

A MULTI-OBJECTIVE OPTIMIZATION-BASED PAVEMENT MANAGEMENT DECISION-SUPPORT SYSTEM FOR ENHANCING PAVEMENT SUSTAINABILITY

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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 and decision-makers 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 activity 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. To address this multifaceted problem, this paper presents a comprehensive and modular multi-objective optimization (MOO) based pavement management decision-support system (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 one case study 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 trade-off between the following three often conflicting objectives: (1) minimization of the present value (PV) of the total life-cycle highway agency costs; (2) minimization of the PV of the life-cycle road user costs; and (3) minimization of the life-cycle greenhouse gas emissions.

Keywords: pavement management, life cycle cost analysis, multi-objective optimization, decision-support system

1 Introduction

Current asset management practices adopted by transportation agencies consist of applying economic analysis techniques, such as the life cycle costs analysis (LCCA), to select from among various infrastructures designs and/or maintenance and rehabilitations (M&R) intervention alternatives those that are most economically appealing, according to their interests and existing constraints. However, recent recognition that transportation infrastructure management decisions and practices also have substantial impacts on the environment [1], along with the

increasing awareness of sustainability and climate change, have motivated governmental agencies to promote a shift in focus in the management of transportation infrastructures towards achieving sustainable transportation systems. In the particular case of the road pavement sector, the implementation of effective sustainable pavement management systems requires the development of approaches that enable the prediction of: (1) the pavement performance; (2) the construction and maintenance-related budget requirements; and (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 [2], the environmental impacts associated with their life cycle are best characterized using a life cycle assessment (LCA) approach [3]. 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 trade-off of relationships and interactions between life cycle sustainability indicators. Rather, they are better employed when integrated into an optimization-based pavement life cycle management framework accounting for various objectives and constraints, and allowing LCCA and LCA to be carried out in parallel. However, the traditional practice in optimized decision-making in pavement management has been based on the optimization of a single objective, mostly the minimization of LCC, which can be either the total highway agency costs (HAC) or, less often, the summation of the total HAC and road user costs (RUC). It is therefore evident that a steady and effective implementation of a sustainable pavement management system, 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 to the multi-objective optimization (MOO) domain, in which the decision makers (DMs) are provided not with one single preferred solution, but with a set of potentially preferred solutions.

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

2 Decision support system methodology

The methodological framework of the DSS comprises three main modules: (1) a MOO module; (2) a comprehensive and integrated pavement LCC-LCA module; and (3) a decision-support module. The MOO module is further divided into three subcomponents: (i) the formulation of the MOO model, which consists of defining the decision variables, the objective functions and constraints; (ii) the solution approach, which hosts the method to be employed to solve the MOO model and find the Pareto optimal set of solutions; and (iii) the optimization algorithm developed to solve the MOO model. The main set of decision variables of the pavement M&R strategy selection problem, which are defined by an integer number is designed to represent all feasible M&R activities to be performed in each pavement section and in each year of the project analysis period (PAP). As far the definition of the objective functions is concerned, 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 user 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. To solve the MOO model and find the Pareto optimal set of solutions the augmented weighted Tchebycheff method is adopted in the proposed DSS. To that end, the MOO problem is converted into a SOO one, by combining the several objective functions into a single objective function. However, the optimization model 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. Therefore, a Genetic Algorithm (GA) based search heuristic was developed and implemented. Summarily, the GA possesses a hybrid nature in that local search 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 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) work zone 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. Further details on the integrated pavement LCC-LCA model are given in [4], whereas [5] and [6] describe the LCA sub-model and [7] the LCC sub-model.

Once a set of non-dominated solutions is generated representing the optimums for the problem being tackled, the DM faces a multi-criteria decision making problem should he desire to choose a single Pareto optimal solution out of the Pareto optimal set. 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 [8]. The normalized membership function (NMF) provides de fuzzy cardinal priority ranking of each non-dominated solution. The solution with the maximum value of NMF is considered as the best optimal compromise solution (BOCS).

3 Case study

3.1 General description

In order to illustrate the capabilities of the proposed DSS, it is applied to a case study consisting of determining the optimal M&R strategy for a one-way flexible pavement section of a typical Interstate highway in Virginia, USA, that yields the best trade-off 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 Climate Change (CC) impact category, expressed in terms of CO₂-eq, was selected because it is increasingly regulated and discussed by both governmental and non-governmental institutions. Furthermore, two scenarios are 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 study is shown in Table 1. To ensure practicality of the present model, a set of constraints is defined. Among that set of constraints, the following ones are worthy of mention: (i) the Critical Condition Index (CCI) of a pavement section cannot be lower than 40; and (ii) due to technical limitations which impose limits to the life of the initial pavement design and the most structurally robust M&R activities, the maximum time interval between the application of two consecutive M&R activities of that type is 30 years.

Table 1 Features of the case study

| Parameter | Value |
|--------------------------------|----------------|
| PAP | 50 years |
| Beginning year | 2011 |
| Initial AADT | 20000 vehicles |
| Percentage of PCs in the AADT | 75% |
| Percentage of HDVs in the AADT | 25% |
| Traffic growth rate | 3%/year |
| Initial CCI | 87 |
| Initial IRI | 1.27 m/km |
| Age | 5 year |
| Number of lanes | 4 |
| Lanes length | 1 km |
| Lanes width | 3.66 m |
| Discount rate | 2.3% |

PAP – project analysis period; AADT – annual average daily traffic; PCs – passenger cars; HDVs – heavy duty vehicles; CCI – critical condition index; IRI – international roughness index

3.2 Maintenance and rehabilitation activities

The M&R activities considered for application over the PAP are based on [9], and defined as: (1) Do Nothing (DN); (2) Preventative Maintenance (PrM); (3) Corrective Maintenance (CM); (4) Restorative Maintenance (RM); and (5) Reconstruction (RC). In the case of the PrM treatments, two types of treatments are considered: microsurfacing (McrS) and thin hot mix asphalt overlay concrete (TH). As for the RC treatment, two alternatives are also considered. They were named conventional RC and recycling-based RC and differ from each other in that the former comprises exclusively conventional asphalt layers, whereas the latter consists of a combination of conventional asphalt layers with in-place recycling layers. The recycling-based RC activity is designed in such a way that it provides equivalent structural capacity to its non-recycling-based counterpart and takes into account the Virginia Department of Transportation's (VDOT's) surface layer requirements for layers placed over recycling-based layers [10]. Details on the M&R actions comprising each M&R activity are presented in [4].

3.3 Pavement performance prediction model

In order to determine the pavement performance over time, the VDOT pavement performance prediction models (PPPM) are used (Eq. (1) and Table 2). VDOT developed a set of PPPM in units of CCI as a function of time and category of the last M&R activity applied [11]. CCI is an aggregated indicator ranging from 0 (complete failure) to 100 (perfect pavement) that represents the worst of either load-related or non-load-related distresses.

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

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 load-related PPPM coefficients (Table 2).

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. McrS and TH, are respectively modelled as an 8-point and 15-point improvement in the CCI of the road segment.

Once the treatment is applied, it is assumed that the pavement deteriorates according to the PPPM of a CM, but without reduction of the effective age. On the other hand, in the case of the application of CM, RM and RC treatments, the CCI is brought to the condition of a brand new pavement (CCI equal to 100) and the age is restored to 0 regardless of the CCI value prior to the M&R activity application.

Table 2 Coefficients of VDOT's load-related PPPM expressed by Eq. (1) 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 |

3.4 Results and discussion

The MOO model was written in MATLAB® programming software [12], 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. Figures 1a and 1b display the Pareto optimal set of solutions in the objective space, outlining the optimal pavement M&R strategies for the non-recycling-base and recycling-base scenarios, respectively, along with the M&R strategy defined by VDOT. Table 3 details the features of the BOCSs chosen according to the methodology described in Section 2 as well as the M&R strategy defined by VDOT. The results displayed in Figure 1 show that overall, and for both scenarios, an increase in the LCHAC not only leads to a reduction in the LCRUC but it is also beneficial in reducing the LCCCsc. However, a carefully analysis of this Figure reveals that there exists an investment level after which the Pareto fronts denote a flat trend. That trend means that any increase in pavement M&R expenditures has a greatly reduced reflex in reducing both the LCRUC and LCCCsc.

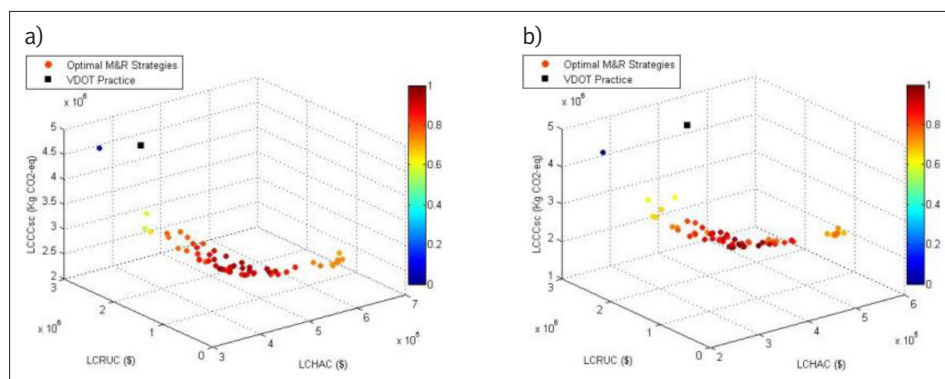


Figure 1 M&R strategy defined by VDOT and Pareto optimal fronts: a) scenario I; b) scenario II. Legend: LCHAC – life cycle highway agency costs; LCRUC – life cycle road user costs; LCCCsc – life cycle climate change score. Note: The fuzzy cardinal priority ranking of each non-dominated solution was normalized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

Table 3 M&R strategies of the BOCSs for both scenarios and current VDOT practice

| Scenario | Type of M&R strategy | M&R activity (application year) | | | | | | | | Avg CCI | Avg IRI [m/km] |
|----------|-----------------------|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------|----------------|
| | | 1 st | 2 nd | 3 rd | 4 th | 5 th | 6 th | 7 th | 8 th | | |
| I and II | Current VDOT practice | CM (7) | RM (17) | RC (27) | CM (39) | RM (49) | – | – | – | 83 | 1.3 |
| I | BOCS | CM (13) | RC (25) | McrS (32) | CM (36) | CM (41) | TH (46) | – | – | 77 | 1.3 |
| II | | McrS (2) | CM (4) | TH (12) | CM (18) | RC (24) | CM (30) | TH (36) | CM (41) | 81 | 1.1 |

Figure 1a, when analysed in conjunction with Figure 1b, 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.

Specifically, 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 greenhouse gas (GHG) emissions, the lower and upper boundaries are likely to be reduced by 8% and 3%, respectively. From the analysis of Figure 1, one can still conclude that the selected optimal M&R strategies (i.e. BOCS) always improve on VDOT practice with regard to the three metrics. Such improvements are obtained by increasing the number of M&R activities applied over the PAP, 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. The increase in the frequency of M&R activities is particularly notorious in the recycling-base scenario and was only possible without raising the expenditures incurred by the highway agency 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.

4 Conclusions

This paper presented the development of a DSS framework for pavement management that has the ability to optimize environmental and road user-related objectives, along with the traditional economic objective (i.e. minimization of HAC), 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. The results of the application of the DSS to a high-volume traffic road flexible pavement section of a typical Interstate highway in Virginia, USA, showed that the best optimal compromise M&R plans have the potential to improve on current VDOT's pavement M&R practice with regard to the three considered metrics. In addition, it was also shown that such improvements can be more expressive if the most structurally robust M&R activity initially considered was replaced by an equivalent recycling-based M&R activity and the best recycling-based optimal compromise M&R strategy was implemented.

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