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A multi-objective optimization approach for sustainable pavement management

João Santos, PhD

IFSTTAR, AME-EASE, Route de Bouaye, CS4, F-44341 Bouguenais, France, Email: joao.oliveira-dos-santos@ifsttar.fr

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

Veronique Cerezo, PhD

LUNAM Université, IFSTTAR, AME-EASE, Route de Bouaye, CS4, F-44341 Bouguenais, France, Email: veronique.cerezo@ifsttar.fr

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Addressing the multidimensional challenges involved in advancing the sustainability of pavement systems requires the development of optimization-based decision support system (DSS) for pavement management with the capability to identify optimally sustainable pavement M&R strategies. The main objective of this research work is to develop a multi-objective optimization framework that hosts a comprehensive and integrated pavement life cycle costs-life cycle assessment model that covers the pavement's whole 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. The capability of the proposed DSS is analysed in a case study aiming at investigating, from a full life cycle perspective, the extent to which a number of pavement engineering solutions are efficient in improving the environmental and economic aspects 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 that relies on a modified formulation of the membership function concept in the fuzzy set theory was used to find the best compromise solution for pavement management.

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

Introduction

The increasing global awareness of sustainability and climate change (CC) has motivated an ever-growing number of transportation agencies to embrace the principles of sustainability in pavement management practices. Traditionally, transportation agencies rely on the use of economic analysis techniques, such as the life cycle costs analysis (LCCA), to evaluate the overall long-term economic efficiency of competing pavement designs and maintenance and rehabilitations (M&R) intervention alternatives. However, this way of supporting the decision-making process for pavement management does not seem to be effective and efficient in advancing sustainability in pavement systems. Indeed, in the current context in which increased importance is been given to social and environmental responsibility, highway agencies may [depending on the geographic context and policies adopted by the ruling authorities (e.g. AB32 in California)] benefit from federal grants and tax reduction incentives if their business is conducted according to the sustainability principles. Therefore, it may happen that the overall costs associated with the highway agencies' activities are reduced, even if the direct expenses incurred initially by these authorities with pavement M&R increase. In addition, sustainable M&R solutions may also prove to be more advantageous for road users and environment.

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 and (3) the economic and environmental performance of the pavement life cycle, using multi-disciplinary and complementary pavement life cycle modelling approaches. Such requirements underline the need to develop an optimization-based DSS for pavement management with the capability to identify optimal pavement M&R strategies.

Two instruments with a life cycle thinking-based philosophy that can be used to quantify the economic and environmental performances of sustainability considerations are life cycle assessment (LCA) and LCCA (Santero, Loijos, & Ochsendorf, 2013). LCCA has the potential to contribute to enhancing the sustainability of road pavement systems, since it provides a means to minimize the costs incurred by the various pavement stakeholders throughout the project analysis period (PAP) (Santos & Ferreira, 2013). LCA, meanwhile, is a versatile method capable of informing decisions on resource and process selection to better understand, measure, and reduce the environmental impacts of a system (Glass et al., 2013). However, LCCA and LCA methodologies when applied singly are not synonymous with a sustainability assessment but they provide critical information and metrics, which, when complemented with other techniques, can be used either to find the most cost-effective paving solutions to reduce environmental impacts or, at a higher decision level, to measure progress towards sustainability targets.

Furthermore, commonly environmental and economic objectives tend to be conflicting targets. Therefore, to provide the decision makers with solutions that further extend the achievements obtained through the conjoint application of the aforementioned life cycle-based approaches, we need to resort to multi-objective optimization (MOO) techniques. MOO has been identified as an effective technique for infrastructure management problems (Wu, Flintsch, Ferreira, & Picado-Santos, 2012) and is well suited to incorporating environmental concerns in the optimization of sustainable processes, since it allows them to be treated as decision-making objectives to be optimized in conjunction with the traditional technical and economic-based criteria (Furuta et al., 2006; Caetano & Teixeira, 2013; Yang, Kang, Schonfeld, & Jha, 2014; Tapia, & Padgett, 2016; Hamdy, Nguyen, & Hensen, 2016; Abdallah, & El-Rayes, 2016). Therefore, by embracing these concepts and incorporating them into decision-support systems (DSSs) for pavement management, those in charge of deciding how sustainable pavement systems will be tackled, will be in a much better position to adapt and advance current pavement management practices towards enhancing pavement sustainability.

Literature review

In the past few years, the pavement community has allocated its research efforts to address concomitantly the consideration of multiple issues related to (1) LCC incurred by highway agencies and road users, (2) environmental metrics covering the whole or partial 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).

The features of the most recent studies addressing the points mentioned above are detailed in Table 1.

Although the studies summarized in Table 1 provide valuable and distinct contributions to the literature and have undeniable merits in incorporating components of sustainability in the optimal design of M&R plans, all of them suffer from at least one or more drawbacks, such as: (1) the inability to estimate the environmental and economic burdens associated with the usage and/or work-zone (WZ) traffic management phases; (2) the consideration of a reduced number of M&R treatment alternatives; (3) the consideration of short (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 trade-off analysis between the costs incurred by the several pavement management stakeholders (i.e., highway agencies and road users) and environmental indicators were frequently not carried out.

These limitations underline the need to develop an optimization-based DSS for pavement management with the capability to design optimal pavement M&R plans that properly address the potential trade-offs between environmental impacts arising from the all pavement life cycle phases and the costs incurred by the highway agencies and road users over the whole pavement life cycle.

Table 1. Summary of the life cycle optimization models.

Reference	Decision level	Roadway type	Type of pavement	Pavement life cycle phases	Type of costs	Type of M&R activities	PAP (years)	Type of optimization	Type of solution algorithm	Objective function(s)
Pilson, Hudson, & Anderson (1999)	Project and Network	Highway	NS	M&R	HAC	Surface treatment; Overlay; Major rehabilitation	10	SOO and MOO	GA	Max. pavement performance
Fwa, Chan, & Hoque (2000)	Network	Highway (different classes)	HMA	M&R	HAC	Shallow patching; Deep patching; Premix patching; Crack sealing	45[a]	MOO	GA	Bi-objective problem: Min. HAC and maintenance work production; Tri-objective problem: Min. HAC, maintenance work production and network pavement condition
Abaza (2002)	Project	Highway	HMA	Construction; M&R	HAC; RUC	Routine maintenance; Major rehabilitation	40 and variable	SOO	“Trial-and-error”	Min. life-cycle disutility (ratio cost to pavement performance)
Li, & Madanat (2002)	Project	Highway	HMA	M&R	HAC; RUC	Resurfacing	Infinite	SOO	“Trial-and-error”	Min. total costs[b]
Chootinan, Chen, Horrocks, & Bolling (2006)	Network	Highway	HMA	M&R	HAC	Routine maintenance; Surface treatment; Minor rehabilitation; Major rehabilitation	10	SOO and MOO	GA	Max. pavement performance; Min. maintenance costs
Yoo, & Garcia-Diaz (2008)	Network	Highway (different classes)	HMA	M&R	HAC	Minor maintenance; Major maintenance; Rehabilitation	From 5 to 7	SOO	Hybrid algorithm featuring DP and branch-and-bound	Max. the total effectiveness of pavement M&R strategies

Reference	Decision level	Roadway type	Type of pavement	Pavement life cycle phases	Type of costs	Type of M&R activities	PAP (years)	Type of optimization	Type of solution algorithm	Objective function(s)
Lamptey, Labi, & Li (2008)	Project	Highway	HMA	M&R; WZ traffic management	HAC; RUC: TD and VOC	PM: thin HMA overlay, microsurfacing and crack sealing	30	SOO	NS	Min. total costs[b]
Li, & Madanu (2009)	Project	Highway	Concrete and HMA	Construction; M&R; WZ traffic management	HAC; RUC: TD and VOC	Rehabilitation; Resurfacing and Routine maintenance	Infinite	SOO	Author's algorithm based on the Lagragian relaxation technique	Max. overall project level life-cycle benefits of M&R strategies
Zhang, Keoleian, Lepech, & Kendall (2010)	Project	Highway	Concrete[c]; EEC[c]; HMA[c]	Materials; Construction; M&R; Transportation; WZ traffic management; Usage; EOL	HAC; RUC: FC, TD, accident costs; EDC	Overlay	40	SOO	DP	Min. total costs[d]; Min. GHG emissions; Min. energy consumption
Gao, Xie, Zhang, & Waller (2011)	Network	Highway	NS	M&R; WZ traffic management	Travel cost	Two maintenance activities not specified	5	SOO	Author's algorithm based on the generalized Benders decomposition (GBD) theory	Min. system level travel time
Irfan, Khurshid, Bai, Labi, & Morin (2012)	Project	Highway	HMA	M&R; WZ traffic management	HAC; RUC: TD and VOC	PM: thin HMA overlay, microsurfacing Rehabilitation: functional HMA overlay; structural HMA; resurfacing	26 and 32	SOO	Outer approximation and branch-and-bound	Max. cost-effectiveness of M&R strategies
Menezes, & Ferreira (2012)	Network	Highway	HMA	M&R; WZ traffic management	HAC; RUC: VOC	Non-structural maintenance; Minor rehabilitation; Medium rehabilitation; Major rehabilitation	20	MOO	GA	Min. total costs[b]

Reference	Decision level	Roadway type	Type of pavement	Pavement life cycle phases	Type of costs	Type of M&R activities	PAP (years)	Type of optimization	Type of solution algorithm	Objective function(s)
Lu & Tolliver (2013)	Network	NS	HMA	M&R	HAC	Minor preservation; seal coat; crack sealing; aggregate sealing; chip seal; hot mix resurfacing; hot mill overlay; RC	1	MOO	GA and SCBM	Min. HAC; Min. pavement network average roughness
Yu, Lu, & Xu (2013)	Project	Highway	Concrete[c]; HMA[c]	Materials; Construction; M&R; Transportation; WZ traffic management; Usage; EOL	HAC; RUC: FC and TD; EDC	Rehabilitation; mill-and-fill; crack, seat and overlay	40	SOO	DP	Min. GHG emissions; Min. energy consumption; Min. total costs[d]
Lidicker, Sathaye, Madanat, & Horvath (2013)	Project	Highway	HMA	Materials; M&R; Transportation; Usage	HAC; RUC: FC, operation, depreciation, vehicle wear and tear, tire wear	Overlay	Infinite (steady-state): perpetual pavement	SOO (solved for Pareto Front analysis)	Li and Madanat (2002)'s steady-state algorithm	Min. total costs[b,e]
Gosse, Smith, & Clarens (2013)	Network	Highway	HMA	Materials; M&R; Transportation	HAC	PM: slurry seal; CM: mill-and-fill[f]; RM: mill-and-fill[f]; RC: mill-and-fill[f]	15	MOO	GA	Min. HAC; Min. GHG emissions; Max. pavement performance
Reger, Madanat, & Horvath (2014)	Network	Highway	HMA	Materials; M&R; Transportation; Usage	HAC; RUC: FC, vehicle wear and tear	Mill-and-fill	Infinite (steady-state): perpetual pavement	SOO (solved for Pareto Front analysis)	Li and Madanat (2002)'s steady-state algorithm	Min. total costs[b,e]
Bryce, Flintsch, & Hall (2014)	Network	Highway	HMA	Materials; M&R; Transportation; Usage	HAC	PM: slurry seal; CM: mill-and-fill[f]; RM: mill-and-fill[f]; RC: mill-and-fill[f]	5	SOO (reference point programming)	GA	Min. HAC; Min. energy consumption; Max. pavement performance
Yu, Gu, Ni, & Guo (2015)	Project	Highway	HMA	Materials; Construction; M&R; Transportation; WZ traffic management; Usage; EOL	HAC; RUC: FC	slurry seal; micro-surfacing; HMA overlay; mil-and-fill; RC	40	MOO	GA	Min. total costs[b]; Min. aggregated environmental impacts; Max. pavement performance
Lee, Madanat, & Reger (2016)	Network	Highway	HMA	Materials; M&R; Transportation; Usage	HAC; RUC: FC, vehicle wear and tear	RC and resurfacing with full overlay thickness	60	SOO	Author's algorithm	Min. total costs[b,e]

Reference	Decision level	Roadway type	Type of pavement	Pavement life cycle phases	Type of costs	Type of M&R activities	PAP (years)	Type of optimization	Type of solution algorithm	Objective function(s)
Torres-Machi, Pellicera, Yepes, & Chamorro (2017)	Network	Urban: primary and secondary	HMA; concrete	Materials; M&R; Transportation	HAC	Fog seal; slurry seal; chip seal; microsurfacing; milling and functional overlay; hot in-place recycling; cold in-place recycling; milling and structural overlay; RC	25	MOO	Hybrid GRASP	Max. Long-term effectiveness of the maintenance program; Min. GHG emissions

Key: M&R- maintenance & rehabilitation; PAP- project analysis period; EEC- engineered cementitious composites; HMA- hot mix asphalt; WZ- work zone; EOL- end-of-life; HAC- highway agency costs; RUC- road user costs; FC- fuel consumption; TD- time delay; VOC- vehicle operation costs; EDC- environmental damage costs; SOO- single objective optimization; DP- dynamic programming; GHG- greenhouse gas; NS- not specified; RC- reconstruction; MOO- multi-objective optimization; GA- genetic algorithm; SCBM- simulated constrained boundary model; PM- preventive maintenance; CM- corrective maintenance; RM- restorative maintenance.

Notes: [a]Working days; [b]Sum of HAC and RUC; [c]Overlay of an existing concrete pavement; [d]Sum of HAC, RUC and EDC; [e]Subject to GHG emissions constraint; [f]Milling and paving depth vary depending on the type of treatment. Excepting the case studies presented by Menezes, & Ferreira (2012), Pellicera, Yepes, & Chamorro (2017) and Abaza (2002), that use data from Portugal, Chile, or without specified provenience, the remaining research works employ data from road pavements located in the US.

Objectives

The objective of this paper is to present a pavement management DSS which utilises a MOO model to enhance pavement sustainability, by allowing not only the minimization of LCC incurred by highway agencies and road users and the environmental metrics related to the whole pavement life cycle phases, but also the maximization of the pavement performance over the PAP. The key contribution of this DSS is that it incorporates 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 support designers, contractors, local and state agencies in their ongoing efforts to identify optimal pavement M&R strategies capable of simultaneously optimizing pavement-related sustainability objectives, and (2) to help decision makers (DMs) to select a final optimum pavement M&R strategy among the set of Pareto optimal pavement M&R strategies.

These unique capabilities of the DSS are expected to enhance the current pavement management practices towards sustainability by enabling DMs to identify and implement optimal pavement M&R strategies that can deliver the best environmental and technical performances within available budgetary constraints.

Decision support system methodology

The DSS is developed in three main modules: (1) a MOO module; (2) a comprehensive and integrated pavement LCC-LCA module; and (3) a decision-support module. Complementary to the aforementioned main modules, the framework of the DSS comprises (1) a data management module, which is responsible for gathering data, storing it in various 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 result. Each submodule is presented in the following individual subsection.

Multi-objective optimization module

Formulation

The formulation of the MOO model is developed in three main steps that focus on: (1) identifying the decision variables of the problem to be addressed; (2) defining the objective functions; and (3) setting the set of constraints.

The main set of decision variables of the present model are integer variables that are designed to represent all feasible alternatives for maintaining and rehabilitating a road pavement section in each year of the PAP. Complementarily, a set of other categories of variables is also required that aim, for instance, to describe the pavement performance in each year of the PAP.

The purpose of the MOO model is to determine optimal pavement M&R strategies taking into account the often conflicting interests of the following agents: highway agency, road users, and environment. Thus, the following objective functions are included in 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) minimization of the PV of the total life cycle road user costs (LCRUC) incurred during both the execution of a M&R activity and the normal operation of the infrastructure; and (4) minimization of the life cycle environmental burdens arising from all pavement life cycle phases.

The environmental performance of an M&R strategy corresponding to a given solution is characterized by adopting 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, 2011) from the US EPA. Specifically, the following TRACI impact categories are considered: (1) CC; (2) acidification due to airborne emissions (AC); (3) eutrophication due to airborne emissions (EU); (4) human health criteria pollutants (HH); and (5) photochemical smog formation (PSF). Complementarily, 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, as far as the definition of the set of constraints is concerned, they are designed to ensure that technical and policy requirements, pavement performance quality requirements and annual budget limitations are respected.

The MOO model introduced above can be formally defined as follows:

$$Minimize\ \ LCHAC=\sum_{t=1}^{PAP}\frac{1}{(1+d)^{t}}\times\sum_{r=1}^{R}\left(C_{rt}^{MatExt\mathrm{Prod}}+C_{rt}^{M\&R}+C_{rt}^{TM}\right)\times X_{rt} \tag{1}$$

$$Minimize\ \ LCRUC=\sum_{t=1}^{PAP}\frac{1}{(1+d)^{t}}\times\left\{\left[\sum_{r=1}^{R}\left(VOC_{rt}^{WZTM}+TDC_{rt}^{WZTM}\right)\times X_{rt}\right]+VOC_{t}^{Usage}\right\} \tag{2}$$

$$Minimize\ \ LCEI=\sum_{k=1}^{K_{ic}}CF_{ic}(k)\times\left\{\begin{array}{l}\sum_{t=1}^{PAP}\left[\sum_{r=1}^{R}\left(\begin{array}{l}LCI_{rt}^{MatExt\mathrm{Prod}}(k)+LCI_{rt}^{M\&R}(k)+LCI_{rt}^{TM}(k)+\\ LCI_{rt}^{WZTM}(k)\end{array}\right)\times X_{rt}\right]\\ \quad +LCI_{t}^{Usage}(k)\end{array}\right\},\forall ic\in IC \tag{3}$$

$$Maximize\ \ LCPP=\sum_{t=0}^{PAP-1}\frac{CCI_{t}+CCI_{t+1}}{2}\times 1year \tag{4}$$

where d is the discount rate; R is the number of alternative M&R activities; $C_{rt}^{MatExtProd}$ are the materials extraction and production phase costs incurred by the highway agency for applying M&R activity r in year t; $C_{rt}^{M\&R}$ are 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 vehicle operation costs (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, which include 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, which comprise four types of VOC subcategories: (1) fuel consumption; (2) tyre wear; (4) vehicle maintenance and repair; and (5) mileage-related vehicle depreciation; K_{ic} is the total number of substances contributing to the impact category *ic*; $CF_{ic}(k)$ is the characterization factor assigned to the substance *k* for the calculation of *ic*; $LCI_{rt}^{MatExt\mathrm{Prod}}(k)$ is the inventory of the substance *k* released during the materials extraction and production phase associated with the execution of the M&R activity *r* in year *t*; $LCI_{rt}^{M\&R}(k)$ is the inventory of the substance *k* released during the M&R phase associated with the execution of the M&R activity *r* in year *t*; $LCI_{rt}^{TM}(k)$ is the inventory of the substance *k* released during the transportation of materials phase associated with the execution of the M&R activity *r* in year *t*; $LCI_{rt}^{WZTM}(k)$ is the inventory the substance *k* released during the WZ traffic management phase associated with the execution of the M&R activity *r* in year *t;* $LCI_{t}^{Usage}(k)$ is the inventory of the substance *k* released in year *t* of the usage phase of the road pavement section; CCI_t is the Critical Condition Index (CCI) value in year *t*.

Equation (1) expresses the minimisation of the PV of the total life cycle highway agency costs (LCHAC). Equation (2) formulates the minimization of the PV of the total LCRUC. Equation (3) expresses the minimization of the total life cycle environmental burdens corresponding to impact category *C*. Equation (4) represents the maximization of the area under the CCI curve. It is considered to be a measure of the performance of a given M&R strategy. The area is estimated using the trapezoid method.

The optimization process is subject to the following constraints:

$$CCI_t = \Phi\,(CCI_0, X_{11},..., X_{1t},..., X_{r1},..., X_{rt}), \qquad r = 1,..., R; \quad t = 1,..., PAP \tag{5}$$

$$X_{rs} \in \Omega\left(CCI_t\right), \qquad r = 1,..., R; \quad t = 1,..., PAP \tag{6}$$

$$CCI_t \geq CCI_{\min}, \qquad t = 1,..., PAP \tag{7}$$

$$\sum_{r=1}^{R} X_{rt} = 1, \quad t = 1,..., PAP \tag{8}$$

$$\Delta t_{RC} \leq \Delta t_{RC}^{max} \tag{9}$$

$$\Delta t_r \geq \Delta t_r^{\min}, \quad r = 2,..., R \tag{10}$$

$$\left\{C_{rt}^{MatExt\mathrm{Prod}}; C_{rt}^{M\&R}; C_{rt}^{TM}\right\} = \Psi a\ \left(CCI_t, X_{rt}\right), \quad r = 1,..., R; \quad t = 1,..., PAP \tag{11}$$

$$\left\{VOC_{rt}^{WZTM}; TDC_{rt}^{WZTM}\right\} = \Psi u\ \left(X_{rt}\right), \quad r = 1,..., R; \quad t = 1,..., PAP \tag{12}$$

$$VOC_t^{Usage} = \Psi u\ \left(CCI_t\right), \quad t = 1,..., PAP \tag{13}$$

$$\left\{LCI_{rt}^{MatExt\mathrm{Prod}}(k); LCI_{rt}^{M\&R}(k); LCI_{rt}^{TM}(k); LCI_{rt}^{WZTM}(k)\right\} = \mathit{\Psi} LCI_k\ \left(X_{rt}\right), \quad r=1,..., R; \\ t=1,..., PAP; \quad \forall\, k \in K_{ic}; \quad \forall\, ic \in IC \tag{14}$$

$$\left\{LCI_t^{Usage}(k)\right\} = \mathit{\Psi} LCI_k\ \left(CCI_t\right), \quad t=1,..., PAP; \quad \forall\, k \in K_{ic}; \quad \forall\, ic \in IC \tag{15}$$

where 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 consecutive M&R activities of type Reconstruction (RC); Δt_{RC}^{max} is the maximum time interval between the application of two consecutive M&R activities of type RC; Δt_r is the time interval between the application of two consecutive M&R activities of any type; $\Delta t_r^{\min}$ is the minimum time interval between the applications of two consecutive M&R activities of any type; Φ are the pavement condition functions; Ω are the feasible M&R activity sets; Ψa are the HAC functions; Ψu are the RUC functions; *IMP* are the set of impact categories; ΨLCI_C are the life cycle inventory (LCI) functions of impact category *C*.

Constraints (5) correspond to the pavement condition functions. In this formulation, they are expressed as 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 (6) 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 condition. Constraints (7) are the warning level constraints which define the minimum CCI value allowed for a pavement structure. Constraints (8) indicate that only one M&R activity should be performed in each year. Constraint (9) 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 (10) ensure that the time interval between the application of two consecutives M&R activities is not inferior to $\Delta t_r^{\min}$. Constraints (11) 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. Constraints (12) represent the LCRUC, which are computed in relation to the M&R activity applied to the pavement in a given year. Constraints (13) represent the LCRUC, which are computed in relation to the pavement condition observed in each year *t* of the PAP. Constraints (14) correspond to the LCI functions of the substance *k*, which are computed in relation to the M&R activity applied to the pavement in a given year. Constraints (15) correspond to the LCI functions of the substance *k*, which are computed in relation to the pavement condition observed in each year *t* of the PAP.

Solution approach

The solution of a MOO problem is given by a set of Pareto points, which represent the optimal trade-off between the objectives considered. A given solution is said to be Pareto-optimal if it 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 the objective values of the *Pareto optimal set* in the objective space is named *Pareto front.*

In the highway asset management field several approaches have been used to solve the MOO problem, which include the weighting sum method, goal programming, compromising programming, the ε-constraint method, dominance-based approaches, the multi-attribute utility theory, the analytic hierarchy process (AHP), and evolutionary algorithms (Wu et al., 2012). In the proposed DSS, a dominance-based approach is adopted to solve the MOO model.

Solution algorithm

The deterministic optimization model presented in the previous sections is complex, and is extremely difficult to solve with exact optimization methods available through commercial packages like XPRESS-MP (FICO, 2009) or GAMS-CPLEX (IBM, 2009) given its combinatorial nature. Therefore, the MOO model is solved with heuristic algorithms. Among several 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, Pratap, Agarwal, & Meyarivan, 2002) is implemented in the proposed DSS. The NSGA-II is an efficient and well-tested MOGA (Konak, Coit, & Smith, 2006), designed to search for a set of well distributed non-dominated solutions that approximates the entire Pareto front, and is proven to perform particularly very well on two-objective engineering problems involving different types of infrastructures, such as bridges (Furuta et al., 2006), buildings (Xu, Chong, Karaguzel, & Lam, 2016; Abdallah, & El-Rayes, 2016), roadways (Bai, Labi, & Sinha, 2012; Hyari, Khelifi, & Katkhuda, 2016), railways (Caetano, & Teixeira, 2013), water distribution systems (Dridi, Parizeau, Mailhot, & Villeneuve, 2008), etc. Further details on the NSGA-II are presented in Deb et al. (2002).

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) 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 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. For further details on the pavement LCC-LCA model the reader is referred to Santos, Ferreira, & Flintsch (2017).

Decision support module

Finding a Pareto optimal set and the corresponding Pareto front is the first step towards the practical solution of a MOO problem. However, in practical terms, a single final solution from the Pareto set must be chosen according to some preference information. In order to assist the DM in making post-optimization decisions, a decision-support model is implemented in the proposed DSS that relies on a modified formulation of the membership function concept in the fuzzy set theory (Zimmormann, 1996). The idea underlying the selection of this method is 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.

To do so, firstly, the accomplishment level of each non-dominated solution j in satisfying the objective i is expressed by a membership function defined by Equation (16). Secondly, the sum of the weighted accomplishment levels of each non-dominated solution j is rated in relation to all the M non-dominated solutions by normalizing its weighted accomplishment over the sum of the weighted accomplishments of the M non-dominated solutions (Equation (17)). The normalized membership function β_j gives the fuzzy cardinal priority ranking of each non-dominated solution j, provided that the sum of the weights assigned to the objective functions totals 1 (Equation (18)). Finally, the solution with the maximum value of β_j is considered as the best optimal compromise solution (BOCS).

$$u_i^j = \frac{f_i^{\max} - f_i^j}{f_i^{\max} - f_i^{\min}} \tag{16}$$

$$\beta_j = \frac{\sum_{i=1}^{N_{obj}} w_i u_i^j}{\sum_{i=1}^{N_{obj}} \sum_{j=1}^{M} w_i u_i^j} \tag{17}$$

$$\sum_{i=1}^{N_{obj}} w_i = 1 \tag{18}$$

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; w_i is the weight assigned to the i^{th} objective; 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.

Case study

General description

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, which yields the best trade-off between two objectives, was adopted to exemplify the capabilities of the proposed DSS. The MOO module undertakes the optimization process by considering two objectives simultaneously to be chosen from the following set: (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); 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 CC impact category, expressed in terms of carbon dioxide-equivalent (CO2-eq), is selected because public highway agencies are facing increasing pressure to identify and address potential significant impacts due to greenhouse gases (GHG) emissions (California Air Resources Board, 2008). In this DSS the following GHG are considered to contribute to the CC impact category: CO_2, methane (CH_4) and nitrous oxide (N_2O). The characterization factors given by the International Panel on Climate Change's (IPCC's) characterization model for a horizon period of 100 years (IPCC, 2007) were considered to quantify the contribution of the GHG mentioned previously to the CC impact category.

The main characteristics of the case study are presented in Table 2. In the particular case of the traffic composition, the two classes considered are representative of the most meaningful categories of vehicles generally existing in Virginia Interstates. In addition, two modelling M&R scenarios were considered depending on whether or not the most structurally robust M&R activity (i.e., RC) available for application throughout the PAP includes recycling-based layers.

Table 2. 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[a]	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)	%

Key: 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.

Notes: [a]5% of the truck traffic consisted of single-unit trucks and the remaining percentage of combination trucks.

The economic and environmental performances of the road pavement section described in Table 2 were assessed throughout 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 disregarded from the system boundaries on the basis that 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. According to this scenario, the salvage value 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., 2015b). As far as the environmental impacts assigned to this phase are concerned, they were not taken into account in light of the 'cut-off' allocation method, which is the most widely used technique to handle the EOL phase in pavements LCAs (Aurangzeb, Al-Qadi, Ozer, & Yang, 2014). According to this technique, the pavement taking advantage of the reduction in the use of virgin materials, due to the structural capacity provided by the existing pavement structure, receives the benefits.

Maintenance and rehabilitation alternatives

The typology of M&R activities available for application throughout the PAP are those defined by VDOT (Chowdhury, 2011), and consist of: (1) Do Nothing (DN); (2) Preventative Maintenance (PrM); (3) Corrective Maintenance (CM); (4) Restorative Maintenance (RM); and (5) RC. Regarding the PrM treatments, two types of treatments are considered: microsurfacing and thin hot mix asphalt overlay concrete (THMACO). In the specific case of the RC treatment, two alternatives are also considered and named as conventional RC and recycling-based RC. They 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 to provide equivalent structural capacity to its non-recycling-based counterpart but taking into account the Virginia Department of Transportation (VDOT)'s surface layer requirements for layers placed over recycling-based layers (Virginia Department of Transportation [VDOT], 2013). Details regarding the M&R actions comprising each M&R activity are provided by Santos et al. (2017).

The total unitary costs of each M&R activity are presented in Table 3 and were computed according to the methodology presented in Santos et al. (2015b). The value of the unit costs for travel time required to calculate the time delay costs incurred by the road users during the WZ traffic management phase due to the application of the M&R activities are given in Table 4. The PV of all future costs was determined by using a discount rate equal to 2.3% (OMB, 2013). For a deeper understanding of 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, 2015b, 2017).

Table 3. Unit costs of the M&R activities (in 2011 US dollars).

ID	Name	Total MC ($/Km.lane)
1	DN	0
2	PrM: microsurfacing	5,732
3	PrM: THMACO	16,951
4	CM	34,681
5	RM	57,679
6	Conventional RC	197,978
7	RC	120,309

Key: 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 4. Unit cost of travel time for the several categories of vehicles (in 2011 US dollars).

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

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

Pavement performance modelling

The pavement performance prediction models (PPPM) considered in this case study were specifically developed for the management of the VDOT network. The pavement condition is assessed in terms of an overall condition index named Critical Condition Index (CCI). This index is an aggregated indicator that represents the worst of either load-related or non-load-related distresses, and ranges from 0 to 100. A value of 100 is assigned to a perfect pavement, whereas a pavement in a complete state of failure is given 0.

VDOT defines PPPM for the CM, RM and CM M&R activities using the base form corresponding to Equation (19) (Stantec Consulting Services & Lochner, 2007). The coefficients of VDOT's load-related PPPM represented by Equation (19) for asphalt pavements of Interstate highways are presented in Table 5.

$$CCI(t) = CCI_0 - e^{a + b \times c^{ln\left(\frac{1}{t}\right)}} \tag{19}$$

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 5).

Table 5. Coefficients of VDOT's load-related PPPM expressed by Equation (19) 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

For the PrM treatments VDOT did not develop individual PPPM. Thus, in this case study the considered preventive treatments, i.e. microsurfacing and THMACO, were respectively modelled as a 8-point and 15-point improvement in the CCI of a road segment which take place whenever the CCI falls below the trigger value of 85 (Chowdhury, 2011). After the application of a treatment, it is assumed that the pavement deteriorates according to the PPPM of a CM but without a reduction of the effective age. On the other hand, in the case of the application of CM, RM and RC treatments, the CCI is restored to the condition of a brand new pavement (CCI equal to 100) and the age is set at 0 regardless of the CCI value preceding the M&R activity application.

As pointed out by Glass et al. (2013), the PPPM considered in this case study are a function of time only, which compromise the ability to take into account the existing conditions (e.g., traffic volume and subgrade quality), as well as the features of the M&R activities (e.g., thickness). While more complex deterioration models exist (Gao & Zhang, 2008), they require more extensive data inputs, which are not consistently collected and maintained by DOTs. This fact, along with the intention of adopting as much as possible and suitable the practices considered by VDOT underpinned the option for the time-dependent PPPM introduced previously.

In order to estimate the environmental impacts and costs incurred by road users during the pavement usage phase as a consequence of the vehicles travelling over a rough pavement surface, a linear roughness prediction model, expressed in terms of International Roughness Index (IRI), was considered (Equation (20)).

$$IRI(t) = IRI_0 + IRI_{grw} \times t \tag{20}$$

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 different of the type PrM brings the IRI to the value of a brand new pavement (IRI equal to 0.87 m/km). 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). The reductions in the IRI value of 0.24 and 0.40 m/km, considered respectively for microsurfacing and THMACO treatments, were obtained by assuming treatment life periods of 3 and 5 years (Chowdhury, 2011).

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.

The parameter settings for MOO algorithm are as follows: the population size and the maximum number of evaluations are 500 and 750, respectively; new candidate solutions are generated by the simulated binary crossover operator and the polynomial mutation operator (Deb et al., 2002), and; the crossover and mutation probabilities are 90% and 10%, respectively. This configuration of the parameters was determined on the basis of the best and most stable results obtained from preliminary and exploratory tests conducted on parameter sensitivity.

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 square and circle in those figures represents a pavement M&R strategy and accordingly, provides a unique and optimal trade-off among the metrics being considered.

The analysis of the generated trade-offs between the objectives considered in a pairwise fashion reveals that the model was able to generate a wide range of optimal trade-off solutions complying with all specified constraints that the DM can select based on the available budget for pavement maintenance. Generally, 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 (Figure 1c). This last point can be explained by the fact that for an expenditure value greater than approximately $800,000 the number of M&R activities included in the optimal M&R plan is such that the pavement is barely allowed to deteriorate. In other words, the ceiling for effectiveness has been reached. Then, no (or reduced) further increase in the pavement condition can be obtained by increasing the highway agency’s expenditures in pavement M&R. These results, therefore, highlight the importance of proper maintenance planning and the need for effective decision support tools.

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 cost and emissions savings and pavement performance gains across the pavement life cycle, although they are particularly meaningful for low highway agency budgets, as proved by the steeper slope of the curve representing the Pareto front.

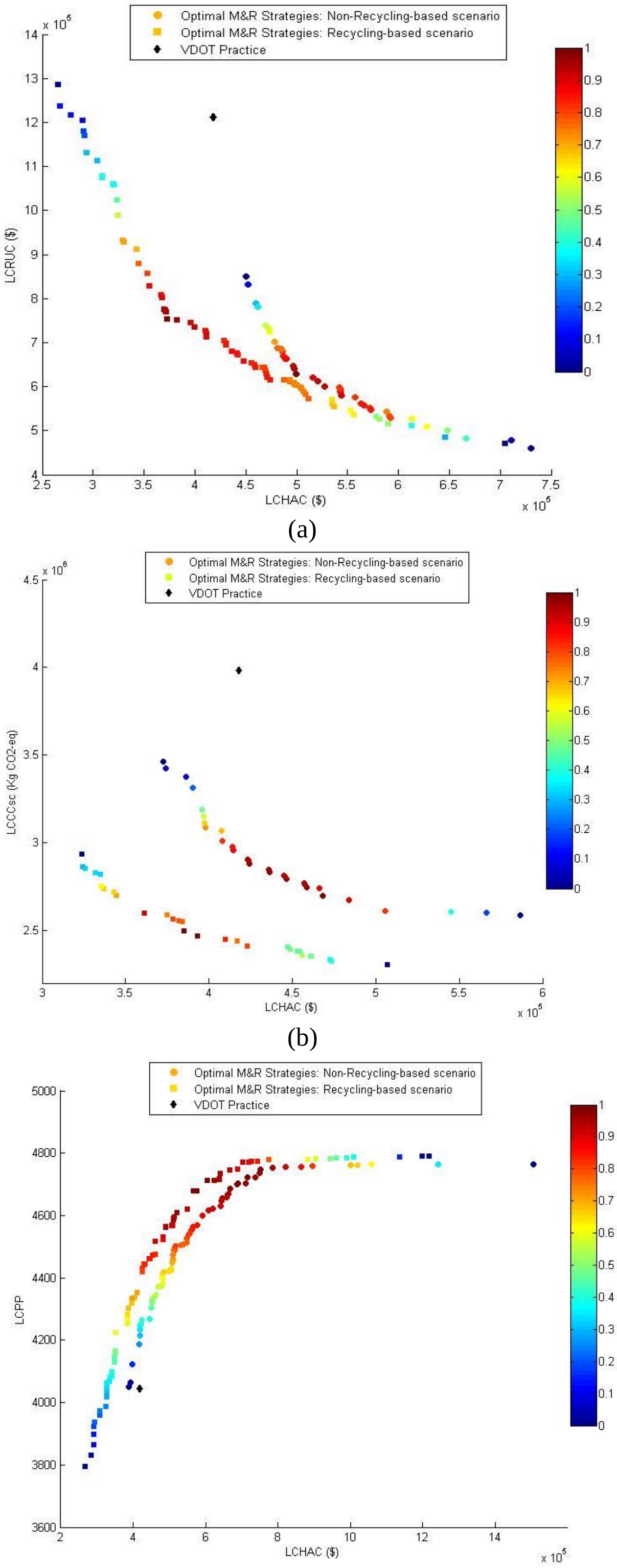


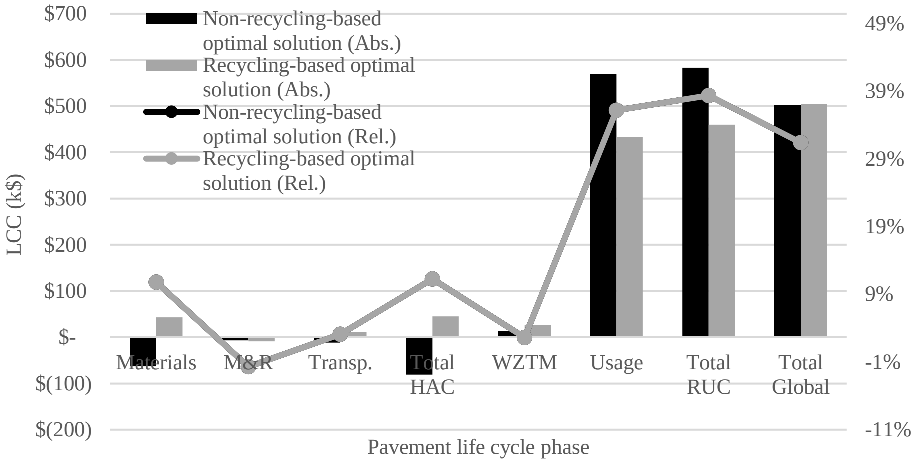
Figure 1. Pareto optimal sets of solutions in the objective space for both scenarios, along with the M&R strategy defined by VDOT: (a) Min. LCHAC vs. Min. LCRUC; (b) Min. LCHAC vs. LCCCsc; and (c) Min. LCHAC vs. Max. LCPP. Note: The fuzzy cardinal priority ranking of each non-dominated solution was normalized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

Tables 6 details the features of the BOCSs selected according to the methodology incorporated into the Decision Support module for a weighting scenario where all the objective functions being considered have equal importance (weights equal to 0.5). The numbers in brackets represent the application year of the corresponding M&R treatment. 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.

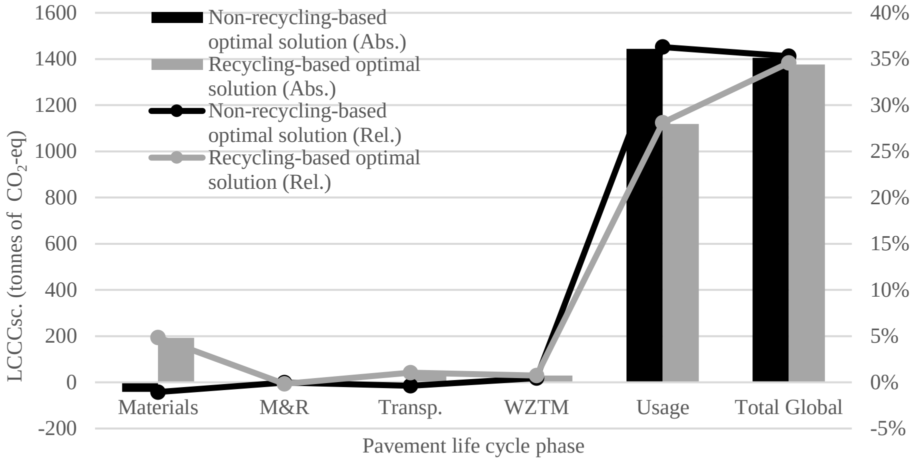
Table 6. M&R strategies of the best optimal compromise solutions (BOCSs) and current VDOT practices, and respective objective function values.

Sequence of M&R treatments	Current VDOT Practice	MOO problem					
		Min. LCHAC vs Min. LCRUC		Min. LCHAC vs Min. LCCCsc		Min. LCHAC vs Max. LCPP	
		NRbBOCS	RbBOCS	NRbBOCS	RbBOCS	NRbBOCS	RbBOCS
1st	4 (7)	4 (2)	4 (5)	2 (1)	4 (8)	4 (1)	4 (2)
2nd	5 (17)	2 (7)	4 (11)	4 (10)	2 (13)	4 (6)	4 (8)
3rd	6 (27)	4 (10)	3 (16)	2 (15)	4 (17)	4 (9)	4 (12)
4th	4 (39)	3 (14)	7 (23)	4 (19)	7 (22)	4 (13)	4 (16)
5th	5 (49)	6 (22)	2 (30)	6 (24)	4 (28)	4 (17)	4 (21)
6th		3 (28)	4 (33)	3 (27)	3 (31)	4 (21)	7 (24)
7th		4 (33)	4 (40)	4 (31)	4 (36)	6 (24)	4 (30)
8th		3 (37)	4 (46)	3 (37)	4 (42)	4 (28)	3 (33)
9th		4 (43)		4 (41)	3 (45)	4 (32)	4 (36)
10th		3 (46)		4 (46)	3 (49)	4 (36)	4 (39)
11th						5 (41)	4 (43)
12th						4 (44)	4 (47)
13th						4 (47)	
Average CCI	82.7	83.0	85.9	85.1	86.8	96.9	95.3
Average IRI [m/km]	1.27	1.05	1.11	1.09	1.11	0.99	1.01
LCHAC [k$]	418. 25	499.37	372. 95	467.97	393.42	751.55	567.70
LCRUC [$]	1 212. 50	629.39	752.66	708.30	745.93	529.96	547.59
LCCCsc. [tonnes of CO_2-eq]	3 980	2 575	2 604	2 697	2 466	2 929	2 507
Area under CCI curve	4046	4073	4209	4171	4273	4749	4677

BOCS- best optimal compromise solution; VDOT- Virginia Department of Transportation; MOO- multi-objective optimization; M&R- maintenance & rehabilitation; LCHAC- life cycle highway agency costs; LCRUC- life cycle road user costs; LCCCsc.- life cycle climate change score; LCPP- life cycle pavement performance; NRbBOCS- non-recycling-based best optimal compromise solution; RbBOCS- recycling-based best optimal compromise solution; CCI- critical condition index; IRI- international roughness index.



(a1)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1400
1200
1000
800
600
400
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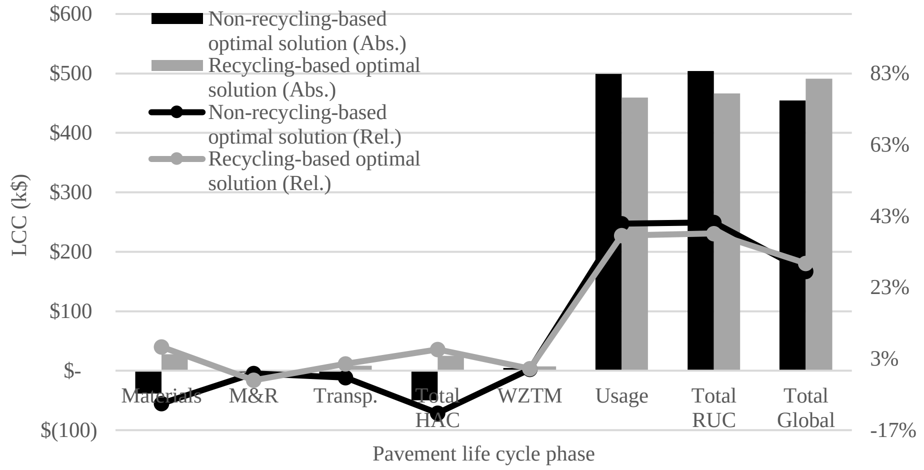
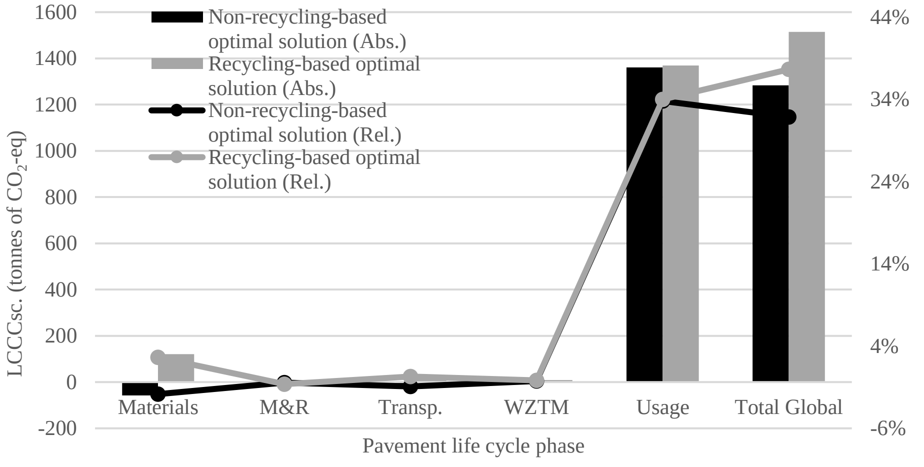
0
-200
40%
35%
30%
25%
20%
15%
10%
5%
0%
-5%
LCCCsc. (tonnes of CO_2-eq)
Non-recycling-based optimal solution (Abs.)
Recycling-based optimal solution (Abs.)
Non-recycling-based optimal solution (Rel.)
Recycling-based optimal solution (Rel.)
Materials
M&R
Transp.
WZTM
Usage
Total Global
Pavement life cycle phase

(a2)


$600
$500
$400
$300
$200
$100
$-
$(100)
83%
63%
43%
23%
3%
-17%
LCC (k$)
Non-recycling-based optimal solution (Abs.)
Recycling-based optimal solution (Abs.)
Non-recycling-based optimal solution (Rel.)
Recycling-based optimal solution (Rel.)
Materials
M&R
Transp.
Total HAC
WZTM
Usage
Total RUC
Total Global
Pavement life cycle phase

(b1)


1600
1400
1200
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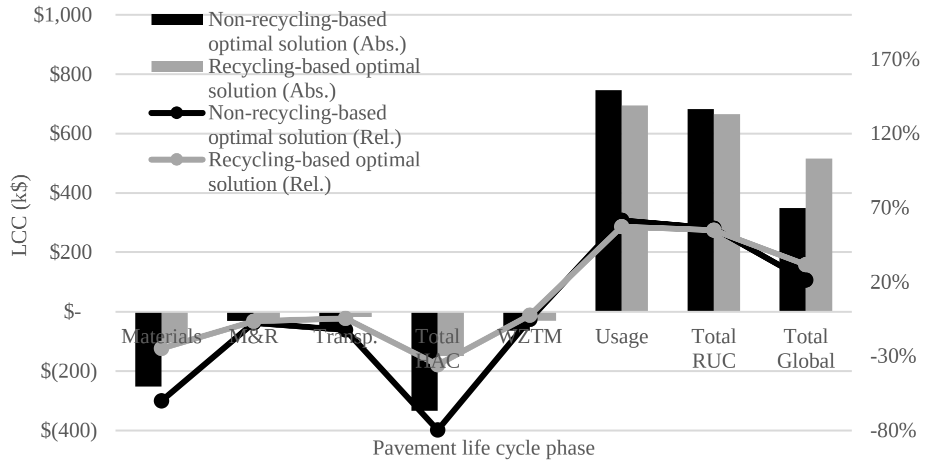
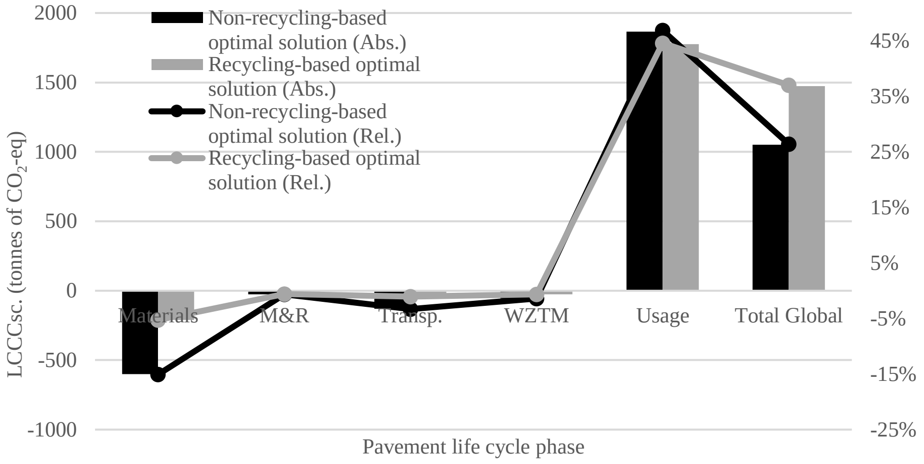
-200
44%
34%
24%
14%
4%
-6%
LCCCsc. (tonnes of CO_2-eq)
Non-recycling-based optimal solution (Abs.)
Recycling-based optimal solution (Abs.)
Non-recycling-based optimal solution (Rel.)
Recycling-based optimal solution (Rel.)
Materials
M&R
Transp.
WZTM
Usage
Total Global
Pavement life cycle phase

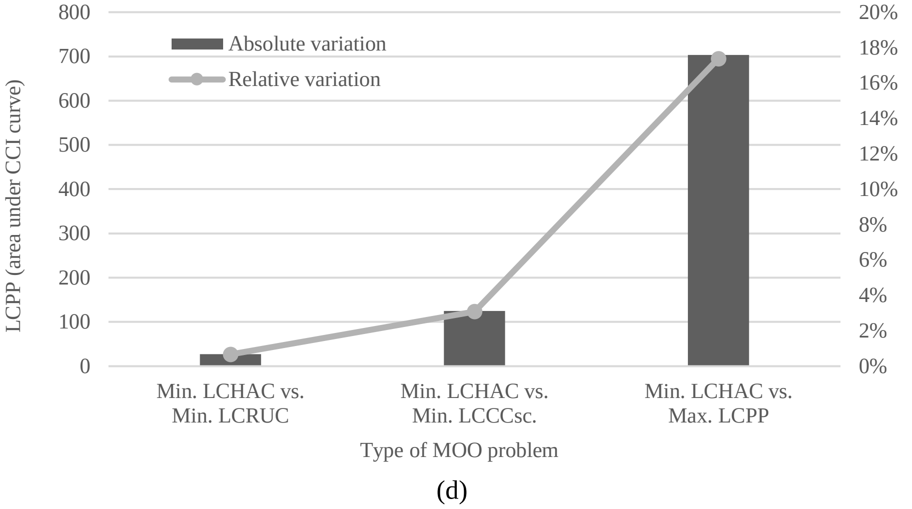
(b2)



(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.

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 the highway agency is required to substantially intensify the frequency of M&R activities in order to maintain the pavement condition at a good level. This is particularly evident when the average CCI values corresponding to this MOO problem are compared to those obtained in the remaining MOO problems (Table 6). In general, an increase in the average CCI value of approximately 10 points is observed in the third MOO problem.

Regarding the road users and environment perspectives, the NRbBOCS is always beneficial regardless of the MOO problem being 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 in 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 improves 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 the highway agency to increase its expenditure with pavement M&R by approx. 36%. Once again, this result is explained by the increase in the maintenance frequency. Specifically, 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 raises this value to twelve and thirteen, depending on the scenario considered, with CM being the most common M&R activity applied.

To provide DMs with insights on the most competitive M&R treatments in economic, environmental and technical terms, the optimal M&R strategies will be analysed in detail. Data presented in Table 6 allows the conclusion to be drawn that a M&R treatment of type RM is not sustainable, since it was included just once in one out of six optimal M&R strategies. On the contrary, M&R treatment of type CM is frequently applied in the design of sustainable M&R strategies, since the optimal M&R strategies consists, to a great extent, of this typology of M&R treatments. This result is particularly noticeable in the third MOO problem, to the extent that the optimal M&R strategies consist overwhelmingly of this type of M&R treatment. Expressly, it makes up 85% and 83% of the M&R strategies corresponding to NRbBOCS and RbBOCS, respectively.

As far as the PrM treatments are concerned, Table 6 shows that the optimal M&R strategies in the two first MOO problems are pretty much based on a proactive maintenance policy, in which PrM treatments are applied when the pavement is still in good condition. Among the two types of PrM treatments considered, THMACO denotes a slight supremacy of utilization over microsurfacing. On the other hand, in the case of the third MOO problem the PrM treatments are hardly applied or not even applied at all, such as is seen in the optimal M&R strategy corresponding to the NRbBOCS. The absence (total or almost total) of PrM treatments in the optimal M&R strategies of the third MOO problem, in which the maximization of the LCPP is sought to be optimized, may be due to the fact that they may not be able to bring the pavement condition to the state equal to that of a brand new pavement, and most of all, they do not restore the pavement age to 0. In practical terms, this means that the pavement degradation rate will increase quickly in the short-term period following its application. From this analysis, it can thus be concluded that PrM treatments do not suit optimal M&R strategies, in which the maximization of the LCPP is optimized along with the minimization of the LCHAC.

Summary and conclusions

This paper presents the development of a DSS framework for pavement management that aims to enhance the sustainability of the road pavement maintenance decision-making process by including road users and environmental concerns, in addition to the highway agencies, in the design of optimal M&R strategies. Specifically, by comprehensively identifying and quantifying from a cradle-to-grave perspective the HAC, RUC and environmental impacts arising throughout the pavement life cycle, it enables environmental and road user-related objectives to be optimized along with the traditional economic objective (i.e., minimization of HAC), through the implementation a bi-objective optimization procedure. This mechanism provides the DM with 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 proposes to DMs the BOCS among those lying on the Pareto front.

The capabilities of the proposed DSS were illustrated through 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 that the pairwise optimization of the four objective functions considered is conflicting, whereby an increase in one of the objectives leads to a decrease in the other.

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.

Other practical recommendations resulting from this case study pertain to the inclusion of certain types of M&R treatments in the design of optimal M&R strategies. Regarding the M&R treatments defined by VDOT, CM is highly recommended, as it was found to make up the majority of the M&R treatments adopted in the optimal solutions. It contrasts with the RM, that was only included once in an optimal solution. Regarding the PrM treatments, they were found to be particularly suitable for M&R strategies that account for the joint interests of highways agencies and road users.

Although the authors believe that the DSS presented in this paper can already be seen as a useful tool for helping DMs striving for more sustainable pavement systems, it can still benefit from further improvements. Therefore, further work concerning its development will follow four main directions. First, the total number of objective functions allowed to be simultaneously optimized will be increased from two to three. Second, 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. Third, the number of objective functions referring to LCEI indicators able to be simultaneously optimized will increase. This enhancement in the analysis capability of the proposed MOO model can be introduced, for instance, by employing dimensionality reduction techniques to overcome the computational limitations associated with solving Many Objective Optimization (MaOO) problems. In parallel to this, the pavement performance modelling module of the proposed optimisation-based DSS will be improved to allow the consideration of individual PPPM for modelling the development and progression of each pavement state parameter.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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