OPTIMAL RESOURCE ALLOCATION MODEL FOR PAVEMENTMAINTENANCE ESTABLISHED BY DE NOVO PROGRAMMINGMETHOD

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ABSTRACT

Pavement management, in its broadest sense, includes all the activities involved in the planning, design, construction, maintenance, and rehabilitation of the pavement portion of a public works program. A pavement management system (PMS) is a set of tools or methods that assist decision makers in searching optimal resource allocation and then deciding optimal maintenance strategies for keeping pavements in a serviceable condition over a given period of time.

There are several methodologies adopted by road agencies to allocate maintenance resources. When dealing with a multiple criteria optimization problem, we usually confront a situation that it is almost impossible to optimize all criteria in a given system. Zeleny gave a different point of view to this problem. He developed a De Novo Programming for designing system by reshaping the feasible set (resource constrains). An optimum-path ration was introduced in De Novo Programming to contract the resource to available resource along the optimal path. De Novo programming is a vital tool for designing an optimal system.

In the study, we identify the optimal maintenance strategies by three objectives – maximizing pavement improvement, minimizing the incremental cost during maintenance activities, and maximizing pavement serviceability. De Novo Programming is used to reallocate maintenance resources and obtain the actual optimal resource allocation model for

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pavement maintenance sections in Taiwan Area National Freeway Bureau (TANFB) and Taiwan Area National Freeway Bureau (TANFB) based on real data. According to the findings, the direction of resources adjustment and improvement strategies are proposed as well.

KEYWORDS:

Pavement management systems (PMS), Pavement maintenance, Resource allocation, De Novo programming method, Optimization

1. INTRODUCTION

Pavement provides fast, steady and economic surface for road users with safety and comfort while riding. Pavement management system (PMS) is developed and based on concepts described by AASHTO: "A PMS is a set of systematic tools or methods that assist highway administrators and engineers in effectively and efficiently managing their highway pavements(AASHTO 1990)." However, pavement often suffers distresses caused by internal and external causes, such as poor subgrades, defective drainage system, unstable embankment and problematic quality control, etc.

In order to find optimal strategies for providing, evaluating, and maintaining pavements in a serviceable condition over a period of time, maintenance resource allocation should be identified in a PMS and usually completed by a ranking system (prioritization methods) or an optimization model (network optimization) (Haas et al. 1978). Some PMS's have priority-ranking criteria or a ranking matrix to prioritize the resources allocation to alternative maintenance strategies; some PMS's contain a network optimization model with its objective functions and constraints to identify the optimal maintenance strategies; and some PMS's have both of them. The paper reviewed both prioritization methods and network optimization in a PMS. One network optimization model based on the three objectives - maximizing pavement improvement, minimizing the incremental cost during maintenance activities, and maximizing pavement serviceability - were proposed to identify the optimal network maintenance strategies by using fuzzy multiple objective programming (FMOP)(e.g., Zimmermann 1978,Martinson 1993) combined with two-phase approach (Lee 1993). The real data from Taiwan Area National Freeway Bureau (TANFB) were collected to conduct an empirical study for revealing and verifying the model's feasibility.

This paper is structured as follows. Overviews of prioritization and optimization in a PMS are illustrated in Section 2. Section 3 briefly reviews the concepts of De Novo programming. In Section 4, three objectives for De Novo programming are identified and applied to conduct one empirical study according to the actual situation in Taiwan. The analytical results are discussed and compared with related studies. Finally, the conclusions are summarized in Section 5.

2. OVERVIEWS OF PRIORITIZATION METHODS AND NETWORK OPTIMIZATION IN A PMS

An ideal PMS would yield the best possible value for the available maintenance resources while providing and operating smooth, safe, and economical pavements. Generally, the minimum requirements of a PMS should contain three main subsystems (Hudson 1994):

(1) A database subsystem is to provide useful information for decision-making. The information involves pavement inventory; pavement condition data; traffic data; history and cost data of construction, maintenance, and reconstruction; etc.

(2) A data analysis subsystem that uses information provided from database to allocate resources to feasible maintenance activities. The subsystem is data-intensive and contains various methodologies range from subjective judgment to mathematical programming depend on different road agencies.

(3) A feedback subsystem to verify and enhance the reliability of a PMS in a cyclic way.

Several methodologies are used to allocate maintenance resources, such as pavement ranking criteria, pavement condition analysis, priority assessment models, network optimization models, prioritization models, and identification of maintenance strategies, etc (Kulkarni et al. 1980, Kulkarni et al. 1983, Zimmerman 1995). Some of them are developed unique by different agencies but addressed similar techniques. In general, these methodologies can be categorized into prioritization methods and network optimization. In a PMS, pavement condition data are combined into some index to represent actual pavement condition. Prioritization is conducted to rank and categorize the whole pavement sections by using priority-ranking criteria to establish pavement section ranking. The common used ranking factors include pavement type, traffic volume, friction, structural capacity, etc. Maintenance resources are allocated in the light of ranking and the priority assigned to it.

A network optimization model identifies the network maintenance strategies. The objectives can be specified as maximizing the whole network performance or minimizing the total network cost subject to constraints such as budget limits and acceptable serviceability.

The pavement section condition data are used as model inputs, decision variables represent the application of possible maintenance strategies to sections, and resource limits and minimal acceptable network serviceability are constraints.

In 1991, a survey was conducted to explore the status of PMS's developed and operated in most U.S. state highway agencies (Federico 1993). Table 1 shows the percentage of states that implement and plan to implement a prioritization model in their PMS's are 77% and 2%, respectively. The percentages of PMS's have and plan to have a network optimization model are 28% and 19%, respectively. It is noted that the total percentage is more than 100% because the some PMS's have an optimization model often implement a prioritization model.

Thirteen states have optimization models in their PMS's. However, just four techniques are used to conduct the optimization methodology, as shown in Table 2. Linear and integer programming are the most common mathematical programming techniques in various fields to allocate available resources. Incremental benefit-cost is similar to marginal cost-effectiveness.

Both of them allocate the incremental resources to projects that provide the optimal increment of benefits or effectiveness. Besides, other mathematical programming techniques are proposed, such as dynamic programming, etc (Phillips et al. 1981, Butt et al. 1994, Kulkarni 1984, Wang et al. 1997, Feighan et al. 1988, Ningyuan et al. 1998).

Table 1 Methodologies for maintenance strategies used in U. S. state's PMS

Prioritization/Optimization	Number	Percentage
No PMS	4	0
Prioritization model	36	77
Plans for prioritization model	1	2
Optimization model	13	28
Plans for optimization model	9	19

Table 2 Techniques used optimization models

Technique	Number	Percentage
Linear programming	7	55
Integer programming	2	15
Incremental benefit-cost	2	15
Marginal cost-effectiveness	2	15

All feasible maintenance strategies are constrained by different factors and cannot be funded in one year or even a multiyear. The process of decision-making has to base on specific objective and constraints. The mathematical programming selects solution to decision variables that optimally satisfy specific objective functions and identified constraints. The common objective functions and constraints are summarized in Table 3 and 4, respectively, with the used percentage in optimization models. In Table 3, the total percentage is more than 100% because some optimization models have more than one objective function.

In the prioritization model, simple priority-ranking criteria are made by some available factors, such as pavement conditions, traffic, structural capacity, age, etc., to prioritize maintenance strategies without taking pavement performance prediction models into account, needless to say establishing an economic model. The prioritization methods is suitable for project-level PMS's only and no longer used to network-level PMS's. Network-level PMS's focus on the whole pavement network and use budget limitations and maintenance performance as programming objectives (Phillips et al. 1981). The paper considers network-level pavement sections and identifies multiple objective - maximizing pavement improvement, minimizing the incremental cost during maintenance activities, maximizing pavement serviceability - for maintenance strategies optimization model.

Table 3 Objective function used in optimization models

Objective Function	Number	Percentage
Minimize cost	8	62
Maximize area under performance curve	5	39
Minimize disutility	1	8
Maximize maintenance effectiveness	1	8

Table 4 Constraints used in optimization models

Constraint	Number	Percentage
Budget	13	100
Minimal pavement condition requirement	5	39
Resources	2	15
Other	5	39

3. DE NOVO PROGRAMMING

De Novo programming was proposed by Zelenyto redesign or re shape given systems to achieve a aspiration/desired level(Zeleny M. 1986, Zeleny M. 1990, Zeleny M. 1995). The transitional mathematical programming is based on the assumption that in the production model resources and constraints are predefined. For example, the quantities of available raw materials, market potential, transport facilities, output, and the available means are all predefined. In such cases, if they are dealt with by multi-objectives decision making, the result is a compromise solution, as according to some criteria a value lower then optimal or ideals is achieved.

However, De Novo programming approach does not constraint resources, because it assumes that most of the required resources can be purchased at an appropriate price. The only constraint is the available quantity of money, i.e. the budget needed for the purchase of required resources. By this we do not mean that certain constraints cannot be set in the model, like in the standard approach, if it is necessary for the normal functioning of the production model.

According, the essential difference between these approaches is that the standard approaches treat the problem by optimizing the given system, while De Novo, enabling the varying of constraints, tries to find out a solution more favorable than one found out at fixed constraints. Therefore, it is often said that De Novo instead of "optimizing the given system" suggests the way how to "design an optimal system". Such an approach of course, has to be introduced before the production plan can determine the quantities of raw materials necessary for optimal production.

In relation to standard programming models, De Novo programming provides other possibilities like finding out the best solution when prices, technological coefficients or some other circumstances implied by the production model are changed. Particularly important is the advantage of this approach in the case of multi-objectives decision as it enables adjustment of resource constraints in such a way that the initial ideal or infeasible solution becomes feasible at the same or lower costs.

4. EMPIRICAL STUDY: THE FMOP MODEL FOR OPTIMIZING PAVEMENT MAINTENANCE STRATEGIES

Generally, road users expect that the pavement serviceability would remain acceptable at all time. The pavement maintenance strategies are employed to improve the whole pavement serviceability. In the meanwhile, the incremental cost during maintenance activities (e.g. traffic congestion, circumvent driving, etc.) would be minimized. Therefore, based on the foregoing viewpoints and the actual situation in Taiwan (annual maintenance budget has to be exhausted without retaining), we identify the three objectives, that is - maximizing network improvement (maximization of maintenance performance), minimizing the incremental cost during maintenance activities (minimization of maintenance effects) and maximizing pavement serviceability (maximization of the whole pavement serviceability) - as the three objectives for De Novo programming model. The solution can be obtained under optimizing the three objectives (Chang et al. 2004).

The selection of the most appropriate maintenance strategy has to consider the existing pavement conditions (e.g. surface distress, roughness, etc.), traffic volume, costs, and maintenance performance, etc. The related studies show that surface distress and roughness are the two factors frequently considered in the pavement maintenance optimization. Roughness refers to the longitudinal evenness; its representative index is International Roughness Index (IRI). The smaller IRI means that pavement surface is more even; in other words, higher pavement serviceability. The empirical study focuses on the freeway that mainly provides even pavement for road users. Hence, it is rational to adopt IRI as one factor to optimize maintenance strategies. It is noted that the third objective should express the “maximizing pavement serviceability”; and since a smaller IRI means better pavement serviceability, this objective function was minimized.

$$Max\ Z_1 = \sum_{i=1}^{I}\sum_{j=1}^{J} X_{ij} \cdot \Delta IRI_j \quad \text{......} (1)$$

$$Min\ Z_2 = \sum_{i=1}^{I}\sum_{j=1}^{J} X_{ij} \cdot A_i \cdot T_j \quad \text{......} (2)$$

$$Min\ Z_3 = \sum_{i=1}^{I}\sum_{j=1}^{J} X_{ij} \cdot IRI \quad \text{......} (3)$$

subject to:

$$\sum_{i=1}^{I}\sum_{j=1}^{J} X_{ij} \cdot C_j \cdot A_i \le B \quad \text{......} (4)$$

$$\sum_{i=1}^{I} X_{ij} \leq D$$

$$\sum_{j=1}^{J} X_{ij} \leq 1 \quad \forall i = 1,2,\cdots,I \quad \text{.......} \quad (5)$$

其中：

I ：total pavement sections

J ：total feasible maintenance strategies, frequently adopted in Taiwan are 1.5 cm milling overlay, direct overlay, and localized repair

i ：candidate sections, $i \in \{1,2,\cdots,I\}$

j ：maintenance strategies, $j \in \{1,2,\cdots,J\}$

X_{ij} ：the *j* maintenance strategy applied on the *i* section

C_j ：unit cost of the *j* maintenance strategy

ΔIRI_j ：performance of the *j* maintenance strategy (i.e. roughness improvement)

T_j ：the incremental cost during construction of the *j* maintenance strategy

A_i ：maintenance area of the *i* section

B ：annual budget

D ：the number of maintenance project that agency can handel

4.1 EMPIRICAL DATA

Part of flexible pavement sections on the 3rd National Freeway in Taiwan was selected as the empirical network. The empirical data were collected from Taiwan Area National Freeway Bureau (TANFB). The entire length of the network is 67.968 km (042k+000~109k+698); wherein the length of 6-lane section is 35.258 km, the length of 7-lane section is 20.454 km, and the length of 8-lane section is 11.462 km. Except for the 1.330 km section at Shulin toll station (045k+870~047k+200) and 9.250 km section at Lungtan toll station (063k+935~073k+185) are rigid pavement, the rest of sections are flexible pavement and it occupies 83.6% of the whole network. The lane-km and integer mileage are used to divide the network into elementary units. For instance, 1-kilometer section (042+000~043k+000) is demarcated into four elementary units since it has four lanes. According to this principle, the whole network can be demarcated as 387 elementary units for De Novo programming model.

4.2 ANALYTICAL RESULTS

The LINGO software was used to solve the mathematical programming problem. The solved budget, number of maintained section, and achievability of each objective are shown in Table 5. The results can be illustrated as follows:

"Assumption of the annual budget is NT$ 8 million, the agency can process 20 projects per year, every project can instead of NT$ 540,000. So we use the de novo programming in this problem and compare the result with Fuzzy Multiple Objective Programming[20]. We increase the original budget to 9,610,089 that three objectives will be better then FMOP. So de novo programming give us a new way to resolving the maintenance problem. If we change some budget item to engage more people dealing the project, the pavement network performance will better. So de novo programming apply to pavement maintenance is suitable.

Table 5 Compare the MODM and De Novo result at each objective function

	MODM	De Novo
Maximization of network improvement	1.13	1.00
Minimization of the incremental cost during maintenance activity	203,840	181,675
Maximization pavement serviceability	17,901,718	20,085,727

5. CONCLUSIONS

Considering related literatures and the actual maintenance situation in Taiwan, maximization of pavement improvement, minimization of the incremental cost during maintenance, and maximization of whole pavement serviceability are identified as three objectives to optimize the maintenance strategies. The analytical results completed by de novo programming, we can reconsider the constraint allotment. In the example, we see change the budget that can improve the performance. So de novo programming apply to pavement maintenance can give a new way to resolute the problem.

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