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Review on Multi-Objective Optimization in Highway Pavement Maintenance and Rehabilitation Project Selection and Scheduling

Sandip Sampat More, Assistant Professor Shashikant B.Dhobale
Department of Civil Engineering,
Jawaharlal Institute of Technology, Borawan Dist. Khargone

Abstract- This study review an efficient asset management framework that enables decision makers to prioritize the maintenance of their roads, while focusing on the most critical road segments. In particular, this study first extends the application of reliability theory to estimate the overall network condition. Following that, this study proposes a new consequence of failure function for the whole road network based on road segments' reliability, age, and road agency preferences. Finally, the study proposes an efficient multi-objective optimization algorithm, with the goal of maximizing overall network performance with the least maintenance and computational cost. The suggested framework was applied to three main roads in Jordan and validated statistically by comparing its performance to that of a typical multi-objective genetic algorithm (GA) under various scenarios and utilizing multiple performance metrics.

Index Terms- Road pavement management systems; performance indicators; prediction models; Markov chains; multi-objective optimization; genetic algorithms; two-stage optimization; sustainability; costs of CO2e emissions.

I. INTRODUCTION

With the rapid development of pavement networks, by the end of 2016, the total length of the city's roads exceeded 13,000 km; this increase has necessarily resulted in a constant increase in tasks related to urban pavement maintenance and management. To improve the effectiveness and efficiency of pavement management strategies, it is necessary to evaluate scientifically the service level of pavement conditions and use such evaluations to develop an efficient road network maintenance management planning system. Road maintenance decision-making often involves addressing multiple and conflicting objectives and factors, such as road condition performance, maintenance costs, and user disturbance impact. Because funds are limited, decision-makers need to undertake pavement maintenance treatments only on certain sections of the road network, and this parameter increases the challenge inherent in this work.

Therefore, this study looks to help decision-makers develop an optimal pavement network maintenance and rehabilitation (M&R) program over a planning horizon. Multiobjective optimization techniques are often used to create optimal pavement network maintenance programs (i.e., in which pavement sections are maintained at an acceptable service-condition level while incurring low agency costs and not creating significant amounts of user disturbance, environment pollution, or traffic hazard). However, trading off maintenance strategies under such conflicting objectives is difficult, and for each strategy, it requires salient knowledge [1].

Therefore, in developing a pavement network M&R program, it is essential that decision-makers compare representative options and select appropriate strategies. This paper presents a multiobjective pavement network maintenance optimization model that considers three conflicting objectives, namely, the maximization of pavement condition improvement, the minimization of user disturbance costs, and the minimization of agency costs over the planning horizon.

Pavement management covers the processes of data collection, condition assessment and prediction, planning, optimisation and application of maintenance and rehabilitation (M&R) treatments, as well as budgeting. The objective of M&R optimisation is to maximise performance (e.g. network condition), or to minimise agency and user costs, or to minimise risk/environmental impacts by selecting appropriate treatments (decision variables), subject to constraints (e.g. budget). This problem can be formulated for a single road section (single facility), for a travel route consisting of multiple sections, or for the entire network (system) covering all sections and other road assets.

In the context of aging infrastructure, increasing traffic loads, demanding public expectations and limited budgets, road agencies in developed countries are faced with several

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requirements. They have to maintain the network condition, allocating their budget according to the needs by balancing trade-offs between agency and user costs in the long term, but also to reduce accidents, emissions and traffic flow interruptions in the short term. An ideal pavement management system (PMS) would therefore address these goals simultaneously, providing optimal budgets at the network level, as well as detailed location-specific treatment recommendations in terms of timing, type, work-zone length and layout that could be accepted by road engineers and applied with limited need for manual adaptation.

Common PMSs aggregate short survey sections to long homogeneous sections based on different algorithms, effectively resulting in an averaging of measured condition data. The purpose of this approach is to reduce the computing effort and the complexity of the optimisation problem. However, there is a growing discrepancy between the on-going development of automated condition survey systems (laser technology), delivering more accurate measurements with higher resolution and collection frequency, sharply contrasting with the limited capabilities of current PMS, using only a fraction of the provided information in prediction and optimisation.

Surprisingly, the validity of the approaches for sectioning and data aggregation is not questioned in the literature and the consequences of their use are not investigated. The assumption that a similar condition (at the time of the survey) implies similar future deterioration is proven wrong by empirical research. Thus, condition predictions based on homogeneous sections cannot be accurate. Moreover, the defined condition thresholds are systematically violated due to averaging effects, and it is not possible to select optimal work zones since the formation of homogeneous sections is conducted prior to prediction and optimisation.

II. RESEARCH MOTIVATION

Appropriate management, study and planning are effective factors in maintaining the level of service provided by infrastructure projects and preventing possible deterioration through maintenance of the integrity of such projects. Neglect or misuse and mismanagement of these public services can result in additional expenses and subversive alternatives as well as significant failures [1]. Decision-makers (DMs) need mathematical solutions and process research models to find appropriate decisions in case of a number of conflicting goals that need to deal effectively and ideally to reach the optimal decision. As an example of this case when there is a desire to improve the level of performance of a particular project at the same time there are financial constraints through limited budget or lack of financial allocations available for maintenance work. Therefore, there is a need for a multi-objective decision support system (MODSS) to improve the effective use of available resources and to create a distinct cost-benefit ratio.

It is necessary to understand the nature of the infrastructure projects and the history of maintenance of its parts and study the mechanism of degradation of the project, as the process of optimal decision-making requires knowledge of the problem and determine its variables and what are the most important constraints that may hinder the achievement of the appropriate decision which in turn leads to the creation of an effective maintenance and rehabilitation program for the project under study. In fact, the current state of the project and its future development are determinants of the effectiveness of any (DSS) [2]. In this paper, performance will be increased through benefiting from expertise in pavement engineering as well as information and knowledge available from other areas such as management science, decision support systems, mathematical modeling and artificial intelligence. Furthermore, this research is part of the study of the benefits of using multi-objective systems in the management of pavement maintenance.

III. PAVEMENT CONDITION INDEX CALCULATION

The rating of roadway is specified from a correlation that display roadway rating as a result of the PCI pavement condition index value calculation. When explaining data that was collected from field survey and visual inspection for road condition, three varied type of the collected data must have concerned: the traffic density, the type, density and severity of distress at survey time and at last the evolution of road deterioration. The PCI value presents a general conception of the pavement state and the nature of the work that will be wanted to maintain the pavement. Pavements at surface layer are more potential to require a simple repair and minor maintenance, while the lower layers of road are more suitable to be nomination for essential rehabilitation or reconstruction. There are two methods for calculating PCI, which are the manual method, it depends on the use of equations and curves, while the second method uses the MATLAB software.

IV. PROBLEM DESCRIPTION

The problem addressed in this study relates to the allocation of limited funds to pavement network M&R programming over a certain planning horizon. Three stakeholders are involved in developing the pavement maintenance program, namely, the government, the agency, and the users. Each decision-maker needs to consider a variety of objectives and factors, and so when creating a maintenance plan for a pavement network in a certain planning period and with limited funding, trade-offs are inevitable. For example, the execution of too many heavy maintenance treatments will

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effectively improve the road condition, but it will also increase the user disturbance costs. More importantly, funding limitations mean that only a few road sections can be considered for heavy maintenance. The execution of a lower cost maintenance treatment may reduce both user disturbance costs and agency costs, but it will also lead to poor road conditions—conditions that are perhaps even lower than those dictated by the government—and thus reduce road safety. Therefore, for decision-makers, it is especially important to decide upon a pavement network M&R plan under limited budgets, while considering conflicting objectives that involve a variety of maintenance treatments. +is constitutes a multi objective optimization problem.

Objectives

The present doctoral thesis emerged, at first, within the scope of the project mentioned in Section, in order to contribute with scientific knowledge for the project development regarding the optimization of pavement management. The principal aim of this work was to develop an optimization methodology to support decision making regarding the planning of pavement preservation activities, considering pavement quality and administration costs. Pavement quality is related to several pavement dis tresses that must not exceed certain threshold values on its deterioration. Costs for the administration are mainly related to the direct costs of M&R. In addition, increasing attention has been given to user costs and environmental impacts due to the use and preservation activities of pavements.

V. LITERATURE REVIEW

Mohammadhosein Pourgholamali et al. [1] The motivation for cost-effective management of highway pavements is evidenced not only by the massive expenditures associated with these activities at a national level but also by the consequences of poor pavement condition on road users. This paper presents a state-of-the-art review of multi-objective optimization (MOO) problems that have been formulated and solution techniques that have been used in selecting and scheduling highway pavement rehabilitation and maintenance activities. First, the paper presents a taxonomy and hierarchy for these activities, the role of funding sources, and levels of jurisdiction. The paper then describes how three different decision mechanisms have been used in past research and practice for project selection and scheduling (historical practices, expert opinion, and explicit mathematical optimization) and identifies the pros and cons of each mechanism.

Wang Chen et al. [2] Pavement maintenance timing series (PMTS) optimization at the project level should consider multiple interventional maintenance impacts within the planning horizon, while making trade-offs between investment and environmental burden, which is difficult to address with traditional methods, partly due to the lack of understanding of the interaction mechanism between the sustainable objectives. To bridge this gap, this paper presents a customized project-based PTMS decision-making method using multi-objective optimization, and applied it to explore the PMTS generation mechanisms by decomposing the sustainable objectives. Results show that among the three sustainable objectives, life-cycle agency cost and greenhouse gas (GHG) emissions drive the timing series formation of maintenance technologies, and GHG emissions can also limit the “greedy” growth of non-zero decision variables, while the integral function form of the benefit of pavement maintenance can improve the lowest performance condition. In addition, the proposed approach allows for the maximization of the trade-offs between the three sustainable objectives using the Euclidean norm strategy, while providing a prioritized set of potential PMTS solutions. Based on that, a benefit-to-cost & GHG emissions ratio model (BCGRM) was proposed to compare with the above tri-objective optimization model in generating PMTS. Since the non-dominating nature of the three objectives cannot be directly considered, BCGRM will get higher investment benefits by increasing the maintenance frequency.

Qiang Wei et al. [3] Highway engineering construction is a complex multi-objective management project, and the traditional multi-objective task management approach has been difficult to cope with the uniqueness of highway engineering construction management. In order to improve the efficiency of multi-objective management in highway engineering, the study proposes to construct a multi-objective management model using particle swarm and harmony search algorithms for highway engineering management. First of all, the study first explores the management indexes in highway engineering, and constructs the functional relationship according to the selected indexes. Then the particle swarm algorithm is used to optimize the database of the harmonic search algorithm, and the harmony search algorithm can be based on the optimized database to find the optimal solution for objective management.

Wang Chen et al. [4] The next-generation of pavement maintenance and rehabilitation (M&R) decision-making needs to weigh multiple strategic goals to achieve sustainable development through the pavement maintenance management system (PMMS). Motivated by good versatility in solving highly complex conflict problems, the application of multi-objective optimization (MOO) for pavement M&R has recently become a hot-spot issue. This review aims to provide the state-of-the-art development and application of MOO methods for the PMMS decision-making module and the associated MOO model, decision-making tools, and optimization techniques. The strategic decision-making goals, decision processes, sources and characterization methods of uncertainty, intelligent algorithm followed across the globe

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were reviewed. Further, the latest development of multi-objective decision-aid tools (MODAT) for PMMS was discussed while emphasizing the importance of establishing joint MOO optimization model of multiple facilities and multiple M&R techniques for PMMS to achieve intelligent decision-making. The existing deficiencies and future direction of research have been discussed.

Mengyu Huang et al. [5] With growing maintenance demands whereas limited budgets, an integrated methodology unifying life-cycle assessment (LCA), life cycle cost assessment (LCCA) and multi-objective optimization is proposed to establish maintenance decision-making system, considering performance, economic as well as environmental dimensions. Firstly, system scope and unit process of the methodology are redefined considering pavement industry in India. Next, assessment models and parameters are determined to establish the inventory. Then, LCCA is adopted to convert environmental footprint into an economically measurable unit - environmental damage cost (EDC). Lastly, a programming optimization is executed to obtain the optimal maintenance schedule over the whole pavement life cycle. To verify, a case study based on an existing highway in southeast India is conducted, considering ECA-10 thin overly (ECA-10), milling and resurfacing the upper layer (MRU) and hot-in-place rehabilitation (HR) strategies. Results indicate that user cost is the dominant factor whereas environmental impact is relatively negligible. Pavement design life and service life of maintenance alternatives have significant influence on the optimal schedule, and longer pavement design life should be considered when conducting LCA-based programming optimization. With the extension of design life, MRU shows the best long-term benefit. Materials and construction are the main stages potentially improved. Few attempts have been made to introduce LCA into the pavement industry of India, but this model successfully contributes to sustainability goal and scientific decision-making.

VI. CONCLUSION

Highway asset management is becoming increasingly important among public agencies because of increasingly tighter budget, higher public demands and stricter agency accountability, among other factors. Some of the intrinsic characteristics of the highway system make the use of multi-objective optimization techniques particularly attractive for managing highway assets. Recognizing the need for effective tradeoff tools and the limitations of state-of-practice analytical models and tools in highway asset management, this dissertation developed a performance-based asset management framework that includes stand-alone but logically interconnected decision-support tools for different management levels using multi-objective optimization techniques. The problems under investigation are those of network-level programming and project selection under the context of multiple objectives/goals, a finite multi-period horizon, a multi-district public agency, probabilistic constraints, and various performance targets.

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