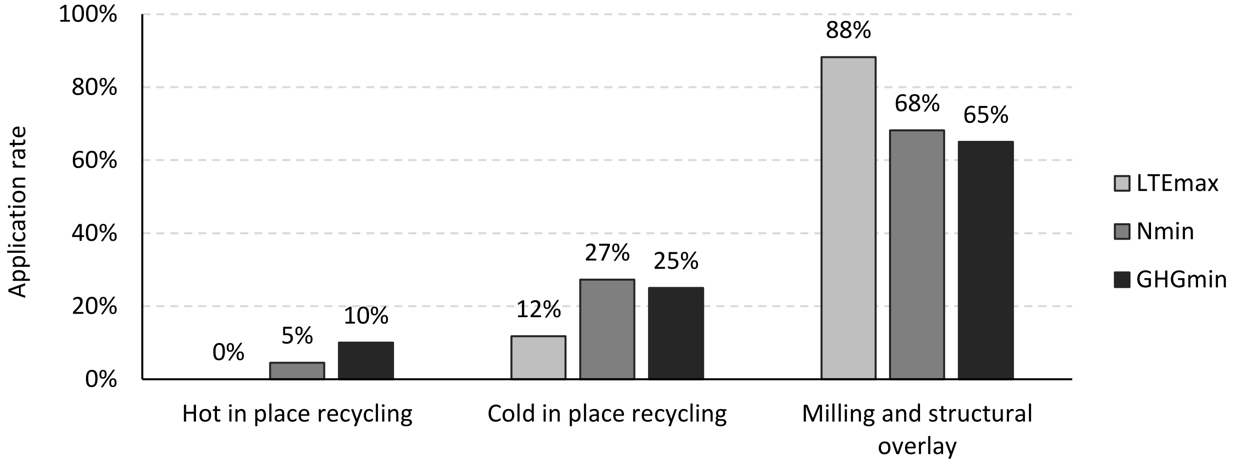

Fig. 7. Optimal maintenance treatments for asphalt pavements.

Regarding concrete pavements, the preservation treatment addressed in all the optimal programs is diamond grinding. Functional overlay is not competitive as it is not included in any optimal solution. The preference for diamond grinding may be due to the fact it is the only treatment whose application does not require the use of raw materials. Indeed, diamond grinding eliminates irregularities by removing a thin layer of the concrete pavement. The optimization tool thus enhances the application of treatments with low consumption of raw materials, and consequently lower emissions derived from their extraction and application.

On the other hand, optimal maintenance treatments for concrete pavements show higher variability (Fig. 8). Although asphalt structural overlay is widely included in the optimal programs, concrete structural overlay and full-depth repair are also considered. Structural overlays are mostly applied in programs seeking maximal LTE, whereas full-depth repair is recommended to minimize GHG emissions (Fig. 8).

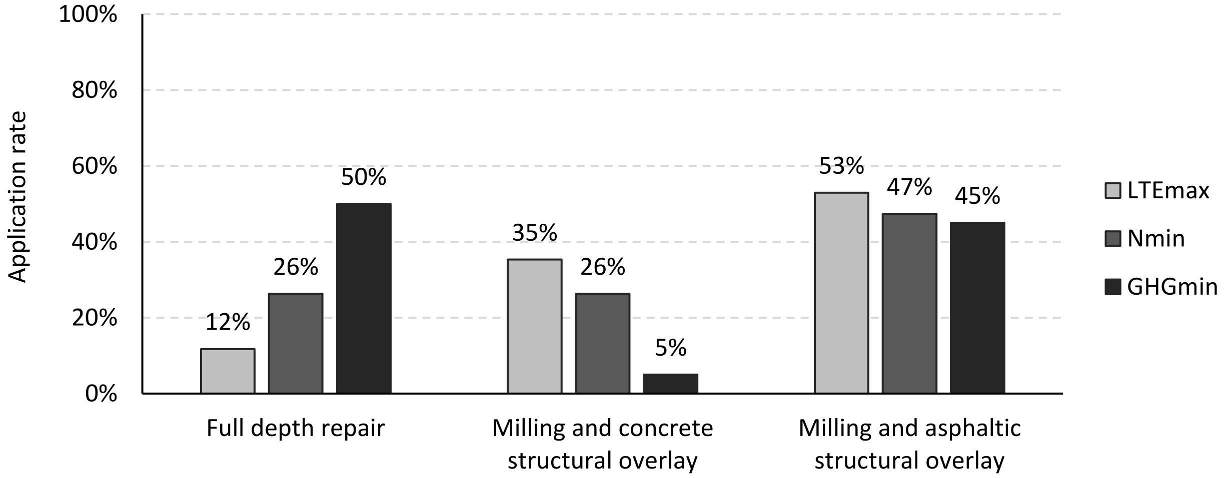

Fig. 8. Optimal maintenance treatments for concrete pavements.

3.3. Analysis of Sensitivity to Budgetary Restrictions

One of the main advantages of the proposed tool is that it analyzes the effect of different budgetary scenarios. To study this capability, this section optimizes maintenance programs for eight budgetary scenarios. These scenarios consider a percentage variation from the initial budget (base case) with modifications within a range of ±20% and variations of 5%. The first conclusion derived from this analysis is that the network is very sensitive to budgetary reductions. Indeed, based on the results of this study, it is not possible to design feasible maintenance programs when the budgetary reductions are higher than 5%.

Fig. 9 shows the GHG emissions and LTE of non-dominated solutions obtained in this analysis. In this figure, the budget available is depicted using a color scale. In scenarios with high budgetary restrictions, there are few non-dominated solutions (blue solutions in Fig. 9). These solutions present high levels of GHG emissions and low LTE, thus implying a low level of service. On the other hand, larger budgets (red solutions in Fig. 9) allow to design maintenance programs with lower GHG emissions and higher LTE.

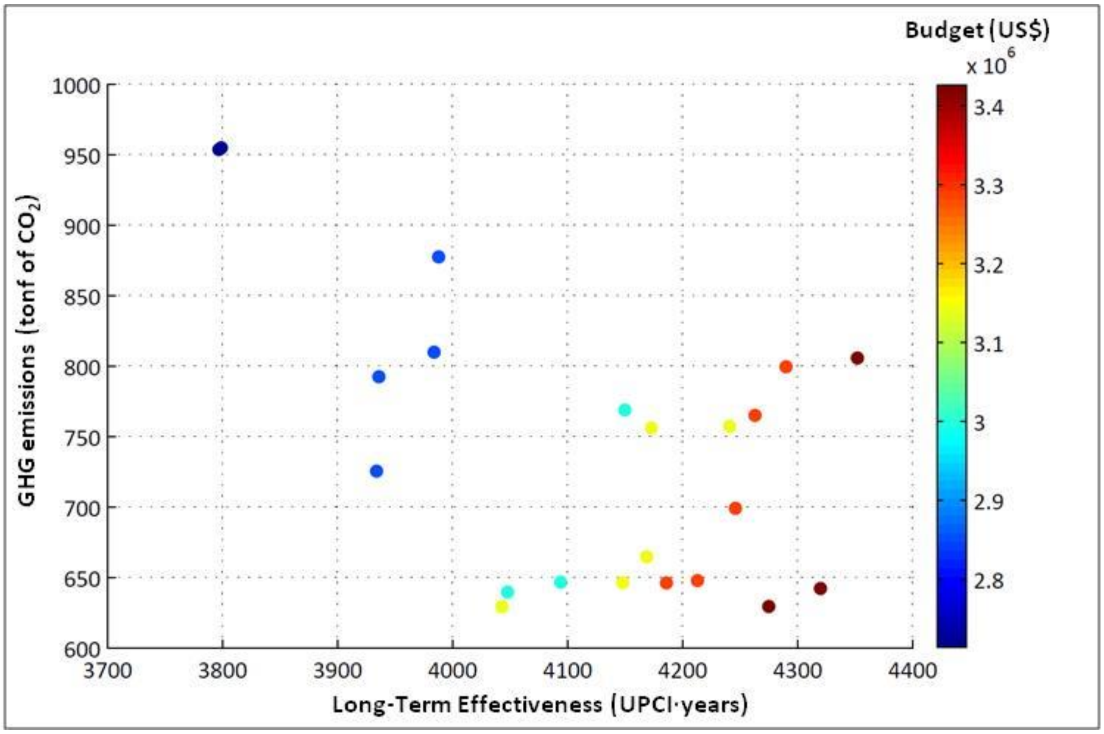

Fig. 9. Non-dominated solutions obtained with percentage variations of available budget.

Among the set of non-dominated solutions depicted in Fig. 9, those with the lowest environmental impact (GHG_{min}) and the highest LTE (LTE_{max}) are analyzed in detail. This analysis provides a better understanding of the effect of budgetary restrictions on the environmental and technical performance of the network. In this analysis, the values of LTE_{max} and GHG_{min} are compared to those obtained in the base case scenario. This is the reason why variations in the base case scenario (for which there are no variations in the budget available), variations in LTE and GHG are 0% (Fig. 10).

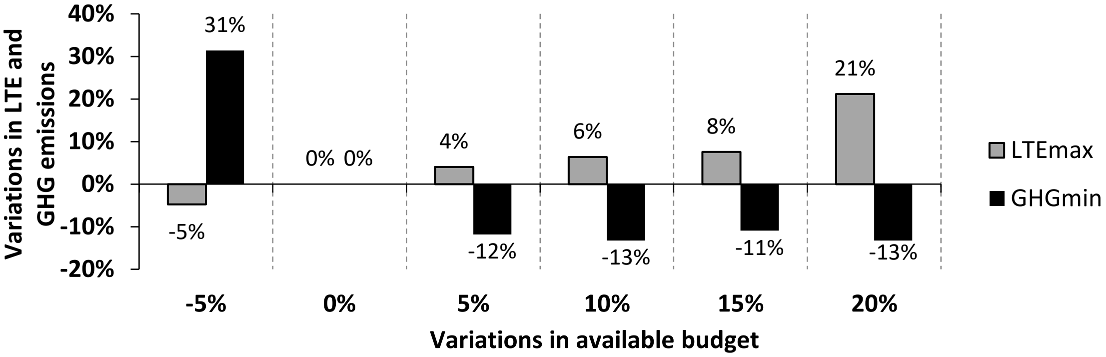

Fig. 10. Variations in LTE and GHG emissions with the available budget.

In technical terms, a slight variation in *LTE_{max}* is observed when variations in the available budget are small (Fig. 10). Indeed, changes in the available budget of between 5% and 15% lead to variations in LTE_{max} of between 5% and 8%. However, this trend changes significantly when a more generous budget is available. When the budget increases by 15% to 20%, LTE_{max} is boosted from 8% to 15%. In environmental terms, optimal solutions are more sensitive to budget reductions than to increases. Fig. 10 shows that a reduction of 5% in the available budget increases GHG emissions by 31%. Meanwhile, a budgetary increase of the same proportion only reduces GHG emissions by 12%. This reduction remains nearly constant in all the scenarios where the available budget is increased (Fig. 10).

In practical terms, results presented above lead to conclude that the budget taken from the base case scenario might be considered reasonable. On the one hand, a budgetary reduction would lead to an appreciable increase in GHG emissions and a reduction in LTE, and therefore a lower level of service. On the other hand, benefits derived from a budget remain nearly constant when the budget varies from 5% to 15%. These benefits become more significant when the available budget increases by 20%. Therefore, if the manager in charge of this network were to be given a higher maintenance budget, the recommendation derived from this analysis would be either to increase the maintenance budget slightly (by around 5%) or significantly (by around 20%). It is in this scenario that both technical and environmental gains are more appreciable, whereas the benefits derived in intermediate scenarios (with budgetary increases of between 5% and 20%) are negligible.

4. CONCLUSIONS

This research has proposed an optimization tool aimed at enhancing the sustainable design of maintenance programs by incorporating environmental aspects in the decision process. The application of the proposed tool to a real case study dealing with an urban pavement network in Chile provides a set of research contributions and practical recommendations.

The results obtained in this study demonstrate that the integration of environmental impacts with the aspects traditionally considered (technical and economic) enables a more sustainable allocation of maintenance resources. Under similar budgetary restrictions, the proposed tool designs maintenance programs that increase the average network condition by up to 22%, with a reduction in GHG emissions of 12%. Therefore, the proposed tool enables a more sustainable management of the pavement network.

In practical terms, this study highlights the importance of proactive maintenance policies. The results show that, compared to reactive policies based on maintenance and rehabilitation, preservation enables a more sustainable allocation of funds. The findings of the case study show that early maintenance, applied when pavements are still in good condition, allows more efficient management in technical, economic, and environmental terms.

One of the capabilities of the proposed tool is that it enables to analyze the effect of different budgetary scenarios in the technical and environmental network performance. This capability enhances trade-off analysis and supports pavement manager in making a better decision. Based on the results obtained, the base case budget considered in the case study is reasonably adequate. On the one hand, a reduction in this budget would generate a substantial increase in GHG emissions and would also reduce the LTE, and consequently the network level of service. On the other hand, the benefits of a budget increase are practically constant for increases of between 5% and 15%, only becoming significant for an increase of 20%.

Based on the evidence of the case study, some practical recommendations regarding the suitability of certain maintenance treatments may be derived. With respect to preservation, the most efficient treatments are fog and slurry seals for asphalt pavements, and diamond grinding for concrete pavements. Regarding maintenance treatments, the optimal solutions are predominantly structural overlays for both asphalt and concrete pavements.

Nevertheless, this study is subject to certain limitations that are recommended to be addressed in further research:

- The environmental evaluation proposed in this paper considers GHG emissions generated by the application of maintenance treatments. Although this approach allows the analysis of the environmental benefits of applying environmentally friendly treatments (e.g., recycling techniques), this method does not consider vehicle emissions derived from pavement condition. In addition, environmental data considered in the case study were taken from previous studies developed by different researchers. More research is thus required to improve the methodology considered for the environmental evaluation. Such improvements could consist of updating data, taking account of vehicle emissions based on pavement condition, and incorporating other environmental indicators (energy consumption, water consumption, etc.) in the analysis.
- The economic evaluation proposed in this paper compares the costs of maintenance program to available budget and also accounts for the benefits to users through an indicator based on effectiveness. However, further work needs to be done to include a monetary evaluation of the social benefits derived from an improvement in network condition.
- This study focuses on the optimal allocation of maintenance resources at the network level. This analysis considers different maintenance alternatives, but it does not consider the design stage. It would thus be interesting to incorporate other phases of the infrastructure life cycle in the optimization process. This would allow the evaluation of different alternatives in the design phase of infrastructure.

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