MULTI-YEAR PAVEMENT MANAGEMENT PROGRAMMING FOR ROAD NETWORK

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Abstract: This paper presents the application of the genetic algorithm programming techniques to solve a multi-year pavement maintenance and rehabilitation activities programming problem at the network level. A problem consisting of 27 pavement segments of an actual road network was considered. The deterioration of pavement segments with time was predicted by a homogeneous Markov chain model. The condition of each pavement segment was defined by the proportions of the segment in different condition states. Like most pavement management problems the problem is highly constrained and suitable techniques are needed to handle the multiple constraints. The solution obtained by means of a mixed-integer optimization technique is first presented and analyzed. The problem was next solved using genetic algorithms with penalty functions to handle the multiple constraints and the results were discussed and compared with that of mixed-integer optimization technique.

Keywords: Pavement management, pavement maintenance programming, network level optimization, Markov chain, genetic algorithms

1. INTRODUCTION

Efficient programming of pavement maintenance and rehabilitation activities over a multi-year planning horizon is a major requirement in a pavement management system for road network. It is a highly complex problem because of the large number of pavement segments and constraints that have to be considered. There are difficulties in applying conventional optimization techniques to solve the problem. Genetic algorithms (GAs) have been found to be an efficient tool to obtain sufficiently good or near-optimal solutions for highly combinatorial pavement management problems (Fwa et al. 1994, Fwa et al. 1996, Fwa et al. 1998) for practical applications.

The applicability of genetic algorithms (GAs) to solve a multi-year pavement management model is presented in this paper. The model was originally solved by a mixed-integer optimization technique (Ferreira et al. 1999). In this study, a problem consisting of 27 pavement segments of an actual road network in Coimbra, Portugal has been solved using genetic algorithms. The problem is highly constrained and for GAs to be successfully applied to solve such a problem, special provision need to be made to handle the multiple constraints.

2. PROBLEM DESCRIPTION

2.1 Model Representation of Problem

The deterioration of pavement condition was described by a probabilistic Markov chain that specified the probabilities of transition from one pavement condition state to another. The initial condition of the pavement segments in the network was represented by the proportions of each segment in the condition states. A multi-year planning period was considered for analysis and constraints such as annual budget limit and network quality control are imposed. Routine maintenance and rehabilitation actions were simultaneously considered in the model. At least one preservation action was to be carried out to all the road segments every year with routine maintenance being a basic requirement. Only one action is allowed to be taken on a road segment in a particular year. The objective of the model is to minimize the present worth of the total maintenance and rehabilitation expenditures while keeping the network within quality standards and subject to an annual budget constraint. The optimization model can be mathematically expressed as follows:

$$\text{Minimize} \quad \sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{k=1}^{K} Y_{t,s,k} \times C_k \times d_t \times W_s \times L_s \tag{1}$$

Subject to

$$\sum_{k=1}^{K} X_{t,s,k,i} = Q_{s,i} \qquad s=1 \text{ to } S,\ i=1 \text{ to } I,\ t=1 \tag{2}$$

$$\sum_{k=1}^{K} X_{t,s,k,j} = \sum_{k=1}^{K}\sum_{i=1}^{I} X_{t-1,s,k,i} \times P_{i,j,k} \qquad s=1 \text{ to } S,\ j=1 \text{ to } I,\ t=2 \text{ to } T \tag{3}$$

$$\sum_{s=1}^{S}\sum_{k=1}^{K} Y_{t,s,k} \times C_k \times L_s \times W_s \le R_t \qquad t=1 \text{ to } T \tag{4}$$

$$Y_{t,s,k} = \sum_{j=1}^{I} X_{t,s,k,j} \qquad t=1 \text{ to } T,\ s=1 \text{ to } S,\ k=1 \text{ to } K \tag{5}$$

$$\sum_{t=1}^{T}\sum_{k=2}^{K} Y_{t,s,k} \le 1 \qquad s=1 \text{ to } S \tag{6}$$

$$\frac{1}{A}\cdot\sum_{s=1}^{S}\sum_{k=1}^{K} X_{t,s,k,j} \times W_s \times L_s \le \gamma_j \qquad j=1 \text{ to } Ju,\ t=4 \tag{7}$$

$$0 \le X_{t,s,k,j} \le 1 \qquad t=1 \text{ to } T,\ s=1 \text{ to } S,\ k=1 \text{ to } K,\ j=1 \text{ to } I \tag{8}$$

$$Y_{t,s,k} \in \{0, 1\} \qquad t=1\,to\,T,\ s=1\,to\,S,\ k=1\,to\,K \qquad (9)$$

where S is the number of road segments; K is the number of M & R (maintenance and rehabilitation) actions; I is the number of pavement condition states; T is the number of time periods (years) in the planning period; Ju is the set of undesirable states; $Q_{s,i}$ is the initial proportion of pavement segment s that is in condition state i; $X_{t,s,k,j}$ is the proportion of pavement segment s at time period t that is in condition state j when action k is applied; $Y_{t,s,k}$ is equal to 1, if action k is applied to the road segment s at the time period t, and is equal to 0 otherwise; $P_{i,j,k}$ is the transition probability from state i to state j when action k is applied to the pavement; R_t is the budget available for time period (year) t; C_k is the cost of applying the preservation action k (per m^2); d_t is the present worth factor at time period t; L_s is the length of road segment s; W_s is the width of road segment s; γ_j is the maximum proportion of road segments in the undesirable state j; A is the paved area of the whole network.

Eqn (1) expresses the minimization of the total present worth of maintenance and rehabilitation cost over the planning horizon. In the beginning of the first year, it is assumed that the condition of pavement segments are known. For each pavement segment, this is specified as the proportion of the pavement segment in each of the condition states. Eqn (2) represents the initial condition of the pavement segments. Eqn (3) is crucial in defining the evolution of the state of the road pavement segments using the entries in the homogeneous Markov transition matrix $P_{i,j,k}$. Eqn (4) shows the budget constraint imposed in the problem. Eqn (5) ensures that for each segment and in each year only one M & R action is applied. Eqn (6) implies that for each segment during the planning horizon of 4 years, only one action can be applied besides the basic routine maintenance action.. Eqn (7) requires the proportion of the whole network in each of the undesirable states at the end of 4^{th} year to be less than or equal to some prescribed value.

2.2 Input Parameters and Data

The model described in Ferreira et al. (1999) was applied to the ring road of Coimbra city in Portugal consisting of 27 segments and 14 Km in length. This problem consisting of 27 segments covering the ring road was considered for this study. The necessary data and information for the problem studied was derived from the work of Ferreira et al. (1999). The 27 pavement segments were of different lengths but identical widths. Table 1 shows the lengths and widths of all the pavement segments. A planning period of 4 years was considered for the analysis. Six maintenance and rehabilitation alternatives were considered, namely. (1) routine maintenance, (2) seal coat, (3) single surface treatment, (4) double surface treatment, (5) asphalt concrete overlay (5 cm) and (6) asphalt concrete overlay (5 cm + 8 cm). The unit costs for all the maintenance and rehabilitation activities are shown in Table 2.

In this problem 9 pavement condition states were assumed. The first 4 states (1-4) were assumed as "desirable" states and the remaining 5 states (5-9) as "undesirable" states. The prescribed values for the undesirable states used in this problem are shown in Table 3. The initial condition of all the pavement segments were available as proportions of the segments in the 9 possible condition states. This information is shown in Table 4. The annual budget for this problem was assumed as 120,000 Euros. The pavement quality constraint was imposed at the end of 4^{th} year as the proportion of the whole network in the "undesirable" states (5-9) to be less than or equal to a prescribed value (see Eqn (7)). A discount rate of 5% is used for the computation of present worth of maintenance and rehabilitation costs.

3. GENETIC-ALGORITHM FORMULATION

3.1 Genetic Representation of Decision Parameters

An integer coding was adopted for the design of the genetic algorithm string structure. As the action with the least cost i.e., routine maintenance was mandatory to all pavement segments, the decision was concerning only the 5 preservation actions in Table 1. It had to be decided which of the 5 actions if required to be applied at what year for all the pavement segments so as to satisfy the constraints imposed and for the system objective of cost-effectiveness. This decision making process dealt with the integer string structure shown in Fig. 1. Here N represents the total number of road segments, and P_i takes any value from 0 to 3, representing the number of the year in the planning period. Q_i takes any value from 0 to 5, each representing a maintenance or rehabilitation activity. Hence this genetic representation automatically satisfies the two controls imposed in this problem shown by Eqns. (5) and (6).

The solution selection phase allocated reproductive trials to strings on the basis of their fitness. In this study, a probabilistic tournament selection scheme was employed. Crossover and mutation operators were the two operators used. The crossover operator took bits from each parent string and combines them to create child strings. A high probability was required for the crossover operator whilst a much lower probability was assigned for the mutation operator. In the case of integer-valued strings the mutation operator swapped the selected gene by a random integer value in the initialization range. The mutation rate (the probability that a gene will undergo mutation) was independent of the data type used. After some initial trials to determine the appropriate values, a crossover rate of 85% and a mutation rate of 5% were employed in the present study. Each run was terminated at the 500th generation.

3.2 Constraints Handling

In the present problem, two types of constraints were imposed: the budget constraint and pavement network quality control. The annual budget constraint required the total expenditure due to maintenance and rehabilitation actions to be less than the budget available. The network quality constraint required the proportion of the whole pavement network in "undesirable" states to be less than or equal to the prescribed values (see Table 3). In this study, penalty functions were used to handle the multiple constraints imposed.

The basic feature of the penalty method was to convert a constrained problem to an unconstrained problem using the modified fitness function. Many researchers have observed that well chosen, graded penalties would preserve the information of all strings and should be advantageous to harsh penalties (Richardson et al. 1989, Smith & Tate 1993, Michalewicz & Schoenauer 1996, Siedlecki and Sklanski 1989). It has also been noted that penalties which are functions of the distance from feasibility are better performers than those which are functions of the number of violated constraints. In this study, a dynamic penalty function where penalty values varied with the distance from feasibility was adopted. For every infeasible solution, the constraints are checked for violation and for each violation, the distance from feasibility or degree of violation was computed in percentage of the prescribed value. This percentage of the fitness value or objective function value was imposed as the penalty value.

4. RESULTS AND DISCUSSION

4.1 Results by Dynamic Penalties

The effect of different parent pool sizes in genetic-algorithm convergence was studied, and a pool size of 300 was selected for subsequent analysis. From several GA runs it was found that new offspring pool size of 70% of parent pool size and mutation rate of 5% gave good performance and hence was adopted. The convergence characteristics of GA solutions for 5 different runs with the GA parameters adopted from the analysis carried out are presented in Fig. 2 where each data point was computed as the percent of the best objective-function value obtained at 500^{th} generation. Each of these runs took about 3 minutes of clock time and 0.01 seconds of system time in a DEC Alpha Workstation. The optimal objective function, which was to minimize the present worth of the total maintenance and rehabilitation expenditure, was found to be 262,950 Euros.

4.2 Comparison of Results of Mixed-Integer Model and Genetic Algorithms

This problem of 27 road segments covering the ring road of Coimbra city was originally solved by a mixed-integer optimization technique (Ferreira et al. 1999). A commercial package XPRESS-MP was used to solve this problem. The objective function value obtained by their analysis is shown in Table 5 along with the results obtained by 3 genetic algorithm solution runs. The results show reasonable improvements in the results obtained by the genetic algorithm optimization model over that of the mixed-integer optimization approach. The percent improvements in the objective-function value were 5.2%, 5.1% and 4.7% for GA runs 1, 2 and 3 respectively.

4. CONCLUSION

A genetic-algorithm program has been developed for the programming of pavement maintenance and rehabilitation activities for a multi-year planning horizon. A numerical example was presented to illustrate its application. A multi-year pavement management Markov chain model originally solved by a mixed-integer optimization technique was adopted for comparison purpose. The problem was been solved using genetic algorithms with penalty functions to handle the multiple constraints and the results were discussed and compared with that of mixed-integer optimization technique. The results obtained by the genetic algorithm program produced an improvement of about 5% in the objective-function value over that of the mixed-integer technique.

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Table 1 The Length, Width and Initial Condition of All Road Segments

Segment Number	Length (L_s) (m)	Width (W_s) (m)	Initial Condition State (100%)
1	440	10	2
2	244	10	1
3	906	10	3
4	885	10	2
5	1114	10	4
6	227	10	2
7	118	10	3
8	199	10	3
9	253	10	4
10	1225	10	6
11	171	10	4
12	140	10	2
13	760	10	3
14	541	10	5
15	354	10	5
16	921	10	7
17	815	10	4
18	135	10	5
19	226	10	7
20	289	10	4
21	637	10	5
22	900	10	6
23	99	10	3
24	358	10	4
25	271	10	2
26	352	10	2
27	1251	10	3

Table 2 Unit Costs of M & R Actions

Action Number	Action Type	Preservation Cost (Euros/m^2)
1	Routine maintenance	0.05
2	Seal coat	0.55
3	Single surface treatment	1.75
4	Double surface treatment	2.50
5	Asphalt concrete overlay (5 cm)	3.70
6	Asphalt concrete overlay (5 cm + 8 cm)	7.50

Table 3 Allowable Values of Proportion of the Whole Network in Undesirable States

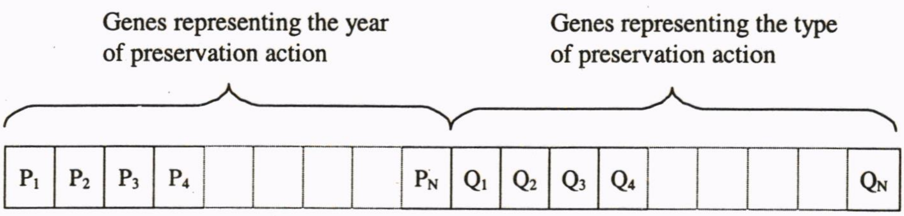
Undesirable State	Allowable Value (γ_j)
5	0.2
6	0.1
7	0.1
8	0.05
9	0.05

Table 4 Initial Proportion of Road Segments in the Set of Condition States

Segment Number	Proportion in Condition States								
	1	2	3	4	5	6	7	8	9
1	0	1	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0
4	0	1	0	0	0	0	0	0	0
5	0	0	0	1	0	0	0	0	0
6	0	1	0	0	0	0	0	0	0
7	0	0	1	0	0	0	0	0	0
8	0	0	1	0	0	0	0	0	0
9	0	0	0	1	0	0	0	0	0
10	0	0	1	0	0	0	0	0	0
11	0	0	0	1	0	0	0	0	0
12	0	1	0	0	0	0	0	0	0
13	0	0	1	0	0	0	0	0	0
14	0	0	0	0	1	0	0	0	0
15	0	0	0	0	1	0	0	0	0
16	0	0	0	0	0	0	1	0	0
17	0	0	0	1	0	0	0	0	0
18	0	0	0	0	1	0	0	0	0
19	0	0	0	0	0	0	1	0	0
20	0	0	0	1	0	0	0	0	0
21	0	0	0	0	1	0	0	0	0
22	0	0	0	0	0	1	0	0	0
23	0	0	1	0	0	0	0	0	0
24	0	0	0	1	0	0	0	0	0
25	0	1	0	0	0	0	0	0	0
26	0	1	0	0	0	0	0	0	0
27	0	0	1	0	0	0	0	0	0

Table 5 Objective-Function Values Obtained by GAs and Mixed-Integer Model

	Mixed-Integer Optimization	Genetic Algorithm Optimization		
		Run 1	Run 2	Run 3
Objective Function Value (Euros)	277,226.4	262,950.3	263,057.0	264,068.8
Improvement (%)	-	5.2	5.1	4.7



P_i = 0 represents the 1st year
1 represents the 2nd year
2 represents the 3rd year
3 represents the 4th year

i = 1 to N
N= Total number of road

Q_i = 0 represents Routine maintenance
1 represents Seal coat
2 represents Single surface treatment
3 represents Double surface treatment
4 represents Asphalt concrete overlay (5cm)
5 represents Asphalt concrete overlay (5cm + 8cm)

Figure 1 Genetic Coding of Decision Parameters for the Present Problem