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A multi-objective optimization approach for sustainable pavement management

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ABSTRACT: To address the multidimensional challenges involved in advancing the sustainability of pavement systems, this study developed a multi-objective optimization framework that hosts a comprehensive and integrated pavement life cycle costs- life cycle assessment model that covers the whole pavement's life cycle, from the extraction and production of materials to construction and maintenance, transportation of materials, work-zone traffic management, usage and end-of-life. Specifically, the model was applied to investigate, from a full life cycle perspective, the extent to which several pavement engineering solutions are efficient in improving the environmental and economic dimensions of pavement sustainability, when applied in the management of a road pavement section. Multiple bi-objective optimization analysis considering accordingly agency costs, user costs and greenhouse gas emissions were conducted based on a multi-objective genetic algorithm. Pareto fronts were obtained for each analysis, originating a set of non-dominated maintenance and rehabilitation solutions. Posteriorly, a multi criteria decision analysis method was used to find the best compromise solution for pavement management.

1 INTRODUCTION

Current asset management (AM) practices adopted by transportation agencies consist of applying economic analysis techniques, such as the life cycle costs analysis (LCCA), to select from among various infrastructures designs and/or maintenance and rehabilitations (M&R) intervention alternatives those that are most economically appealing, according to their interests and existing constraints. However, recent recognition that transportation infrastructure management decisions and practices also have substantial impacts on the environment (Santero & Horvath 2009), along with the increasing awareness of sustainability and climate change, have motivated governmental agencies to promote a shift in focus in the management of transportation infrastructures towards achieving sustainable transportation systems.

In the particular case of the road pavement sector, the implementation of effective sustainable pavement management systems requires the development of approaches that enable the prediction of (1) the pavement performance, (2) the construction and maintenance-related budget requirements, (3) the costs incurred by road users and (4) the environmental impacts related to the pavement life cycle, using appropriate performance measures.

While LCCA provides an effective evaluation to pinpoint cost effective solutions for the design and maintenance of pavement systems (Walls & Smith, 1998), the environmental impacts associated with their life cycle are best characterized using a life cycle assessment (LCA) approach (Santero et al. 2011).

Despite the recognized merits of LCCA and LCA methods in evaluating the economic and environmental dimensions of sustainability, these methods applied individually are inefficient to optimally address the common tradeoff of relationships and interactions between life cycle sustainability indicators. Rather, they are better employed when integrated into an optimization-based pavement life cycle management framework accounting for various objectives and constraints, and allowing LCCA and LCA to be carried out in parallel. However, the traditional practice in optimized decision-making in pavement management has been based on the optimization of a single objective, mostly the minimization of LCC, which can be either the total highway agency costs (HAC) or, less often, the summation of the total HAC and road user costs (RUC). It is therefore evident that a steady and effective implementation of a sustainable pavement management system (SPMS), through the addition of the environmental dimension to the traditional cost-based optimization framework, requires the mathematic formulation of the decision problems to migrate from the single-objective optimization (SSO) to the multi-objective optimization (MOO) domain, in which the decision makers (DMs), are provided not with one single preferred solution, but with a set of potentially preferred solutions.

Currently, the literature addressing the concomitant consideration of (1) LCC incurred by highway agencies and road users, (2) environmental metrics covering the whole pavement life cycle phases and (3) life cycle optimization models aiming to identify optimal pavement designs and/or M&R strategies based on specific objectives and constraint(s) is still in its infancy.

Despite the important steps forward given by Zhang et al. (2010), Lidicker et al. (2013) and Reger et al. (2014, 2015), to name few, all of them suffer from at least one or a combination of drawbacks such as: (1) the inability to estimate the environmental and economic burdens associated with the usage and/or work zone traffic management (WZTM) phases; (2) the consideration of a reduced number of M&R treatment alternatives, which in some studies means that promising treatments for improving the sustainability of pavement systems, such as preventive and in-place recycling-based treatments, were not considered; (3) the consideration of short project analysis periods (PAPs), which do not allow for the assessment of the long-term and cumulative economic and environmental impacts resulting from the decision-making process; and (4) the HAC, RUC are environmental impacts are presented in an excessively aggregated manner, making it difficult for the DM to acquire insights into (i) the relative contribution of the subcomponents to the total figures, and (ii) the economic and environmental implications resulting from implementing new pavement management policies and practices, due to the lack of understanding of the relationship between parameters/processes and outcomes.

2 OBJECTIVES

The objective of this paper is to present a comprehensive and modular MOO-based pavement management decision support system (DSS) for enhancing pavement sustainability. The main novelty of the DSS lies in the incorporation of a comprehensive and integrated pavement LCC-LCA model, along with a decision-support module, within a MOO framework applicable to pavement management. The aims of the DSS are twofold: (1) to enhance the sustainability of the pavement management policies and practices by identifying the most economically and environmentally promising pavement M&R strategies, given a set of constraints, and (2) to help DMs to select a final optimum pavement M&R strategy among the set of Pareto optimal pavement M&R strategies.

3 DECISION SUPPORT SYSTEM METHODOLOGY

The methodological framework of the DSS comprises three main modules: (1) a MOO module; (2) a comprehensive and integrated pavement LCC-LCA module; and (3) a decision-support module. The MOO module is further divided into three subcomponents: (i) the formulation of the MOO model, which consists of defining the decision variables, the objective functions and constraints; (ii) the solution approach, which hosts the method to be employed to solve the MOO model and find the Pareto optimal set of solutions; and (iii) the optimization algorithm developed to solve the MOO model. In addition to the aforementioned main modules, the architecture of the DSS includes (1) a data management module, which is responsible for gathering data, storing it in several libraries and ensuring the integrity and readiness of the data required by the multiple models incorporated into the DSS, and (2) a results report module, which provides a detailed description of the optimization results. In the following sections, each main component will be introduced in detail.

3.1 *Multi-objective optimization model module*

3.1.1 *Multi-objective model formulation*

The formulation of the MOO model encompasses three main steps: (1) identification of the decision variables of the problem to be tackled; (2) definition of the objective functions; and (3) set the constraints.

The main set of decision variables of the pavement M&R strategy selection problem, which are defined by an integer figure, is designed to represent all feasible M&R activities to be performed in each pavement section and in each year of the PAP. Examples of other sets of variables include those describing the pavement performance in each year of the PAP.

As far the definition of the objective functions is concerned, the main goal underlying the development of this DSS suggests the definition of objective functions representing the commonly conflicting perspectives and interests of the three main pavement management stakeholders: highway agency, road users, and environment. Given this, the following objectives were inserted by default into the DSS: (1) minimization of the present value (PV) of the total costs incurred by highway agencies with the construction, M&R and end-of-life (EOL) of a road pavement section throughout its life cycle; (2) maximization of the pavement performance over the PAP; (3) the minimization of the PV of the total LCRUC incurred during both the execution of a M&R activity and the normal operation of the infrastructure; and (4) the minimization of the life cycle environmental burdens arising from all pavement life cycle phases.

3.1.2 *Solution approach*

Several approaches have been developed to solve MOO problems, which include, among others, aggregation methods, weighted metric methods, goal programming method, achievement functions method, goal attainment method, ε-constrained method, dominance-based approaches.

In the proposed DSS, a dominance-based approach is adopted to solve the MOO model.

3.1.3 *Solution algorithm*

The optimization model described in the previous sections is extremely difficult to solve to an exact optimum given its marked combinatorial nature and the difficulties in verifying, when they exist, the required mathematical properties of continuity, convexity and derivability. In fact, previous experience with a segment-linked optimization model (Ferreira et al. 2002), has shown that we cannot rely on exact methods to find guaranteed optimal solutions within an acceptable time period when applying this type of models to a real-world road network. Even for small-size instances, those algorithms may require impractically high computational times to solve them to the exact optimum when the pavement performance in the years following the application of a given treatment is modelled through a non-linear equation, which varies depending on the type of the last treatment, and in some circumstances, on the type of treatments preceding the last one, as in case study introduced later on in this paper.

Therefore, the MOO model is solved with heuristic algorithms. Among a few categories of heuristic algorithms, multi-objective genetic algorithms (MOGA) are the most popular solution algorithms for solving multi-objective (bi-objective) optimization problems. Specifically, the NSGA-II (Deb et al. 2002) is implemented in the proposed DSS. The NSGA-II is an efficient and well-tested MOGA (Konak et al. 2006), designed to search for a set of well distributed non-dominated solutions that approximates the entire Pareto front, and has proved to perform particularly very well on two-objective engineering problems. Further details on the NSGA-II are presented in Deb et al. (2002).

3.2 *Integrated pavement life cycle costs-life cycle assessment model module*

The integrated pavement LCC-LCA model follows a cradle-to-grave approach and covers six phases: (1) materials extraction and production; (2) construction and M&R; (3) transportation of materials; (4) WZTM; (5) usage; and (6) EOL. These phases were broken down into multiple components which connect to each other by data flows computed through a hybrid life cycle inventory (LCI) approach. Further details on the integrated pavement LCC-LCA model are given in Santos et al. (2015a), whereas Santos et al. (2015b,c) describe the LCA sub-model and Santos et al. (2015d) the LCC sub-model.

3.3 *Decision support module*

Once a set of non-dominated solutions is generated representing the optimums for the problem being tackled, the DM faces a MCDM problem should he desire to choose a single Pareto optimal solution out of the Pareto optimal set. A natural idea would be to choose the solution in the Pareto front furthest from the most inferior solution, in which the most inferior solution is the one with the maximum value for all objectives, assuming that all the objective functions are meant to be minimized. In order to assist the DM with this task, a decision-support model is implemented in the proposed DSS, where the calculation of distances from the most inferior solution relies on the membership function concept in the fuzzy set theory (Zimmormann 1996).

According to the adopted methodology the accomplishment level of each non-dominated solution *j* in satisfying the objective *i* is given by the membership function represented by Equation 1. The sum of the accomplishment levels of each non-dominated solution *j* is posteriorly rated with respect to all the *M* non-dominated solutions by normalizing its accomplishment over the sum of the accomplishments of the *M* non-dominated solutions (Equation 2). The normalized membership function β_j provides de fuzzy cardinal priority ranking of each non-dominated solution *j*. The solution with the maximum value of β_j is considered as the best optimal compromise solution (BOCS).

$$u_i^j = \frac{f_i^{max} - f_i^j}{f_i^{max} - f_i^{min}} \tag{1}$$

$$\beta_j = \frac{\sum_{i=1}^{N_{obj}} u_i^j}{\sum_{i=1}^{N_{obj}} \sum_{j=1}^{M} u_i^j} \tag{2}$$

where u_i^j = membership function value for the j^{th} non-dominated solution with respect to the i^{th} objective; f_i^{max} and f_i^{min} = maximum and minimum values of the i^{th} objective, respectively; f_i^j = i^{th} objective value for the j^{th} non-dominated solution; β_j = normalized membership function value for the j^{th} non-dominated solution; N_{obj} = number of objectives for the MOO problem; and M = number of non-dominated solutions.

4 CASE STUDY

4.1 *General description*

In order to illustrate the capabilities of the proposed DSS, it is applied to a case study consisting of determining the optimal M&R strategy for a one-way flexible pavement section of a typical Interstate highway in Virginia, USA, that yields the best tradeoff between two, often conflicting, objectives. They are the following: (1) minimization of the PV of the total LCHAC and minimization of the PV of the LCRUC; (2) minimization of the PV of the total LCHAC and minimization of the life cycle environmental impacts (LCEI), which in this case study is limited to one impact category for the sake of brevity; and (3) minimization of the PV of the total LCHAC and maximization of the life cycle pavement performance (LCPP). As far as the minimization of the LCEI is concerned, the Climate Change (CC) impact category, expressed in terms of CO_2-eq, is selected because it is increasingly regulated and discussed by both governmental and non-governmental institutions. The following greenhouse gas (GHG) are considered to contribute to CC impact category: CO_2, CH_4 and N_2O.

To ensure practicality of the present model, a set of constraints is defined: (i) the Critical Condition Index (CCI) of a pavement section cannot be lower than 40; (ii) due to technical limitations which impose limits to the life of the initial pavement design and RC treatment, the maximum time interval between the application of two consecutives M&R activities of type RC is 30 years; and (iii) no more than one M&R activity can be applied within a time frame of 3 years.

Furthermore, two scenarios are considered depending on whether or not the RC M&R activity includes recycling-based layers. The features of the case study is shown in Table 1.

The road pavement section described in the abovementioned Table is assessed according to its economic and environmental performances in all pavement life cycle phases, excepting the EOL phase. This phase is excluded from the system boundaries because the road pavement section is expected to remain in place after reaching the end of the PAP, serving as a support for the new pavement structure. In view of this scenario, the salvage values of the pavement structure is given as the value of its remaining service life, which was proven to be negligible when compared to the costs incurred during the remaining pavement life cycle phases (Santos et al. 2015d). With regard to the environmental impacts assigned to this phase, they are disregarded on the basis of the ‘cut-off’ allocation method, which is the most widely used technique to handle the EOL phase in pavements LCAs (Aurangzeb et al. 2014).

For a deep understanding on the methodologies and formulations adopted to calculate the multiple subcategories of HAC and RUC as well as the LCI associated with the several pavement life cycle phases, the reader is referred to Santos et al. (2015a,c,d).

Table 1. Features of the case study.

Name	Parameter	
	Value	Unit
PAP	50	year
Beginning year	2011	year
Initial AADT	20000	vehicle
Percentage of PCs in the AADT	75	%
Percentage of HDVs in the AADT	25	%
Traffic growth rate	3	%/year
Initial CCI	87	-
Initial IRI	1.27	m/km
Age	5	year
Number of lanes	4	-
Lanes length	1	km
Lanes width	3.66	m
Discount rate	2.3 (OMB, 2013)	%

PAP- project analysis period; AADT- annual average daily traffic; PCs- passenger cars; HDVs- heavy duty vehicles; CCI- critical condition index; IRI- international roughness index; OMB- Office Management Budget.

4.2 *Maintenance and rehabilitation alternatives*

The M&R activities considered for application over the PAP are based on Chowdhury (2011), and defined as: (1) Do Nothing (DN); (2) Preventative Maintenance (PrM); (3) Corrective Maintenance (CM); (4) Restorative Maintenance (RM); and (5) Reconstruction (RC). In the case of the PrM treatments, two types of treatments are considered: microsurfacing and thin hot mix asphalt overlay concrete (THMACO). As for the RC treatment, two alternatives are also considered. They were named conventional RC and recycling-based RC and differ from each other in that the former comprises exclusively conventional asphalt layers, whereas the latter consists of a combination of conventional asphalt layers with in-place recycling layers. The recycling-based RC activity is designed in such a way that it provides equivalent structural capacity to its non-recycling-based counterpart and takes into account the VDOT’s surface layer requirements for layers placed over recycling-based layers (VDOT 2013). Details on the M&R actions comprising each M&R activity are presented in Santos et al. (2015a).

4.3 *Pavement performance modelling*

In order to determine the pavement performance over time, the VDOT pavement performance prediction models (PPPM) are used. VDOT developed a set of PPPM in units of CCI as a function of time and category of the last M&R activity applied. CCI is an aggregated indicator ranging from 0 (complete failure) to 100 (perfect pavement) that represents the worst of either load-related or non-load-related distresses.

Using the base form corresponding to Equation 3, VDOT defines PPPM for the last three categories (Stantec Consulting Services and Lochner 2007). The coefficients of VDOT's load-related PPPM expressed through the Equation 3 for asphalt pavements of Interstate highways are presented in Table 2 (Stantec Consulting Services and Lochner 2007).

$$CCI(t) = CCI_0 - e^{a+b\times c^{ln\left(\frac{1}{t}\right)}} \qquad (3)$$

where $CCI(t)$ = critical condition index in year *t* since the last M&R activity, i.e. CM, RM or RC; CCI_0 = critical condition index immediately after treatment; and *a*, *b*, and *c* = load-related PPPM coefficients (Table 2).

Table 2. Coefficients of VDOT's load-related PPPM expressed by Equation 3 for asphalt pavements of interstate highways.

M&R activity category	CCI_0	*a*	*b*	*c*
CM	100	9.176	9.18	1.27295
RM	100	9.176	9.18	1.25062
RC	100	9.176	9.18	1.22777

Unlike the previous M&R activity categories, VDOT did not develop individual PPPM for PrM treatments. Thus, in this case study the considered PrM treatments, i.e. microsurfacing and THMACO, are respectively modelled as an 8-point and 15-point improvement in the CCI of the road segment. Once the treatment is applied, it is assumed that the pavement deteriorates according to the PPPM of a CM, but without reduction of the effective age. On the other hand, in the case of the application of CM, RM and RC treatments, the CCI is brought to the condition of a brand new pavement (CCI equal to 100) and the age is restored to 0 regardless of the CCI value prior to the M&R activity application.

For the purpose of estimating the environmental impacts and costs incurred by road users during the pavement usage phase due to the vehicles travelling over a rough pavement surface, a linear roughness prediction model, expressed in terms of International Roughness Index (IRI), is considered (Equation 4).

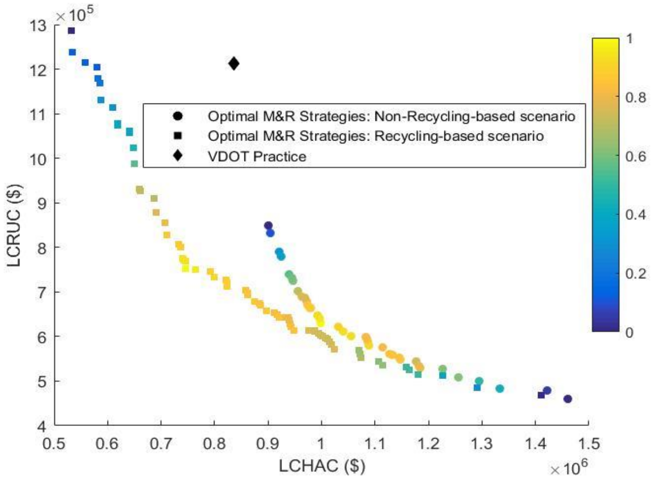
$$IRI(t) = IRI_0 + IRI_{grw} \times t \qquad (4)$$

where $IRI(t)$ = IRI value (m/km) in year *t*; IRI_0 = IRI immediately after the application of a given M&R activity; and IRI_{grw} = IRI growth rate over time, which is set at 0.08 m/km (Bryce et al. 2014). It is assumed that the application of an M&R activity other than PrM restores the IRI to the value of a brand new pavement (IRI equal to 0.87 km/h). The IRI reduction due to the application of a PrM treatment is determined based on the expected treatment life and assuming that there is no change in the value after the PrM application (the same assumption is also made in the case of the remaining M&R activities). Thus, by assuming treatment life periods of 3 and 5 years (Chowdhury 2011), respectively for microsurfacing and THMACO treatments, reductions in the IRI value of 0.24 and 0.40 m/km are obtained.

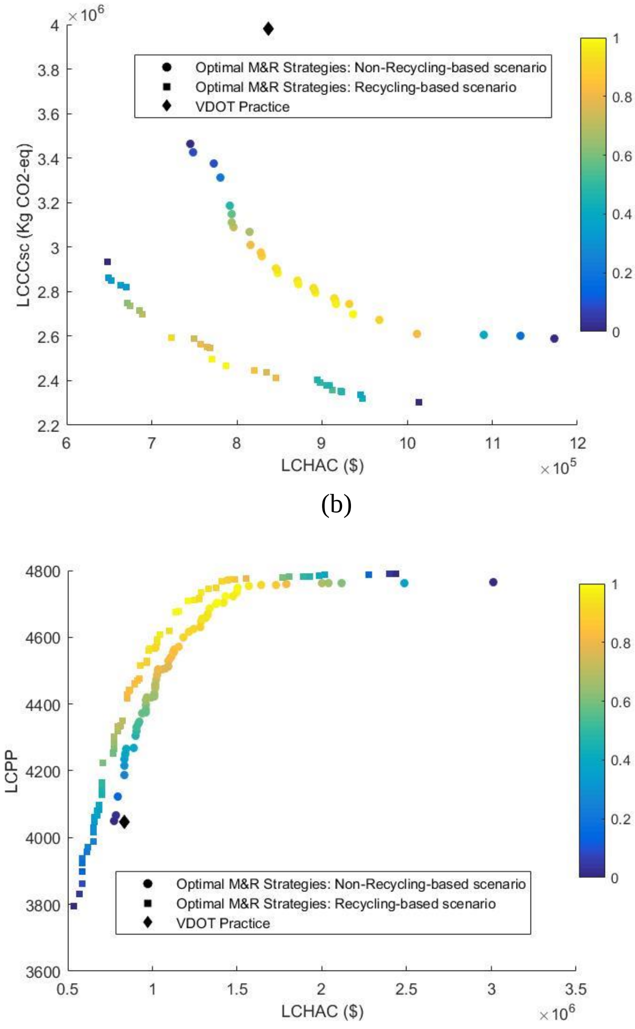
4.4 *Results and discussion*

The MOO model was written in MATLAB® programming software (MATLAB 2015), and run on a computational platform Intel Core i7-6700HQ 2.60 GHz processor with 16.00 GB of RAM, on the Windows 10 Home operating system.

Figures 1a-1c display the Pareto optimal sets of solutions in the objective space for both scenarios, along with the M&R strategy defined by VDOT. Each point in figures represents an optimal non-dominated pavement M&R strategy. As it can be observed in the abovementioned figures, an increase in the expenditures incurred by the highway agency has a triple benefit, in that it leads not only to a reduction in the LCRUC and life cycle climate change score (LCCCsc), but also to an increase in the pavement performance, although with diminishing or null marginal returns at higher expenditures levels. Figures 1a-1c also show the effects resulting from considering a maintenance scenario where the M&R activity of type RC available for application combines conventional asphalt layers with in-place recycling layers. In this case, the entire LCHAC-LCRUC and LCHAC-LCCCsc Pareto fronts shifts down and towards the axis intersection, whereas the LCHAC-LCPP Pareto front shifts up and towards the LCPP axis. In practical terms, these movements result in costs and emissions savings and pavement performance gains across the pavement life cycle, although they are particular meaningful for low highway agency budgets.



(a)



(b)

(c)

Figure 1. Pareto optimal sets of solutions in the objective space for both scenarios, along with the M&R strategy defined by VDOT: (a) Min. LCHAC vs. Min. LCRUC; (b) Min. LCHAC vs. LCCCsc; and (c) Min. LCHAC vs. Max. LCPP. Note: The fuzzy cardinal priority ranking of each non-dominated solution was normalized so that it falls into the range [0;1].

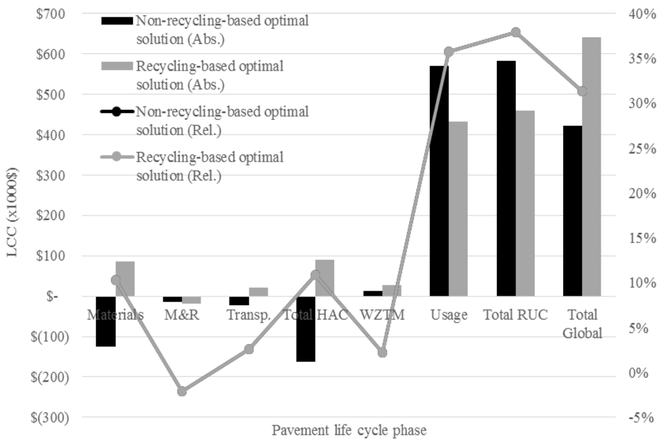
Figures 2a1-2d present the variation of the LCHAC, LCRUC, LCCCsc and LCPP for the non-recycling-based best optimal compromise solutions (NRbBOCS) and the recycling-based BOCS (RbBOCS) when compared to the current VDOT practice. These results are to be understood as follows: positive numbers mean that the BOCS improve on VDOT practice, while negative numbers represent a deterioration of the metrics considered.

For the conditions considered in this case study, the results presented in these figures show that the BOCS always increase the highway agency expenditures if the RC M&R activity does not include recycling-based layers. This increase is particularly meaningful in the third MOO problem, where the LCHAC are expected to rise by approximately 80%. This is because highway agency is required to intensify substantially the frequency of M&R activities application.

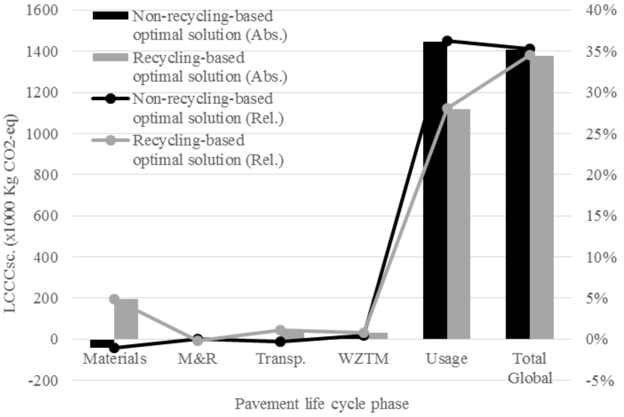
From the road users and environment perspectives, the NRbBOCS is always beneficial regardless the MOO problem considered, although the life cycle emissions directly related to the highway agencies' responsibilities (i.e., materials extraction and production, M&R and transportation of materials) are estimated to increase. However, they are offset by the considerable savings occurring during the usage phase, as a consequence of the reduction of the fuel consumed by the vehicles to overcome the rolling resistance.

On the other hand, in a scenario where the recycling-based RC is available for implementation, the M&R strategy corresponding to the RbBOCS always improve on VDOT practice with regard to the four considered metrics for the first two MOO problems. The only exception to the overall benefits resulting from implementing the RbBOCS is observed in the third MOO problem, which requires highway agency to increase its expenditure with pavement M&R by approx. 36%. Once again, this result is explained by the remarkable increase in the maintenance frequency. While in the remaining MOO problems the general number of M&R activities which comprise the M&R strategies of the BOCS is in general equal to ten, the consideration of the maximization of the LCPP as an objective function rises this value to twelve and thirteen, depending on the scenario considered, being the CM the most common M&R activity applied.

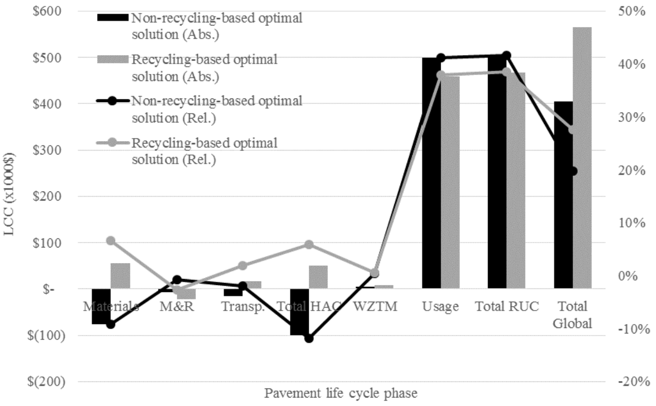
The results presented in Figures 2a1-2d also corroborate the general assumption performed in the literature, which considers the maximization of the pavement performance as a surrogate for the minimization of the RUC.



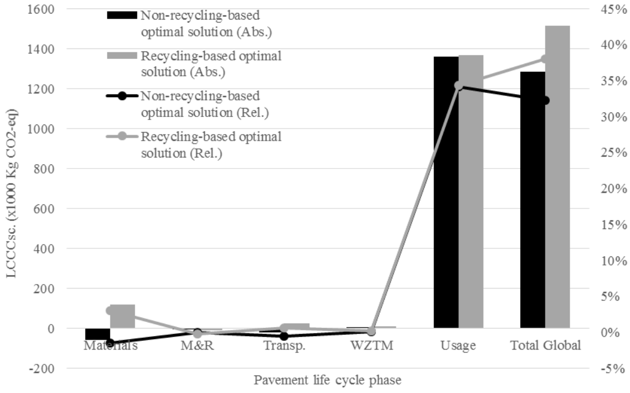
(a1)



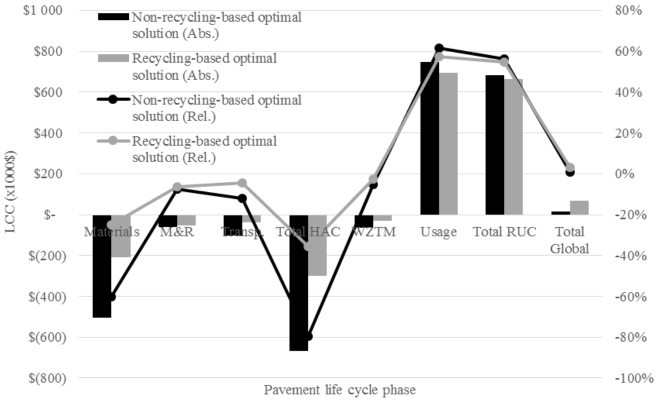
(a2)



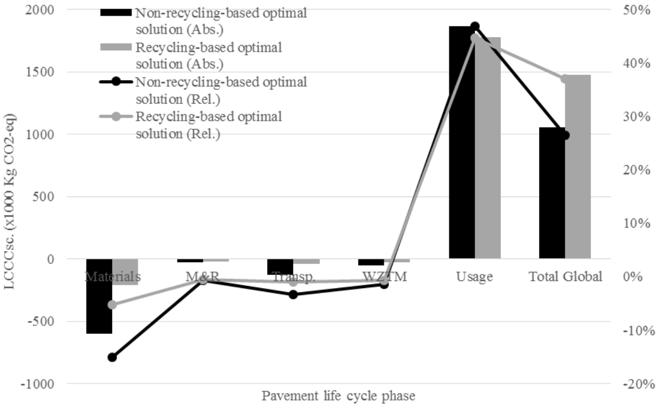
(b1)



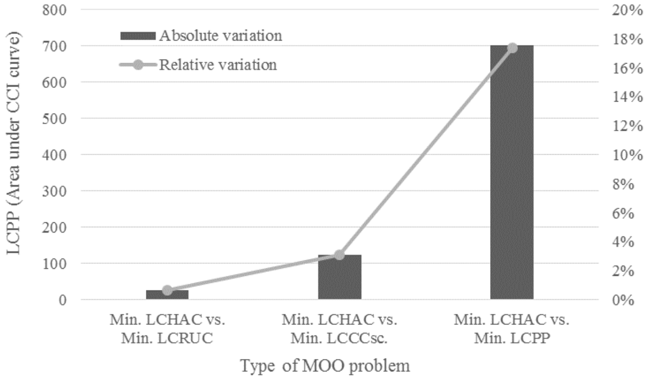
(b2)



(c1)



(c2)



(d)

Figure 2. Variation, in absolute and relative values, of the LCHAC, LCRUC, LCCCsc and LCPP associated with the BOCS, in relation to the current VDOT practice: (a1)-(a2) Min. LCHAC vs. Min. LCRUC; (b1)-(b2) Min. LCHAC vs. Min. LCCCsc; (c1)-(c2) Min. LCHAC vs. Max. LCPP; and (d) all MOO problems.

5 CONCLUSIONS

This paper presents the development of a DSS framework for pavement management that has the ability to involve road users and environmental concerns, in addition to the highway agencies, in the road pavement maintenance decision-making process, by comprehensively identifying and quantifying from a cradle-to-grave perspective the HAC, RUC and environmental impacts arisen throughout the pavement life cycle. Moreover, beyond the traditional economic objective (i.e., minimization of HAC), it enables environmental and road user-related objectives to be jointly optimized by employing a bi-objective optimization procedure to generate a set of potentially optimal pavement M&R strategies for a road pavement section while satisfying multiple constraints. Finally, the capabilities of the presented framework are enhanced by including a decision-support module that provides the DM with the BOCS among those lying on the Pareto front.

The capabilities of the proposed DSS were demonstrated by mean of a case study consisting of determining the optimal M&R strategy for a high-volume traffic road flexible pavement section of a typical Interstate highway in Virginia, USA. The MOO results revealed the existence of conflict between the LCHAC and LCRUC and between LCHAC and LCCCsc, whereby an increase in one of the objectives leads to a decrease in the other. In turn, LCHAC and LCPP were found to follow the same trend since an increase in one metric is accompanied by an increase in the other, to some extent.

Furthermore, in order to assess the extent to which new pavement engineering solutions can potentially enhance pavement sustainability, a complementary analysis scenario was performed in which the most structurally robust M&R activity initially considered was replaced by an equivalent recycling-based M&R activity. The results of this analysis showed that reductions in all four considered metrics can be achieved by moving from the current pavement M&R practice to the RbBOCS.

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