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A multi-objective optimization-based pavement management decision-support system for enhancing pavement sustainability

João Santos
Road Pavements Laboratory, Research Center for Territory, Transports and Environment, Department of Civil Engineering, University of Coimbra, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal, Email: jmos@student.dec.uc.pt

Adelino Ferreira, PhD (corresponding author)
Road Pavements Laboratory, Research Center for Territory, Transports and Environment, Department of Civil Engineering, University of Coimbra, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal, Email: adelino@dec.uc.pt

Gerardo Flintsch, PhD
Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute, The Charles Via, Jr. Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, 3500 Transportation Research Plaza, Blacksburg, VA 24061, USA, Email: flintsch@vt.edu

Abstract

In a society where the public awareness of environmental protection is increasing remarkably and the availability of resources and funding is limited, it is more vital than ever that departments of transportation (DOTs) and decision-makers (DMs) seek new tools that enable them to make the best and most rational use of these resources, taking into account environmental and social factors, along with economic and technical considerations. However, the practice adopted by highway agencies with regards to pavement management, has mostly consisted of employing life cycle costs analysis (LCCA) systems to evaluate the overall long-term economic efficiency of competing pavement design and maintenance and rehabilitation (M&R) activities alternatives. This way of supporting the decision-making process as it relates to pavement management, in which little or no importance is given to environmental considerations, does not seem to be effective in advancing sustainability in pavement systems. In view of this, it is clear there is an urgent need for pavement management decision-support systems (DSS), which, by integrating multi-disciplinary and complementary pavement life cycle modelling approaches, enable the DMs to properly account for, consider and assess the cumulative and long-term impacts of their decisions and practices regarding sustainability

goals and targets. This only can be achieved by employing techniques and tools provided with a comprehensive and wide-scoped cradle-to-grave capacity of analysis.

To address this multifaceted problem, this paper presents a comprehensive and modular multi-objective optimization (MOO)-based pavement management DSS which comprises three main components: (1) a MOO module; (2) a comprehensive and integrated pavement life cycle costs - life cycle assessment (LCC-LCA) module that covers the whole life cycle of the pavement; and (3) a decision-support module.

The potential of the proposed DSS is illustrated with two case studies consisting of determining the optimal M&R strategy for an one-way flexible pavement section of a typical Interstate highway in Virginia, USA, which yields the best tradeoff between the following three often conflicting objectives: (1) minimization of the present value (PV) of the total life cycle highway agency costs (LCHAC); (2) minimization of the PV of the life cycle road user costs (LCRUC); and (3) minimization of the life cycle greenhouse gas emissions.

Keywords: Pavement management; life cycle assessment; life cycle costs; greenhouse gas emissions; multi-objective optimization; genetic algorithms.

1. Introduction

Road infrastructure provides a fundamental foundation to the performance of all national economies, delivering a wide range of economic and social benefits. Adequately maintaining road infrastructure is therefore essential to preserve and enhance those benefits. In order to efficiently manage their networks of this physical asset, many private and governmental agencies around the world have relied on the core principles and processes of Asset Management (AM) (World Road Association, 2014).

AM is a business process and a decision-making framework that covers an extended time horizon, drawing from economics and engineering theory and practice, to tradeoff between alternative investment options at multiple levels of decision-making, and uses this information to help agencies make cost-effective investment decisions (FHWA, 2007). Most of the current AM practices adopted by transportation agencies consist of applying economic analysis techniques, such as the life cycle cost analysis (LCCA), to select from among various infrastructures designs and/or maintenance and rehabilitation (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 and 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. For instance, the United States Department of Transportation's (DOT's) Strategic Plan for the fiscal years 2014-2018 includes a separate strategic goal to "*Advance environmentally sustainable policies and investments that reduce carbon and other harmful emissions from transportation sources.*" (US DOT, 2014).

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 and Smith, 1998), the environmental impacts associated with their life cycle are best characterized using a Life Cycle Assessment (LCA) approach (Santero et al., 2011). LCA is a method for determining the environmental sustainability of a product or system by calculating the resources and energy flows consumed and the consequent environmental effects from a "cradle to grave" perspective (Harvey et al., 2015). LCA provides metrics that can be used to measure progress towards sustainability (Keoleian and Spitzley, 2006), and, thus, anticipate unintended consequences of a policy or practice.

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 life cycle costs (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 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.

To the best authors' knowledge, the Zhang et al. (2010) study was the first time that environmental criteria, namely the minimization of the life cycle energy consumption and greenhouse gas (GHG) emissions, were combined with costs (HAC and RUC) in a life cycle optimization model. The developed dynamic programing-based SOO model was applied at project-level to help DMs to select optimal overlay preservation strategies for three pavement overlay systems in Michigan: concrete, hot mix asphalt (HMA) and engineered cementitious composites (ECC), according to three different objective functions.

Since then, a few other studies have been undertaken. Zhang et al. (2012) extended the model introduced above to the network-level and applied it to compare the optimal preservation strategies with the Michigan DOT's current preservation practice. However, they did not analyze the tradeoffs between the costs and environmental indicators, since the former were converted into marginal damage costs. Yu et al. (2013) applied a dynamic programming-based life cycle optimization model to determine an optimal preservation strategy for pavement overlay systems of a road segment that minimized LCC and energy consumption/GHG emissions. Nevertheless, the study only considered the major maintenance activities while ignoring minor ones and, similarly as the previous study, the tradeoffs between the costs and environmental indicators were not performed. Lidicker et al. (2013) used a bi-objective multi-criteria optimization model to account for the tradeoffs between environmental impacts and agency and RUC in the resurfacing problem of two pavement segments already built in California, while Reger et al. (2014) extended the previous model to tackle the multi-facility problem. However, in both cases only one type of pavement treatment, "mill-and-fill" rehabilitation activity, was accounted for and the work zone (WZ) traffic management phase, which is one of the most environmentally damaging and costly for road users, was disregarded. Gosse et al. (2013) presented an expanded PMS framework with respect to the Virginia highway system, to incorporate GHG emissions and pavement performance by utilizing a multi-objective genetic algorithm (MOGA). Despite addressing the tradeoff problem between costs and environmental indicators and considering multiple treatments with different levels of robustness, the system boundaries of the LCA model did not include the two most harmful pavement life cycle phases, i.e. the usage and WZ traffic management phases, and the RUC were not accounted for. Faghih-Imani and Amador-Jimenez (2013) proposed a three-step integer linear programming method to identify the optimal set of treatments for a planning horizon, which minimize highway agency and RUC (i.e., vehicle operation costs (VOC)), energy use and GHG emissions, while trying to achieve as high a level of service as possible. Nevertheless, the environmental burdens associated with the usage and the WZ traffic management phases were once again left out of the system boundaries. Bryce et al. (2014) presents a practical optimization-based multi-criteria decision making (MCDM) technique that relates highway agency costs, pavement condition and energy consumption resulting from implementing pavement maintenance plans at network-level. However, the environmental burdens associated with the WZ traffic management phase and the RUC were not taken into accounted.

Despite the unneglectable merits and achievements of the above mentioned studies, 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 WZ traffic management 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; (4) the tradeoff analysis between the costs incurred by the several pavement management stakeholders (i.e., highway agencies and road users) and environmental indicators were not carried out or if they were, they were limited to a bi-objective perspective encompassing HAC and environmental indicators, and (5) 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 life cycle costs - life cycle assessment (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. Multi-Objective Optimization and Pareto Optimality Concept

Many real-world problems commonly require optimizing more than one objective. In general, these objectives are conflicting and compete with each other, meaning that finding a solution that is optimal for all objectives at the same time is an impossible task. Therefore, the goal becomes a search for a set of solutions that are optimal according to the *Pareto optimum concept*.

Without loss of generality, let us consider a MOO problem defined as (Equation (1)):

$$min\, F(\vec{X}) = [\, f_1(\vec{X}), \ldots, f_{N_{obj}}(\vec{X})]^T \;\; subject\ to\ \vec{X} \in \Omega \qquad (1)$$

Where $F(\vec{X}) = [\, f_1(\vec{X}), \ldots, f_{N_{obj}}(\vec{X})]^T$ is the vector of objective functions, N_{obj} ($N_{obj} \geq 2$) is the number of objectives, $\vec{X} = [x_1, x_2, \ldots, x_n]^T$ is the vector representing the decision variables, $\Omega \subseteq \Re^n$ represents the set of feasible solutions associated with equality and inequality constraints and bounds, $Z = F(\Omega)$ represents the set of feasible solutions in the objective space and $z = F(\vec{X}) = (y_1, y_2, \ldots, y_{N_{obj}})$, where $y_i = f_i(\vec{X})$, is a point of the objective space.

In light of the *Pareto dominance concept* extended to solutions, a solution $\vec{X} \in \Omega$ is called *dominated* by a solution $\vec{X}^* \in \Omega$ ($\vec{X}^* \prec \vec{X}$) if and only if (Equation (2)):

$$\forall\, i \in \{1, \ldots, N_{obj}\}:\, f_i(\vec{X}^*) \leq f_i(\vec{X}) \wedge \exists\, i \in \{1, \ldots, N_{obj}\}:\, f_i(\vec{X}^*) < f_i(\vec{X}) \qquad (2)$$

If strict inequality holds for all N_{obj} objective functions, then $\vec{X}^*$ is said to *strictly dominate* $\vec{X}$. The non-dominance relationship determines the concept of *Pareto optimality*. A solution $\vec{X}^* \in \Omega$ is then called *Pareto optimal* if for every $\vec{X} \in \Omega$, $\vec{X}$ does not dominate $\vec{X}^*$. In other words, a Pareto-optimal solution cannot be improved in one objective without losing quality in another one. The set of all these non-dominated solutions is called the *Pareto optimal set* and represents the solutions of the MOO problem. The objective values of the *Pareto optimal set* in the objective space is named *Pareto front*. Finding the *Pareto optimal set* is then the main goal when tackling a MOO problem in the Pareto sense. Given that this goal is in many circumstances computationally intractable, heuristic algorithms are commonly employed to find as good an approximation as possible to the *Pareto front* (Ehrgott and Gandibleux, 2004).

4. Decision-Support System Methodology

The methodological framework of the DSS comprises three main modules (Figure 1): (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 sub-components: (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.

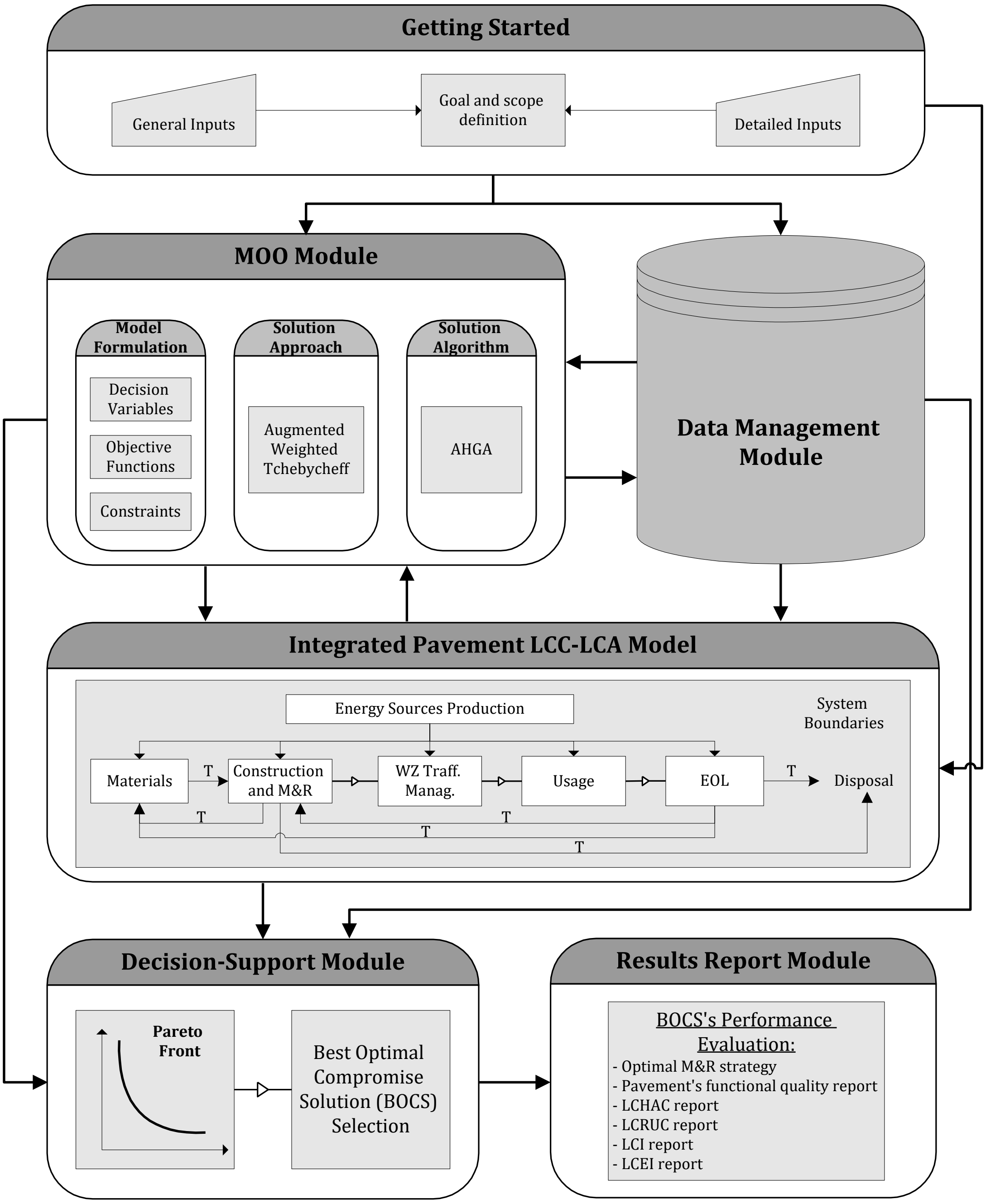


Figure 1- Flowchart outlining the DSS framework. Legend: MOO- multi-objective optimization; AHGA- adaptive hybrid genetic algorithm; T- transportation of materials phase; M&R- maintenance and rehabilitation; WZ Traff. Manag.- work zone traffic management; EOL- end-of-life; BOCS- best optimal compromise solution; LCHAC- life cycle highway agency costs; LCRUC- life cycle road user costs; LCI- life cycle inventory; LCEI- life cycle environmental impacts.

4.1. Multi-objective optimization model module

4.1.1. Multi-objective optimization 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 life cycle road users costs (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. Metrics of environmental impact are obtained by employing the US-based impact assessment methodology, the Tool for the Reduction and Assessment of Chemical and other environmental Impacts 2.0 - TRACI 2.0 (Bare et al., 2011) from the US EPA. The TRACI impact categories available for analysis include: climate change (CC); acidification due to airborne emissions (AC), eutrophication due to airborne emissions (EU), human health criteria pollutants (HH) and photochemical smog formation (PSF). Furthermore, three energy-based indicators are also made available: (1) primary energy obtained from fossil resources; (2) primary energy obtained from non-fossil resources; and (3) feedstock energy.

Finally, the main set of constraints to be considered in the MOO model is meant to ensure that the problem solutions comply with: (1) pavement performance quality requirements; (2) annual budget limitations; and (3) technical and policy requirements.

4.1.2. Solution approach

Several approaches have been developed to solve MOO problems, which include, among others, aggregation methods (e.g., weighted sum method), weighted metric methods (e.g., compromise programming methods), goal programming method, achievement functions method, goal attainment method, ε-constrained method, dominance-based approaches (e.g., NSGA-II, SPEA2, PESA-II, etc.). (Miettinen, 1999; Marler and Arora, 2004; Talbi, 2009). For a thorough review of the application of MOO techniques to the highway AM problems the reader is referred to Wu et al. (2012).

In the proposed DSS, the augmented weighted Tchebycheff method is adopted to solve the MOO model. This is a modified version of the compromise programming method in which the value of the parameter p is equal to ∞. Unlike the widely applied weighted sum method, it can be applied to generate solutions on the non-convex portions of the Pareto front and overcomes the drawback of its unmodified version by alleviating the potential for solutions that are only weakly Pareto optimal (Marler and Arora, 2004).

4.1.3. 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, to solve the transformed single-objective optimization (SOO) model, and thus generate the Pareto front, the genetic algorithm (GA)-based search heuristic developed in Chapter 7 (Santos et al., 2015e) was employed. Although the GA has been thoroughly presented in the aforementioned reference, a brief overview of the method is provided in this section because it is a core component of the optimization-based DSS introduced in this paper.

This GA possesses a hybrid nature in that Local Search (LS) techniques have been incorporated into the traditional GA framework to improve the overall efficiency of the search. Specifically, it contains two dynamic learning mechanisms to adaptively guide and combine the exploration and exploitation search processes. The first learning mechanism aims to reactively assess the worthiness of conducting an LS and to efficiently control the computational resources allocated to the application of this search technique.

The second learning mechanism uses instantaneously learned probabilities to select which one, from a set of pre-defined LS operators which compete against each other for selection, is the most appropriate for a particular stage of the search to take over from the evolutionary-based search process.

Compared to its initial version, a change was made in the set of LS operators available for on-line selection. In particular, the "delete" LS operator originally defined in Chapter 7 (Santos et al., 2015e) was replaced by another one, named "displacement" LS operator, which can be described by the following steps: (1) randomly select a subchromosome corresponding to the time period between the application of two of the most structurally robust M&R activities; (2) randomly select one gene of the subchromosome which encodes a real M&R activity; (3) displace backwards all genes between the first gene of the subchromosome and the gene picked in the previous step; (4) in the position of the gene picked in step (1) encode a "Do Nothing" (DN) M&R activity. The remainders components and parameters of the algorithm remained unchanged.

4.2. Integrated pavement life cycle costs - life cycle assessment model

The integrated pavement LCC-LCA model follows a cradle-to-grave approach, and consists of a parallel application of the LCA methodology taking into account, as far as possible and suitable, the guidelines provided by the International Standard Organization (ISO, 2006a; ISO, 2006b) and the University of California Pavement Research Center's (UCPRC's) Pavement LCA Guideline (Harvey et al., 2010) and the LCC methodology based on the Swarr et al. (2011).

The pavement life cycle model covers six phases: (1) materials extraction and production; (2) construction and M&R; (3) transportation of materials; (4) WZ traffic management; (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. Specifically, the monetary flows associated with exchanges of the pavement life cycle system that are directly covered by the LCC model but for which specific process data are either completely or partially unavailable are combined with an Input-Output (I-O) methodology for deriving the underpinning environmental burdens. By interactively integrating the strengths of process-based LCI (P-LCI) and I-O LCI, the resources which are readily available are used in a more efficient, consistent and rational way and with less effort, helping to reduce the "cutoff" errors and improving the consistency between the system boundaries of the pavement life cycle when analyzed concomitantly from the economic and environmental viewpoint.

For this purpose, the pavement LCC-LCA model builds on the process-based LCA (P-LCA) and LCC models introduced in Chapters 2 and 4 (Santos et al., 2015a; Santos et al., 2015b) and Chapter 5 (Santos et al., 2015c), respectively, and complement them with the Carnegie Mellon University's Economic Input-Output Life Cycle Assessment tool (EIO-LCA) (Carnegie Mellon University Green Design Institute, 2010). This tool utilizes the Leontief's methodology to relate the inter-sector monetary transactions sectors in the US economy, compiled in a set of matrices by the Bureau of Economic Analysis (BEA) of the US Department of Commerce, with a set of environmental indicators (e.g., consumption of fossil energy, airborne emissions, etc.) per monetary output of each industry sector of the economy. The environmental burdens at sector level associated with a particular commodity under analysis are therefore calculated by multiplying its monetary value, previously adjusted to US dollars of the EIO-LCA model's year according to sector-specific economic indices from the US Department of Labor, by the respective sectorial environmental multipliers obtained from the EIO-LCA model.

4.3. Decision-support model

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 (3). 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 (4)). 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).

$$u_i^j = \frac{f_i^{max} - f_i^j}{f_i^{max} - f_i^{min}} \tag{3}$$

$$\beta_j = \frac{\sum_{i=1}^{N_{obj}} u_i^j}{\sum_{i=1}^{N_{obj}} \sum_{j=1}^{M} u_i^j} \tag{4}$$

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

5. Case Studies

5.1. General description

In order to illustrate the capabilities of the proposed DSS, it is applied to two case studies 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 the following three often conflicting objectives: (1) minimization of the PV of the total life cycle highway agency costs (LCHAC); (2) minimization of the PV of the LCRUC; and (3) minimization of the life cycle environmental impacts (LCEI), which in this case study is limited to one impact category for the sake of brevity. In that sense, the CC was selected because it is increasingly regulated and discussed by both governmental and non-governmental institutions.

Furthermore, for each case study two scenarios were considered depending on whether or not the most structurally robust M&R activity available for employment throughout the PAP includes recycling-based layers. The features of the case studies are shown in Table 1.

Table 1- Features of the case study.

Name	Parameter value		Parameter unit
	Case study I	Case study II	
PAP	50	50	year
Beginning year	2011	2011	year
Initial annual average daily traffic ($AADT_0$)	5000	20000	vehicle
Percentage of passenger cars (PCs) in the AADT	75	75	%
Percentage of heavy vehicles (HDVs) in the AADT	25	25	%
Traffic growth rate	3	3	%/year
Initial CCI	87	87	-
Initial IRI	1.27	1.27	m/km
Age	5	5	year
Number of lanes	2	2	-
Lanes length	1	1	km
Lanes width	3.66	3.66	m

Legend: PAP- project analysis period; AADT- annual average daily traffic; PC- passenger car; HDV- heavy duty vehicle; CCI- critical condition index; IRI- international roughness index.

The road pavement sections previously described were assessed according to their economic and environmental performances in the following pavement life cycle phases: (1) materials extraction and production; (2) construction and M&R; (3) transportation of materials; (4) WZ traffic management; and (5) usage. The EOL phase was excluded from the system boundaries because the road pavement sections are expected to remain in place after reaching the end of the PAP, serving as a support for the new pavement structures. In view of this scenario, the salvage values of the pavement structures are given as the value of their 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., 2015c). With regard to the environmental impacts assigned to this phase, they were 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). According to this technique, all benefits are given to the pavement taking advantage of the reduction in the use of virgin materials due to the structural capacity provided by the existing pavement structure.

For detailed information on the processes within the system boundaries of each life cycle phase, applied modelling methodologies, assumptions and relevant data sources, the reader is referred to (Santos et al., 2015d).

5.2.M&R activities

The M&R activities considered for application over the PAP were based on Chowdhury (2011), and defined as DN, Preventive Maintenance (PrM), Corrective Maintenance (CM), Restorative Maintenance (RM) and Reconstruction (RC). In the case of the PrM treatments, two types of treatments were considered: microsurfacing and thin hot mix asphalt overlay concrete (THMACO). As for the RC treatment, two alternatives were 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 was 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 layers requirements for layers placed over recycling-based layers (VDOT, 2013). Details on the M&R actions comprising each M&R activity are shown in Table 2.

In order to provide insights into the economic and environmental advantages resulting from applying recycling-based M&R activities as opposed to conventional ones, M&R activities 6 and 7 were considered mutually exclusive. Therefore, in the first analysis scenario the set of feasible M&R activities comprises M&R activities numbers 1, 2, 3, 4, 5 and 6, whereas in the second analysis scenario M&R activity number 6 is replaced by its recycling-based counterpart (i.e. M&R activity number 7).

Table 2- Types of M&R activities and M&R actions.

M&R activity ID	M&R activity name	M&R actions	Thickness (cm)	Mixture name
1	DN	-	-	-
2	Microsurfacing	Surface preparation: brushing	-	-
		Surface preparation: tack coat application	-	Diluted bituminous emulsion
		Microsurfacing spreading	-	Microsurf.- Type C[a]
3	THMACO	Mill surface layer	1.91 (0.75 in.)	-
		Surface preparation: brushing	-	-
		Surface preparation: tack coat application	-	Bituminous emulsion
		Thin overlay placement and compaction	1.91 (0.75 in.)	THMACO[b]
4	CM	Mill surface layer	5.08 (2 in.)	-
		Mill full-depth prior patching 1%	25.4 (10 in.)	-
		Surface cleaning	-	-
		Prime coat application prior full-depth patching	-	Bituminous emulsion
		Pre-overlay full-depth patching 1%	25.4 (10 in.)	BM 25.0[c]

		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of AC surface layer	5.08 (2 in.)	SM 12.5[c]
5	RM	Mill surface and intermediate layers	8.89 (3.5 in.)	-
		Mill full-depth prior patching 1%	21.59 (8.5 in.)	-
		Surface cleaning	-	-
		Prime coat application prior full-depth patching	-	Bituminous emulsion
		Pre-overlay full-depth patching 1%	21.59 (8.5 in.)	BM 25.0[c]
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC intermediate layer	5.08 (2 in.)	IM 19.0[c]
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC surface layer	3.81 (1.5 in.)	SM 12.5[c]
6	Conventional RC	Mill surface, intermediate, base layers and 1 in. unbound layer	33.02 (13 in.)	-
		Subgrade compaction	-	-
		Prime coat application	-	Bituminous emulsion
		Lay down and compaction of the AC base layer	17.78 (7 in.)	BM 25.0[c]
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC intermediate layer	10.16 (4 in.)	IM 19.0[c]
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC surface layer	5.08 (2 in.)	SM 12.5[c]
7	Recycling-based RC	Mill surface, intermediate, base layers and 1 in. unbound layer	33.02 (13 in.)	-
		Subgrade compaction	-	-
		Lay down and compaction of CCPR materials in base course	20.32 (8 in.)	CCPR materials[d,e]
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC intermediate layer	7.62 (3 in.)	IM 19.0[c]
		Tack coat application	-	Bituminous emulsion
		Lay down and compaction of the AC surface layer	5.08 (2 in.)	SM 12.5[c]

Legend: BM- base material; IM- intermediate material; SM- surface material; AC- asphalt concrete; CCPR- cold central plant recycling; THMACO- thin hot mix asphalt concrete overlay; DN- do nothing; CM- corrective maintenance; RM- restorative maintenance; RC- reconstruction.

Notes: [a]Based on Ducasse et al. (2004), a mix formulation consisting of 180 liters of emulsion per m^3 aggregates, 3% of SBR by weight of asphalt binder, 2% of Portland cement by weight of aggregate and 140 liters of water by m^3 of aggregate was used.

[b]Mix formulation consists of 58.9% coarse aggregates, 36.1% fine aggregates, 5% asphalt binder PG 70-28 and 1% hydrated lime by weight of asphalt binder (VDOT, 2012).

[c]All mixes have a reclaimed asphalt pavement (RAP) content equal to 15%. For details on mixes properties the reader is referred to Chapter 6 (Santos et al., 2015d).

[d]A layer coefficient value of 0.40 was used for design purpose based on Diefenderfer (2014).

[e]A PG 64-22 asphalt binder at a content of 2% by weight of total mixture was used to produce the foamed asphalt mix. For each mix, 1% of hydraulic cement and 1% of moisture were added and mixed before the foamed asphalt was added (Diefenderfer, 2014).

5.3. Pavement performance modelling

In order to determine the pavement performance over time, the VDOT pavement performance prediction models (PPPM) were 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 stands for Critical Condition Index and 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 (5), VDOT defines PPPM for the following types of M&R activities (Stantec Consulting Services and Lochner, 2007): CM, RM and CM. The coefficients of VDOT's load-related PPPM represented by Equation (5) for asphalt pavements of Interstate highways are presented in Table 3 (Stantec Consulting Services and Lochner, 2007).

$$CCI(t) = CCI_0 - e^{a + b \times c^{ln\left(\frac{1}{t}\right)}} \quad (5)$$

where $CCI(t)$ is the critical condition index in year *t* since the last M&R activity, i.e. CM, RM or RC; CCI_0 is the critical condition index immediately after treatment; and *a, b,* and *c* are the load-related PPPM coefficients (Table 3).

Table 3- Coefficients of VDOT's load-related PPPM expressed by Equation (5) 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, were 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), was considered (Equation (6)).

$$IRI(t) = IRI_0 + IRI_{grw} \times t, \tag{6}$$

where $IRI(t)$ is the IRI value (m/km) in year *t*; IRI_0 is the IRI immediately after the application of a given M&R activity; and IRI_{grw} is the IRI growth rate over time, which was set at 0.08 m/km (Bryce et al., 2014). It was assumed that the application of an M&R activity other than PrM restore 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 was determined based on the expected treatment life and assuming that there is no change in the value after the PrM application (the same assumption was 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 were obtained.

5.4.Model formulation

The MOO problems introduced above can be mathematically expressed as follows:

$$Minimize\, OF_1 = \sum_{t=1}^{50} \frac{1}{(1+d)^t} \times \sum_{r=1}^{6} \left(C_{rt}^{MatExtProd} + C_{rt}^{C.M\&R} + C_{rt}^{TM} \right) \times X_{rt} \tag{7}$$

$$Minimize\, OF_2 = \sum_{t=1}^{50} \frac{1}{(1+d)^t} \times \left\{ \left[\sum_{r=1}^{6} \left(VOC_{rt}^{WZTM} + TDC_{rt}^{WZTM} \right) \times X_{rt} \right] + VOC_t^{Usage} \right\} \tag{8}$$

$$Minimize\, OF_3 = \sum_{i=1}^{3} CF_i^{CC} \times \left\{ \sum_{t=1}^{50} \left[\sum_{r=1}^{6} \left(LCI_{irt}^{MatExtProd} + LCI_{irt}^{C.M\&R} + LCI_{irt}^{TM} + LCI_{irt}^{WZTM} \right) \times X_{rt} \right] + LCI_{it}^{Usage} \right\} \tag{9}$$

Subject to:

$$CCI_t = \Phi(CCI_0, X_{11}, ..., X_{1t}, ..., X_{r1}, ..., X_{rt}), \qquad r = 1, ..., 6; \quad t = 1, ..., 50 \tag{10}$$

$$X_{rs} \in \Omega(CCI_t), \qquad r = 1, ..., 6; \quad t = 1, ..., 50 \tag{11}$$

$$CCI_t \geq CCI_{min}, \qquad t = 1, ..., 50 \tag{12}$$

$$\sum_{r=1}^{6} X_{rt} = 1, \quad t = 1,\ldots,50 \tag{13}$$

$$\Delta t_{RC} \leq \Delta t_{RC}^{max} \tag{14}$$

$$\left\{C_{rt}^{MatExtProd}; C_{rt}^{C.M\&R}; C_{rt}^{TM}\right\} = \Psi a \ \left(CCI_t, X_{rt}\right), \quad r = 1,\ldots,6; \quad t = 1,\ldots,50 \tag{15}$$

$$\left\{VOC_{rt}^{WZTM}; TDC_{rt}^{WZTM}\right\} = \Psi u \ \left(CCI_t, X_{rt}\right), \quad r = 1,\ldots,6; \quad t = 1,\ldots,50 \tag{16}$$

$$VOC_t^{Usage} = \Psi u \ \left(CCI_t\right), \quad t = 1,\ldots,50 \tag{17}$$

$$\left\{LCI_{irt}^{MatExtProd}; LCI_{irt}^{C.M\&R}; LCI_{irt}^{TM}; LCI_{irt}^{WZTM}\right\} = \Psi LCI_i \ \left(CCI_t, X_{rt}\right), \quad i = 1,\ldots,3; \quad r = 1,\ldots,6; \quad t = 1,\ldots,50 \tag{18}$$

$$\left\{LCI_{it}^{Usage}\right\} = \Psi LCI_i \ \left(CCI_t\right), \quad i = 1,\ldots,3; \quad t = 1,\ldots,50 \tag{19}$$

Where *d* is the discount rate and was set to 2.3% according to OMB (2013); $C_{rt}^{MatExtProd}$ is the materials extraction and production phase costs incurred by the highway agency for applying M&R activity *r* in year *t*; $C_{rt}^{C.M\&R}$ is the M&R phase costs incurred by the highway agency for applying M&R activity *r* in year *t*; C_{rt}^{TM} are the transportation of the materials phase costs incurred by the highway agencies for applying M&R activity *r* in year *t*; X_{rt} is equal to one if M&R activity *r* is applied in year *t*, otherwise it is equal to zero; VOC_{rt}^{WZTM} are the VOC incurred by the road users during the WZ traffic management phase due to the application of the M&R activity *r* in year *t*. It includes five types of VOC subcategories: (1) fuel consumption; (2) oil consumption; (3) tyre wear; (4) vehicle maintenance and repair; and (5) vehicle depreciation. TDC_{rt}^{WZTM} are the time delay costs incurred by the road users during the WZ traffic management phase due to the application of the M&R activity *r* in year *t*; VOC_t^{Usage} are the marginal VOC incurred by the road users in year *t* of the PAP as a consequence of the deterioration of the pavement condition. It includes four types of VOC subcategories: (1) fuel consumption; (2) tyre wear; (4) vehicle maintenance and repair; and (5) mileage-related vehicle depreciation. CF_i^{CC} is the CC characterization factor for inventory flow *i*, given by the International Panel on Climate Change's (IPCC's) characterization model for a horizon period of 100 years (IPCC, 2007). The following GHG were considered to contribute to CC impact category: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). $LCI_{irt}^{MatExtProd}$ is the quantity of the inventory flow *i*, released during the materials extraction and production phase associated with the execution of the M&R activity r in year t; $LCI_{irt}^{C.M\&R}$ is the quantity of the inventory flow i, released during the M&R phase associated with the execution of the M&R activity r in year t; LCI_{irt}^{TM} is the quantity of the inventory flow i, released during the transportation of materials phase associated with the execution of the M&R activity r in year t; LCI_{irt}^{WZTM} is the quantity of the inventory flow i, released during the WZ traffic management phase associated with the execution of the M&R activity r in year t; LCI_{it}^{Usage} is the quantity of the inventory flow i, released in year t of the usage phase of the road pavement section; CCI_t is the CCI value in year t; CCI_{min} is the minimum CCI value allowed for a pavement structure and was set to 40; Δt_{RC} is the time interval between the application of two consecutives M&R activities of type RC; Δt_{RC}^{max} is the maximum time interval between the application of two consecutives M&R activities of type RC; Φ are the pavement condition functions; Ω are the feasible M&R activities sets; Ψa are the HAC functions; Ψu are the RUC functions; ΨLCI_i are the LCI functions.

Equation (7), the first objective function of this quite complex, highly non-linear discrete optimization model, expresses the minimisation of the PV of the total LCHAC. Equation (8) expresses the minimization of the PV of the total LCRUC. Equation (9) expresses the minimization of total life cycle CC score (LCCCsc).

Constraints (10) correspond to the pavement condition functions given by Equation 5 and Table 3. They express the CCI of the pavement section in each year t as a set of functions of the initial condition (CCI_0) and the M&R activities previously applied to the pavement. Constraints (11) represent the feasible operation sets, i.e. the M&R activities that can be applied to maintain or rehabilitate the pavement structure in relation to its quality condition. In this case study, two sets were considered. The first one, adopted in scenario analysis I, comprises M&R activities 1, 2, 3, 4, 5 and 6 (Table 2). The second, adopted in scenario analysis II, includes M&R activities 1, 2, 3, 4, 5 and 7 (Table 2). Constraints (12) are the warning level constraints which define the minimum CCI value allowed for a pavement structure. Constraints (13) indicate that only one M&R activity should be performed in each year. Constraint (14) represents technical limitations which impose limits to the life of the initial pavement design and RC treatment. Its inclusion in the model is based on the VDOT criteria according to which the initial pavement design is equal to 30 years (VDOT, 2014). Constraints (15) represent the LCHAC which are computed in relation to the pavement condition and the M&R activity applied to the pavement in a given year. The total unitary M&R costs are presented in Table 4 and were computed according to the methodology presented in Chapter 5 (Santos et al., 2015c). Constraints (16) represent the LCRUC which are computed in relation to the M&R activity applied to the pavement in a given year. Constraints (17) represent the LCRUC which are computed in relation to the pavement condition observed in each year *t* of the PAP. The values of the unit costs of travel time are given in Table 5. Constraints (18) correspond to the LCI functions which are computed in relation to the M&R activity applied to the pavement in a given year. Constraints (19) correspond to the LCI functions which are computed in relation to the pavement condition observed in each year *t* of the PAP. 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 the Chapters 4, 5 and 6 (Santos et al. 2015b; Santos et al. 2015c; Santos et al. 2015d).

Table 4- Unit costs of the M&R activities.

ID	Name	Total MC ($/Km.lane)
1	DN	0
2	PrM: microsurfacing	6,621
3	PrM: THMACO	17,593
4	CM	35,696
5	RM	58,969
6	Conventional RC	199,594
7	RC	120,960

Legend: MC- maintenance and rehabilitation costs; DN- do nothing; PrM- preventive maintenance; THMACO- thin hot-mix asphalt concrete overlay; CM- corrective maintenance; RM- restorative maintenance; RC- reconstruction/rehabilitation.

Table 5- Unit cost of travel time for the several categories of vehicles.

Item	Unit cost of travel time ($/hr)
Hourly time value of passenger cars (PCs)	28.70
Hourly time value of single-unit trucks (SUTs)	22.42
Hourly time value of combination-unit trucks (CUTs)	29.27
Hourly freight inventory costs for SUTs	0.21
Hourly freight inventory costs for CUTs	0.31

Legend: PC- passenger car; SUT- single-unit truck; CUT- combination unit truck.

5.5. Solution approach

In order to solve the MOO model and find the Pareto optimal set of solutions the augmented weighted Tchebycheff method was employed (Dächert et al., 2012). To that end, the MOO problems were converted into a SOO one, by combining the three aforementioned objectives into a single objective, which is expressed as follow (Equations (20) and (21)):

$$\max_{i=1,\ldots,3}\left[w_i \times \frac{f_i\left(\vec{X}\right)-f_i^{min}}{f_i^{max}-f_i^{min}}\right]+\rho\times\sum_{i=1}^{N_{obj}}\frac{f_i\left(\vec{X}\right)-f_i^{min}}{f_i^{max}-f_i^{min}}\,, \tag{20}$$

Subject to:

$$\begin{aligned}&w_i \geq 0, \quad i=1,\ldots,N_{obj}, \quad \sum_{i=1}^{Nobj} w_i = 1, \quad \rho \in \Re\\&w_i+\rho>0, \quad i=1,\ldots,N_{obj}\end{aligned} \tag{21}$$

Where w_i is the weight assigned to the objective *i*; $f_i\left(\vec{X}\right)$ is the value of the objective function *i* for the solution $\vec{X}$; f_i^{min} is the minimum allowed value of the i^{th} objective function; f_i^{max} is the maximum allowed value of the i^{th} objective function; N_{obj} is the number of objectives for the MOO problem being considered (i.e., 3) and ρ is a non-negative scalar, which was set at 10^{-3} based on Steuer (1986).

5.6. Results and discussion

The aforementioned non-linear optimization model was solved with the AHGA developed in Chapter 7 (Santos et al., 2015e), by varying the weights through a grid of values from 0 to 1 in an increment step of 0.01. The AHGA was written in MATLAB® programming software (MATLAB, 2015), and run on a computational platform Intel Core 2 Duo 2.4 GHz processor with 4.00 GB of RAM, on the Windows 7 professional operating system. AHGA parameters utilized for this case study are the same as those determined in Chapter 7 (Santos et al., 2015e).

5.6.1. Non-recycling-based M&R strategies

Figure 2 displays the Pareto optimal set of solutions in the objective space, outlining the optimal pavement M&R strategies for the non-recycling-base case study, along with the M&R strategy defined by VDOT. Complementarily, to determine the strength of the relationship between the objectives considered in the MOO analysis, and thus help to interpret the behavior of the Pareto front, a Spearman's correlation analysis was performed. It uses a correlation coefficient, named Spearman rank correlation coefficient (r_s) to measure the monotonic relationship between two variables (i.e., whether one variable tends to take either a larger or smaller value, though not necessarily linearly) by increasing the value of the other variable (Equation (22)) (Machin et al., 2007). The value of the correlation coefficient defines two properties of the correlation: (1) the sign of r_s

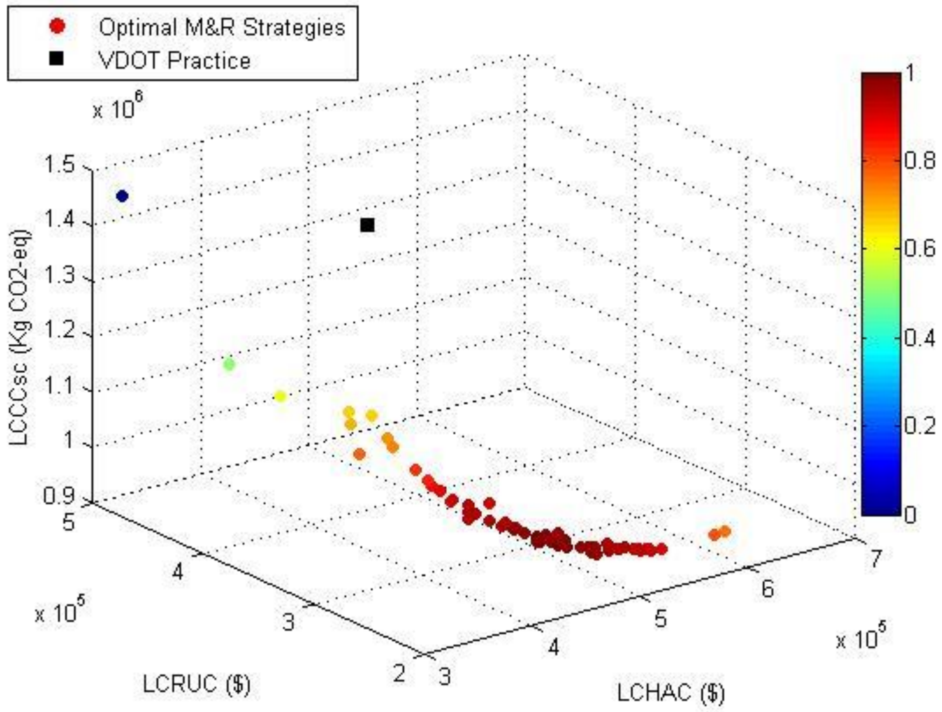
(i.e., negative or positive) defines the direction of the relationship and (2) the absolute value of r_s, which varies between -1 and 1, indicates the strength of the correlation. In turn, the square of r_s, named coefficient of determination, gives the proportion of the variation of one variable explained by the other (Zou et al., 2003).

The Spearman rank correlation method was employed in detriment of the well-known Pearson correlation method because the first does not require the assumptions of normality and linearity. Furthermore, to test whether a calculated r_s value is significantly different from a hypothesized population correlation coefficient (ρ) of zero, a significant test was used. The statistical test of the null hypothesis $\rho = 0$ is given by Equation (23) and follows a Students' t-distribution with $df = n - 2$ (Machin et al., 2007).

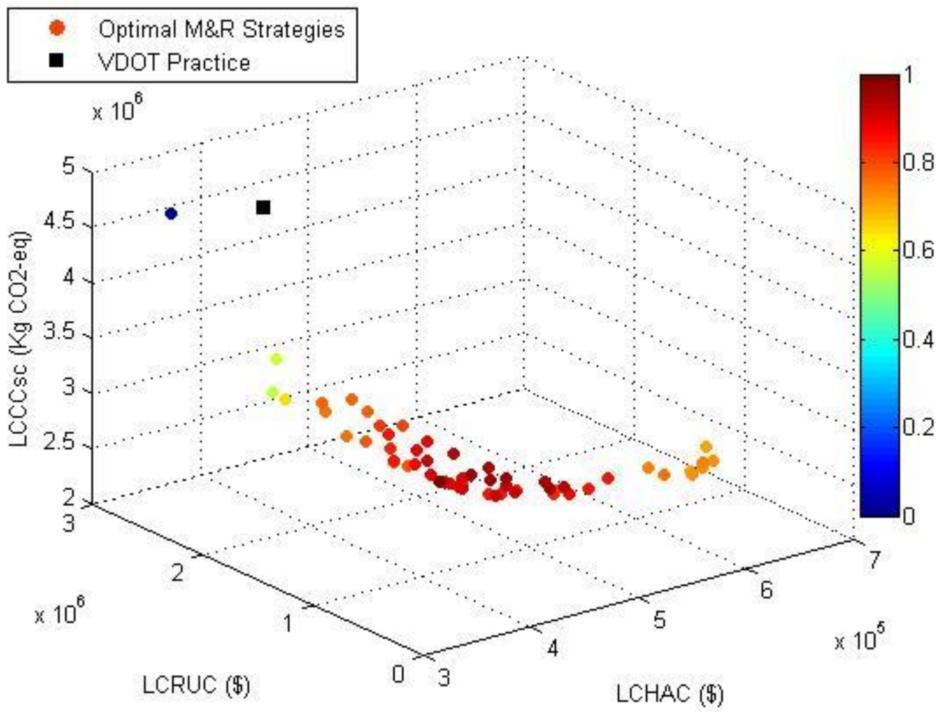
$$r_s = 1 - \frac{6 \times \sum_{i=1}^{n} d_i^2}{n^3 - n} , \quad (22)$$

$$t = r_s \times \frac{\sqrt{n-2}}{\sqrt{1 - r_s^2}} \quad (23)$$

Where r_s is the Spearman rank correlation coefficient; d_i is the difference in paired ranks i; n is the number of paired ranks; and t is the two tailed t-test value calculated for a significance level (α) of 0.05. The r_s and r_s^2 values along with the statistical tests results are presented in Table 6.



(a)



(b)

Figure 2- M&R strategy defined by VDOT and non-recycling-based Pareto optimal fronts: (a) case study I and (b) case study II. Legend: LCHAC- life cycle highway agency costs; LCRUC- life cycle road user costs; LCCCsc- life cycle climate change score. Note: The fuzzy cardinal priority ranking of each non-dominated solution was normalized so that it falls into the range [0;1].

Table 6- Spearman rank correlation coefficient values, determination coefficient values and statistical tests results (*r_s; r_s^2; t(calc.); t(α=0.05)*).

Case study		LCHAC	LCRUC	LCCCsc
I	LCHAC	-	-0.90; 0.81; -79.834; 2.002	-0.86; 0.74; -47.399; 2.002
	LCRUC	-0.90; 0.81; -79.834; 2.002	-	0.98; 0.96; 35.080; 2.002
	LCCCsc	-0.86; 0.74; -47.399; 2.002	0.98; 0.96; 35.080; 2.002	-
II	LCHAC	-	-0.70; 0.49; -8.575; 2.001	-0.81; 0.65; -21.229; 2.001
	LCRUC	-0.70; 0.49; -8.575; 2.001	-	0.74; 0.55; 4.931; 2.001
	LCCCsc	-0.81; 0.65; -21.229; 2.001	0.74; 0.55; 4.931; 2.001	-

Legend: LCHAC- life cycle highway agency costs; LCRUC- life cycle road users costs; LCCCsc- life cycle climate change score; r_s- Spearman rank correlation coefficient; r_s^2- coefficient of determination; *t(calc.)*- two tailed *t*-test value calculated for a significance level (*α*) of 0.05; t(α=0.05)- critical value of the *t*-distribution for *α* equal to 0.05.
Key (http://www.statstutor.ac.uk/): $r_s = 0$: no correlation; $r_s \in$]0; 0.2[: very weak correlation; $r_s \in$ [0.2; 0.4[: weak correlation; $r_s \in$ [0.4; 0.6[: moderate correlation; $r_s \in$ [0.6; 0.8[: strong correlation; $r_s \in$ [0.8; 1[: very strong correlation; $r_s = 1$: perfect correlation.

For a low-volume traffic roadway the results in Table 6 show a very strong correlation between the objective functions. In other words, an increase in the LCHAC not only leads to a reduction in the LCRUC but it is also beneficial in reducing the LCCCsc. Moreover, over 96% of the variance of one objective function can be explained by the other. On the other hand, for a high-volume traffic roadway the results in Table 6 show a degradation of the strength of the association between the objective functions. Specifically, while a 'very strong' correlation between the LCHAC and LCCCsc is still observed, the correlations between LCHAC and LCRUC and between LCRUC and LCCCsc are only 'strong'. That explains why for the low-volume traffic roadway the Pareto front is nearly two-dimensional, whereas for the heavier traffic class its shape is better described as a cloud of points, meaning that highway agencies are presented with a greater variety of potential solutions within a narrow range of LCHAC values.

As far the statistical significance of the relationships between the objective functions described above is concerned, the results presented in Table 6 provide evidence in support of the rejection of the null hypothesis (*|t(calc)|>t(0.05)*) in all statistical hypothesis tests undertaken.

Despite the overall reduction in LCRUC and LCCCsc that can be achieved by increasing highway agency expenditures, a carefully analysis of Figure 2 reveals that there exists an investment level after which the Pareto fronts denote a flat trend, though it is more evident in the case of the least trafficked roadway. That trend means that any increase in pavement M&R expenditures has a greatly reduced reflex in reducing both the LCRUC and LCCCsc. Moreover, when a rough comparison is made, for low-volume traffic roadways, the majority of the non-dominated M&R strategies seems to be located in the flatter section of the Pareto front (which corresponds to the higher LCHAC), whereas for high-volume traffic roadways, the majority of the non-dominated M&R strategies seems to be located in the steeper section of the Pareto front. The practical implication of this change in the tradeoff relationships is that for pavement sections carrying high traffic volumes the money is likely to have a better marginal value than that for pavement sections carrying low traffic volumes. However, due to the deterioration of the strength of the relationships between the objectives observed for the heavier traffic class, the validity of the relationships previously described cannot be fully taken as guaranteed.

Tables 7 and 8 detail the features of the BOCSs chosen according to the methodology described in section 4.3 as well as the M&R strategy defined by VDOT. Tables 9 and 10 present the variation of the LCHAC, LCRUC and LCCCsc for the BOCSs when compared to the current VDOT practice. These results are to be understood as follows: positive numbers mean that the BOCSs improve on VDOT practice, while negative numbers represent a deterioration of the metrics considered. According to the results presented in these tables, the selected optimal M&R strategies always improve on VDOT practice with regard to LCRUC and LCEI for both traffic classes. However, if for the heavier traffic class this result is accompanied by a reduction in the LCHAC (16%), in the case of the least demanding traffic class it comes at the cost of an increase in the expenditures incurred by the highway agency (8%). This result is explained by the type and frequency of M&R activities belonging to the respective optimal M&R strategies. While the optimal M&R strategy for case study II comprises six M&R activities, five of which are scheduled to take place in the second half of the PAP when the traffic volume is more intense and the discounting factors present lower values, the optimal M&R strategy for case study I features ten evenly distributed M&R activities. Although half of the ten M&R activities are PrM treatments (i.e., microsurfacing or THMACO), which incur the lowest costs among those available for selection, the fact that the total number of required M&R activities is double that of the VDOT practice (i.e., 5) explains the increase in the LCHAC.

Table 7- M&R strategies of the best non-recycling-based optimal compromise solutions and current VDOT practice.

Case study	Type of M&R strategy	M&R activity ID (application year)										Average CCI	Average IRI
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		
I	Current VDOT practice	4 (7)	5 (17)	6 (27)	4 (39)	5 (49)	-	-	-	-	-	82.74	1.27
II	Current VDOT practice	4 (7)	5 (17)	6 (27)	4 (39)	5 (49)	-	-	-	-	-	82.74	1.27
I	Optimal	2 (2)	4 (6)	4 (14)	2 (20)	6 (24)	2 (30)	4 (33)	3 (38)	4 (43)	3 (47)	82.88	1.08
II	Optimal	4 (13)	6 (25)	2 (32)	4 (36)	4 (41)	3 (46)	-	-	-	-	77.18	1.30

Legend: M&R- maintenance and rehabilitation; CCI- critical condition index; IRI- international roughness index; VDOT- Virginia Department of Transportation.

Table 8- Objective function values of the best non-recycling-based optimal compromise solutions and current VDOT practice.

Case study	Type of M&R strategy	LCHAC ($)	LCRUC ($)	LCCCsc (Kg CO_2-eq)	W_{HAC}	W_{RUC}	W_{Env}
I	Current VDOT practice	425,163.98	340,897.32	483,195	-	-	-
II	Current VDOT practice	425,163.98	2,665,172.68	4,512,113	-	-	-
I	Optimal	460,727.78	255,321.72	968,758	0.4	0.4	0.2
II	Optimal	357,559.71	1,925,908.77	3,356,906	0.8	0.1	0.1

Legend: M&R- maintenance and rehabilitation; VDOT- Virginia Department of Transportation; LCHAC- life cycle highway agency costs; LCRUC- life cycle road users costs; LCCCsc- life cycle climate change score; W_{HAC}- weight assigned to the highway agency costs objective function; W_{RUC}- weight assigned to the road users costs objective function; W_{Env}- weight assigned to the environmental impacts objective function.

Table 9- Variation of the LCHAC and LCRUC for the non-recycling-based BOCSs when compared to the current VDOT practice.

Stakeholder	Life cycle phase	Case study			
		I		II	
		Absolute ($)	Relative (%)	Absolute ($)	Relative (%)
Highway agency	Materials	-24,315.82	-5.72	49,497.71	11.64
	M&R	-1,194.01	-0.28	7,564.73	1.78
	Transp. of Materials	-10,053.97	-2.36	10,541.82	2.48
	Total	-35,563.80	-8.36	67,604.27	15.90
Road Users	WZ Traffic Management	-11,364.37	-3.05	768,696.39	28.84
	Usage	129,202.31	34.62	-29,432.48	-1.10
	Total	117,837.94	31.58	739,263.91	27.74
	Total global	82,274.14	23.21	806,868.18	43.64

Legend: LCHAC- life cycle highway agency costs; LCRUC- life cycle road users costs; BOCS- best optimal compromise solution; VDOT- Virginia Department of Transportation; M&R- maintenance and rehabilitation; Transp. of Materials- transportation of materials; WZ- work zone.

Table 10- Variation of the LCCCsc for the best non-recycling-based optimal compromise solutions when compared to the current VDOT practice.

Stakeholder	Life cycle phase	Case study			
		I		II	
		Absolute (Kg CO_2-eq)	Relative (%)	Absolute (Kg CO_2-eq)	Relative (%)
Highway agency	Materials	153,878	10.60	210,375	4.66
	M&R	425	0.03	3,661	0.08
	Transp. of Materials	-12,006	-0.83	12,988	0.29
Road Users	WZ Traffic Management	-2,307	-0.16	562,000	12.46
	Usage	343,204	23.64	366,184	8.12
	Total global	483,195	33.28	1,155,207	25.60

Legend: LCCCsc- life cycle climate change score; VDOT- Virginia Department of Transportation; M&R- maintenance and rehabilitation; Transp. of Materials- transportation of materials; WZ- work zone.

Another result of interest shown in Tables 7-10 is the fact that the reduction in the LCRUC and LCEI for the heavier traffic class is achieved even though the optimal M&R strategy leads to a slight reduction in the average pavement condition throughout the pavement life cycle. This is because in the optimal M&R strategy five out of six M&R activities are scheduled to take place in the second half of the PAP, whereas the VDOT practice consists of applying only three M&R activities in the same time period, thereby ensuring that the pavement is kept in good overall condition when the traffic is particularly intense.

When analyzing the relevance of each pavement life cycle phase in the relative variation of the three metrics as a consequence of implementing the optimal M&R plans, Tables 9 and 10 show that the materials phase, among those directly related to the highway agencies' responsibilities (i.e., materials extraction and production, M&R and transportation of materials), always has the greatest influence in either the increase or decrease of the LCHAC. With regard to LCRUC, it can be seen that the traffic volume does not play a uniform role. In other words, for low-volume traffic roadways implementing the best optimal compromise M&R strategy results in a reduction of the non-WZ RUC (approximately 35%) and in a slight increase of the WZ RUC (approximately 3%). In turn, for high-volume traffic roadways there is a reduction in the WZ RUC (approximately 29%) and a small increase in the non-WZ RUC (approximately 1%) when the best optimal compromise M&R strategy is implemented in lieu of the current VDOT's M&R strategy. However, regardless of the traffic volume, the reductions in the LCRUC achieved through the implementation of the optimal M&R strategies always outperform the increase in the costs occurred during either the WZ traffic management phase or the usage phase. Finally, the analysis of the variations of the LCCCsc allows us to come to a conclusion on the GHG emissions reductions that are expected to be obtained across all pavement life cycle phases when the optimal M&R strategy is implemented in a high-volume traffic roadway. Such reductions are more substantial during the WZ traffic management (12%) and materials (5%) phases. Different relative results are reported in the case of low-volume traffic roadways, where the most meaningful reductions are attained during the usage phase (24%), while transportation of materials and WZ traffic management were found to contribute negatively to a small percentage increase in the environmental burdens.

To provide an overall understanding of the relative importance of the traffic volume in the distribution of the costs and environmental impacts, the breakdown of the LCC and LCCCsc per pavement life cycle phase is provided in Figure 3a and Figure 3b, respectively. Figure 3a depicts that for low-volume traffic roadways the LCHAC are slightly greater than the LCRUC. Behind this result are the materials and usage phases that were found to be the biggest contributors to the total LCC in contrast to the M&R phase that is only a minor contributor. This is true for both M&R strategies, i.e. current VDOT practice and optimal M&R strategy, although the latter implies, respectively, an increase and a decrease in the contributions the materials and usage phases and a rise in the importance of the WZ traffic management. For high-volume traffic roadways, the LCRUC overwhelm the LCHAC, although the pavement life cycle phase that is responsible for the greatest share varies depending on the M&R strategy considered. Specifically, in a maintenance scenario where the current VDOT practice is adopted, the majority of the LCRUC are incurred during the WZ traffic management phase, whereas the usage phase is more costly to road users when the optimal M&R strategy is implemented. Regardless of the maintenance scenario adopted, the M&R and transportation of materials remain the least costly life cycle phases.

In terms of the LCCCsc, analysis of Figure 3b reveals the existence of two dominant phases. For heavily trafficked pavements, the cumulative effects of rolling resistance on fuel economy and vehicle emissions become much greater than the environmental burdens arising from the joint effect of the remaining phases. On the other hand, for pavements carrying low volumes of traffic, the materials phase takes the leader in the raking of the least environmentally friendly pavement life cycle phases, although in percentage terms this is not as marked as the usage phase in the case of the high-volume traffic roadways.

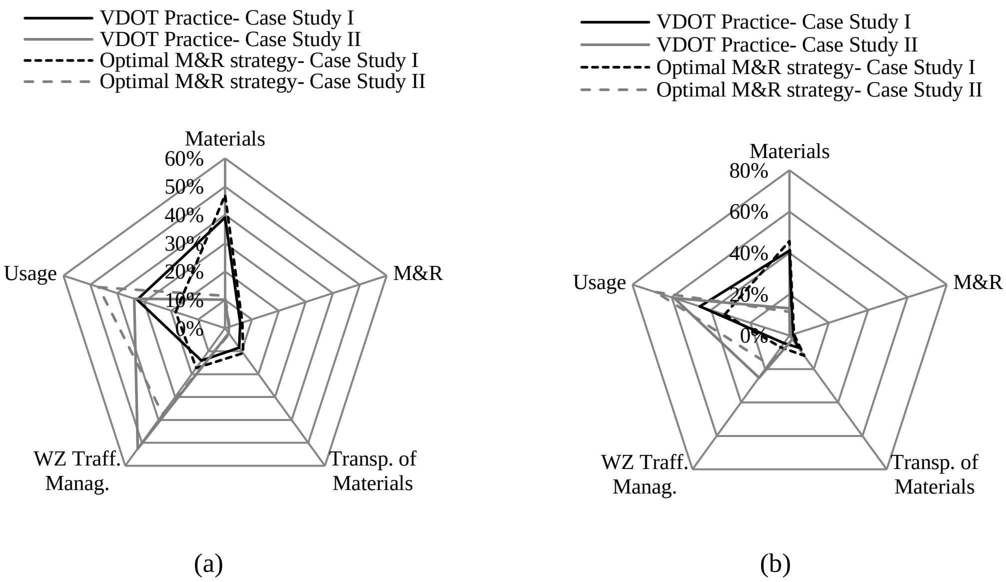
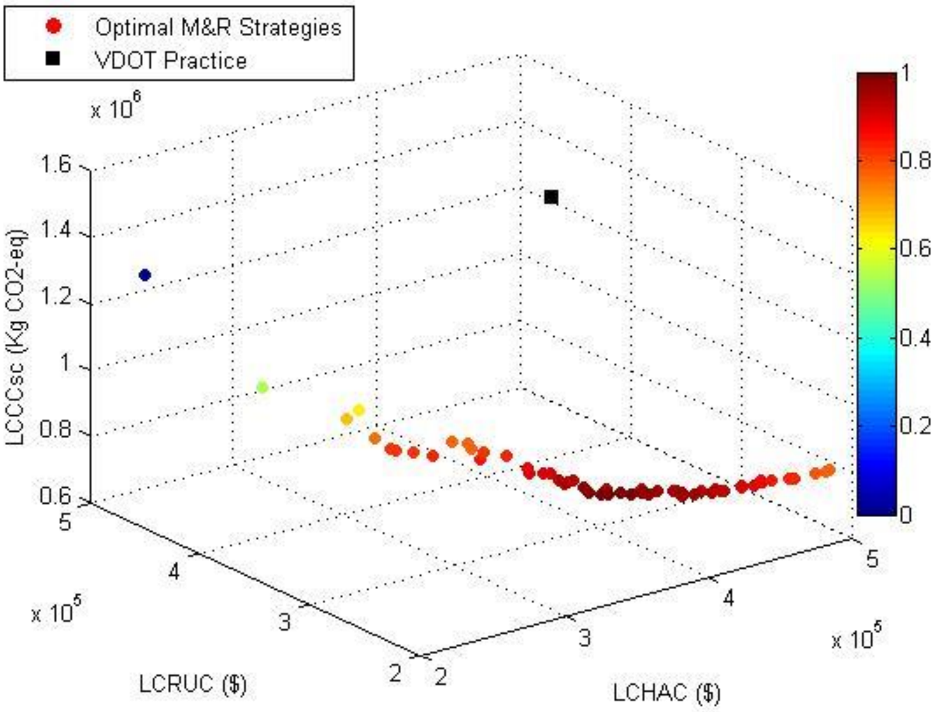


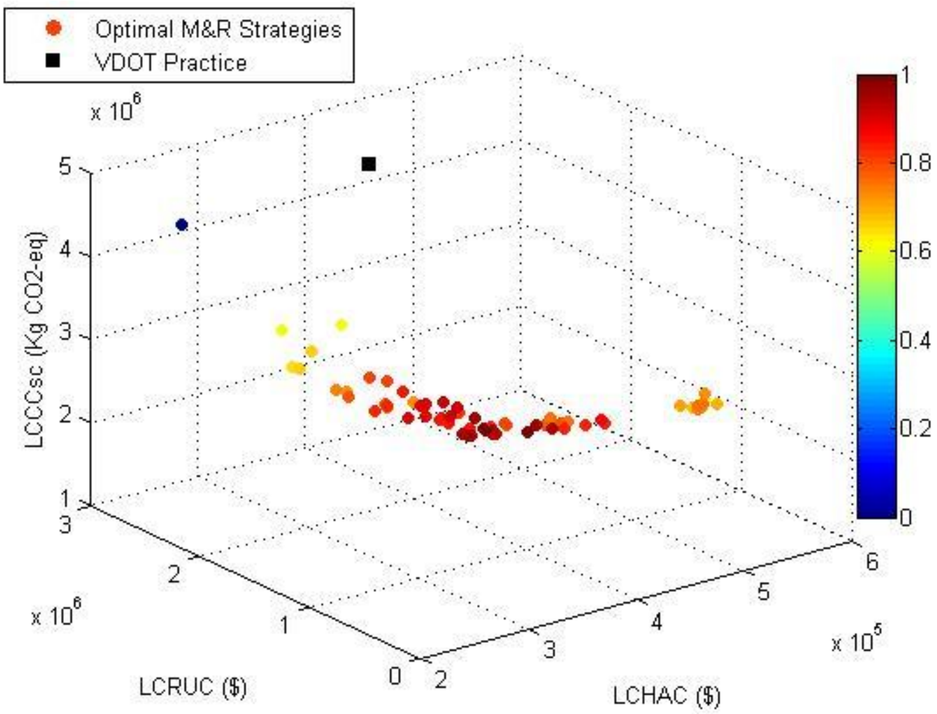
Figure 3- Breakdown of the (a) LCC and (b) LCCCsc per pavement life-cycle phase. Legend: M&R- maintenance and rehabilitation; Transp. of Materials- transportation of materials; WZ- work zone.

5.6.2. Recycling-based M&R strategies

Figure 4 depicts the Pareto optimal set of solutions for the maintenance scenario where the M&R activity of type RC combines conventional asphalt layers with in-place recycling layers. From this figure one can see that the Pareto front exhibits the same overall trend as that observed when the RC treatment consists of exclusively non-recycling-based asphalt layers (Figure 2). More interestingly, this figure, when analyzed in conjunction with Figure 2, also shows that the entire Pareto front shifts down and towards the intersection of the LCHAC and LCRUC axis, resulting in significant costs and emissions savings across the pavement life cycle. This change will benefit both the highway agency and road users, with each seeing a decrease in the limits of the range of costs corresponding to the set of non-dominated solutions. Taking the high-volume traffic roadway section as an example, the lower and upper bounds of the LCHAC will respectively decrease by 29% and 14%, whereas the road users are expected to experience more modest reductions in the incurred costs, which amount to 2% and 1%, respectively, for the lower and upper boundaries. With regard to the range of GHG emissions, the lower and upper boundaries are likely to be reduced by 8% and 3%, respectively.



(a)



(b)

Figure 4- M&R strategy defined by VDOT and recycling-based Pareto optimal fronts: (a) case study I and (b) case study II. Legend: LCHAC- life cycle highway agency costs; LCRUC- life cycle road user costs; LCCCsc- life cycle climate change score. Note: The fuzzy cardinal priority ranking of each non-dominated solution was normalized so that it falls into the range [0;1].

Tables 11 and 12 detail the features of the best recycling-based optimal compromise M&R strategies chosen according to the methodology described in section 4.3 as well as the M&R strategy defined by VDOT, but in which no recycling-based M&R activities are considered. Tables 13 and 14 present the variation of the LCHAC, LCRUC and LCCCsc for the BOCSs when compared to the current VDOT practice. As stated in the previous paragraph, Tables 12-14 show that, compared to the M&R plan in current VDOT practice, both costs and GHG emissions are considerably lower for the best optimal compromise M&R strategies in both traffic scenarios. For instance, GHG emissions could be reduced by 45% and LCHAC and LCRUC by 13% and 59%, respectively, if the highway agency switched the adopted M&R strategy to the BOCS among those lying on the Pareto front for a high-volume traffic roadway.

An interesting analysis is to understand how the use of a recycling-based RC treatment changes the frequency and type of treatments integrating the optimal M&R strategies, and how that translates into savings in both costs and GHG emissions. The results in Tables 11-14 show that for a low-volume traffic roadway, the savings across all considered metrics are achieved by reducing by one the number of M&R activities performed throughout the PAP in relation to that of the optimal non-recycling-based M&R strategy. While the reduction in the LCHAC and in the GHG emissions released during the materials phase are not necessarily surprising, the same cannot be said about the savings in both the LCRUC and GHG emissions released during the remaining phases. With regard to the metrics previously mentioned, the optimal recycling-based M&R strategy would not only mean a reduction in the increase of the WZ RUC in relation to those arising from the VDOT's M&R strategy, but, surprisingly, would also lead to a reduction in the roughness-related environmental and economic burdens, despite the slight deterioration of the average pavement condition over the PAP when compared to that associated with implementation of either the current VDOT practice or the optimal non-recycling-based M&R strategy. This stems from a combination of M&R activities, and respective timing of application, that turns out to be more cost-effective and environmentally friendly over the PAP.

As for the high-volume traffic roadways, the benefits are obtained by increasing the number of M&R activities applied over the PAP (majority PrM treatments), which translates into a smoother pavement surface over the PAP, thus reducing both the RUC and GHG emissions associated with the most important phase for a high-volume traffic roadway, i.e. the usage phase. Obviously, the increase in the frequency of M&R activities, without raising the expenditures incurred by the highway agency, was only possible because the recycling-based RC is cheaper than its non-recycling-based counterpart. Thereby, highway agencies are allowed to get more done with lower consumption of resources.

Table 11- M&R strategies of the best recycling-based optimal compromise solutions and current VDOT practice.

Case study	Type of M&R strategy	M&R activity ID (application year)										Average CCI	Average IRI
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th		
I	Current VDOT practice	4 (7)	5 (17)	6 (27)	4 (39)	5 (49)	-	-	-	-	-	82.74	1.27
II		4 (7)	5 (17)	6 (27)	4 (39)	5 (49)	-	-	-	-	-	82.74	1.27
I	Recycling-based optimal	2 (1)	4 (8)	3 (14)	4 (20)	7 (25)	3 (31)	4 (37)	3 (42)	4 (47)	-	81.24	1.08
II		2 (2)	4 (4)	3 (12)	4 (18)	7 (24)	4 (30)	3 (36)	4 (41)	-	-	80.76	1.11

Legend: M&R- maintenance and rehabilitation; CCI- critical condition index; IRI- international roughness index; VDOT- Virginia Department of Transportation.

Table 12- Objective functions values of the best recycling-based optimal compromise solutions and current VDOT practice.

Case study	Type of M&R strategy	LCHAC ($)	LCRUC ($)	LCCCsc (Kg CO_2-eq)	W_{HAC}	W_{RUC}	W_{Env}
I	Current VDOT practice	425,163.98	340,897.32	483,195	-	-	-
II		425,163.98	2,665,172.68	4,512,113	-	-	-
I	Recycling-based Optimal	366,597.22	247,082.78	814,726	0.3	0.4	0.3
II		369,013.26	1,083,439.83	2,499,971	0.2	0.8	0

Legend: M&R- maintenance and rehabilitation; VDOT- Virginia Department of Transportation; LCHAC- life cycle highway agency costs; LCRUC- life cycle road users costs; LCCCsc- life cycle climate change score; W_{HAC}- weight assigned to the highway agency costs objective function; W_{RUC}- weight assigned to the road users costs objective function; W_{Env}- weight assigned to the environmental impacts objective function.

Table 13- Variation of the LCHAC and LCRUC for the best recycling-based optimal compromise solutions when compared to the current VDOT practice.

Stakeholder	Life cycle phase	Case study			
		I		II	
		Absolute ($)	Relative (%)	Absolute ($)	Relative (%)
Highway agency	Materials	53,930.18	12.68	52,440.58	12.33
	M&R	-6,489.01	-1.53	-7,137.23	-1.68
	Transp. of Materials	11,125.59	2.62	10,847.37	2.55
	Total	58,566.76	13.78	56,150.72	13.21
Road Users	WZ Traffic Management	-4,819.44	-1.29	1,160,552.62	43.55
	Usage	130,896.32	35.08	421,180.23	15.80
	Total	126,076.87	33.79	1,581,732.85	59.35
	Total global	184,643.63	47.56	1,637,883.57	72.56

Legend: M&R- maintenance and rehabilitation; Transp. of Materials- transportation of materials; WZ- work zone.

Table 14- Variation of the LCCCsc for the best recycling-based optimal compromise solutions when compared to the current VDOT practice.

Stakeholder	Life cycle phase	Case study			
		I		II	
		Absolute (Kg CO_2-eq)	Relative (%)	Absolute (Kg CO_2-eq)	Relative (%)
Highway agency	Materials	276,930	19.07	288,159	6.39
	M&R	-3,183	-0.22	-2,304	-0.05
	Transp. of Materials	19,209	1.32	24,286	0.54
Road Users	WZ Traffic Management	122	0.01	804,717	17.83
	Usage	344,149	23.70	897,283	19.89
	Total global	637,227	43.89	2,012,142	44.59

Legend: M&R- maintenance and rehabilitation; Transp. of Materials- transportation of materials; WZ- work zone.

5.7. Key findings

From the results presented and thoroughly discussed in the previous section, the following findings are worth highlighting:

- In a tri-objective optimization analysis, minimizing LCHAC and LCCCsc are conflicting objectives, while LCRUC and LCCCsc denote the same trend;
- For low-volume traffic roadways:
    i) the Pareto front is nearly two-dimensional;
    ii) the best optimal compromise M&R strategy implies an increase in the LCHAC and a reduction in the remaining metrics when compared to the non-optimized pavement M&R strategy;
    iii) the LCHAC are greater than the LCRUC, regardless of the type of M&R strategy adopted;
    iv) the materials phase plays the most important role in driving the road pavement section’s environmental performance;
- For high-volume traffic roadways:
    i) The Pareto front is better described as a cloud of points, meaning that highway agencies are presented with a greater variety of potential solutions within a narrow range of LCHAC values;
    ii) the money has potentially a better marginal value than that for roadways carrying low traffic volumes;
    iii) the best compromise optimal M&R strategy always improves on VDOT practice with regard to the three considered metrics;

iv) the LCRUC are considerably greater than the LCHAC, regardless of the type of M&R strategy adopted;

v) the usage phase is by far the most meaningful driver of the environmental performance of a road pavement section;

- The best recycling-based optimal compromise M&R strategies always improve on VDOT practice with regard to the three considered metrics. Relatively speaking, the greatest reductions are achieved in the LCCCsc for a low-volume traffic roadway (44%), whereas, in the case of a high-volume traffic roadway, there is an outstanding reduction of the LCRUC, which can be up to approximately 60%.

6. Conclusions and future work

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 tri-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 two case studies consisting of determining, respectively, the optimal M&R strategy for a low-volume and a high-volume traffic road flexible pavement section of a typical Interstate highway in Virginia, US. 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, LCRUC and LCCCsc were found to follow the same trend since an increase in one metric is accompanied by an increase in the other. Furthermore, to assess the strength of relationships between the objective functions previously described, Spearman’s correlation analysis was performed along with significant tests of correlation coefficients. The results of the analysis not only demonstrate that the relationships are at least strong but also that they are backed up statistically.

The results of this case study also indicate that for a low-volume traffic roadway the best optimal compromise M&R strategy allows LCRUC and LCCCsc metrics to be reduced in relation to those associated with the current VDOT's pavement M&R practice, although it comes at the cost of an increase in the pavement M&R expenditures (i.e. LCHAC). On the other hand, for a high-volume traffic roadway the best optimal compromise M&R plan has the potential to improve on current VDOT's pavement M&R practice with regard to the three considered metrics.

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 three considered metrics can be achieved by moving from the current pavement M&R practice to the best recycling-based optimal compromise M&R strategy, regardless of the traffic volume the road pavement section is expected to carry throughout the PAP.

In the future, the development of this DSS will proceed in two main directions. First, the decision level for which the current version is intended for will be upgraded from the project level to the network level to ensure that the road pavement maintenance decisions taken at project level end up in optimal sustainable solutions for the whole road pavement network. Second, the number of LCA-based metrics allowed to be simultaneously optimized with highway agencies and road user-related objectives will be extended. In an effort to overcome the computational limitations associated with solving many-objective optimization (MaOO) problems, the use of dimensionality reduction techniques in improving the efficiency and efficacy of the current DSS's solution algorithm when applied to solve MaOO problems will be assessed. If the applicability of those techniques to the pavement management problems is found to be successful, they will become the MaOO problems computationally tractable by identifying redundant objectives that can be omitted while still preserving the problem structure as far as possible.

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