A Genetic Algorithm for Multiyear Pavement Maintenance Optimization

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Synopsis

An ideal pavement management is one that would maintain all pavement sections at a high level of serviceability requiring a low budget and use of resources. Unfortunately these are conflicting requirements. Then, the benefits of pavement management can't be realized if pavement management activities such as maintenance treatments and repairs aren't optimally programmed at network level over an appropriate multi-year planning period.
Due to the complexity and scale involved in the programming of activities for pavement management at the network level, conventional analytical optimization tools have not found widespread applications in practise.
Within this context, emerging technologies, such as soft computing techniques provide efficient alternatives to the traditional mathematical approaches.
In particular, genetic algorithms represent an efficacious approach to extrapolate optimal solutions within a range, even though enormous, of possible solutions in sufficiently quick time spans. In the case of road maintenance management, this technique proves to be particularly appropriate in relation to the numerous variables characteristic of the problem, to the different objectives to be reached and to the necessity to individuate the optimal allocation of the interventions.
This paper describes the development of a genetic algorithm for determining the optimal multi year pavement repair schedule. The problem of finding the best multiyear work plan can be modelled as a combinatorial optimization problem. The objective of which is to achieve the highest possible average network condition for a given budget.
The procedure was applied to a motorway infrastructure belonging to the motorway network of Eastern Sicily (Italy).

A Genetic Algorithm for Multiyear Pavement Maintenance Optimization

A typical pavement management problem requires pavement activities such as maintenance treatment and repairs to be optimally programmed at network level over an appropriate multiyear period. This involves decisions concerning the optimal time to activate certain treatment or repair. The time dimension is a key element to the problem. Besides the distress conditions which vary with pavement age, traffic loading is also a function of time.

Each pavement type and rehabilitation may have different models. Also, each repair method has different costs. These two facts when combined with the number of pavement sections and multiple planning years are the reason that a mathematical method is needed to determine which, when and how pavements should be repaired.

The problem of finding the best multi-year work plan can be modelled as a combinatorial optimization problem. The objective of which is to achieve the highest possible average network condition for a given budget and operating constraints.

The difficulty in formulating and modelling pavement rehabilitation priority programs due to the combinatorial nature of the problem solution, using the traditional programming approaches, have led to research efforts geared towards new and innovative techniques using evolutionary based approaches (Fwa et al. 2000, 2002a and 2002b, Chootinan and Chen 2002, Chou and Tack 2002, Lee et al. 2002, Cheu et al. 2004, Bosurgi and Trifirò 2005a and 2005b).

This paper describes the development of a genetic algorithm based optimization tool for determining the optimal multi-year pavement repair schedule.

The optimization problem was faced by opportunely programming a genetic algorithm that manages the decisional process on the basis of pavement's condition defined using Present Serviceability Index (PSI). The optimization model was designed to maximize the average PSI value of the whole motorway.

The procedure was applied to a real-word situation of A18 motorway, which stretches along the eastern coast of Sicily. This application permitted to verify the theoretical concepts.

GENETIC ALGORITHMS: A SHORT INTRODUCTION

Genetic Algorithm is a heuristic optimization technique based on the mechanics of natural selection and evolution. In GA, feasible solutions of a problem are each represented by a chromosome string. Each chromosome string carries a genetic code that represents the characteristic of an individual. Strings in the current populations are ranked and better ones selected to produce the next generation of solutions, emulating the survival of the fittest mechanism. Favouring the most adapted individuals, the most promising areas of the research space are explored.

GA generates new solutions or offspring applying genetic operators (cross-over, mutation, reproduction) according to user defined probabilities. In crossover, two candidate solutions mutually exchange corresponding parts of themselves to form two new strings. Mutations are small changes to the genetic code usually achieved by altering one or more of the genes in the chromosome. In reproduction the parents simply reproduce copies of themselves as the two children.

The algorithm is terminated after a specified number of generations or the change in the fitness of the population after several generations between successive generations becomes acceptably small.

A powerful aspect of GAs is their use as a search technique in overcoming the combinatorial explosion of certain problems like the road maintenance management problem.

MODEL FORMULATION

The flowchart of the GA designed for multiyear pavement maintenance optimization is presented in figure 1.

First, the problem was defined including the objective function and the constraints that control the solution. In particular, the objective considered has been to manage the multiyear pavement maintenance to maximize the average PSI value of the whole motorway considering a limited budget.

The knowledge of the pavement deterioration curve was very important to the optimal planning of maintenance activities. Therefore, the first step of the procedure has regarded the definition of a pavement deterioration curve. It was decided to define pavement's condition using PSI values. Not having pavement performance condition data it was developed a procedure that applies an incremental analysis of the AASHTO basic design equation (American Association of State Highway and Transportation Officials 1993)

to construct pavement performance curve. In particular, the ∆PSI values were fixed and the corresponding 80 kN ESAL load applications were calculated.
The traffic load applications can be converted into an equivalent time interval, so, varying PSI between its assigned initial value and terminal one was possible to construct the pavement performance curve in the time.
Then, this procedure permitted to have a simple tool to predict the pavement performance condition at any given future time. This procedure can be used in the absence of pavement performance condition data.
Once the PSI prediction model was defined it was possible to create a genetic algorithm for the optimal allocation of the maintenance interventions. The first step consisted in the calibration of the problem to genetics.
In the genetic representation created, each year of the programming period was mapped to a gene for each homogenous section. The value for each genes represents a possible maintenance intervention.
In this way, it was possible to associate a maintenance intervention with a homogeneous section for each programming year.
Subsequently, it was possible to associate the PSI values of the pavements after the interventions by inserting the developed model in the genetic algorithm. It was also important to characterize effectiveness of the maintenance treatments. In particular, it was decide to use a study carried out on the Indiana State highway network (Labi and Sinha 2004). Data used for the study was a comprehensive database that had information on pavement condition, weather, pavement structure, traffic, maintenance and other item. For each treatment, effectiveness was assessed evaluating a performance jump.
It was also estimated the cost of each maintenance intervention in order to verify the compatibility of the solution with the available budget.
The objective function, as aforesaid, was to maximize the average PSI value of the whole motorway.
Once the above-mentioned steps were defined, the following parameters for the genetic algorithm were set:

- The dimension of the population;
- The mutation, reproduction and cross-over rates;
- The generation gap.

The designed genetic algorithm was processed until a predetermined stopping criteria was reached.

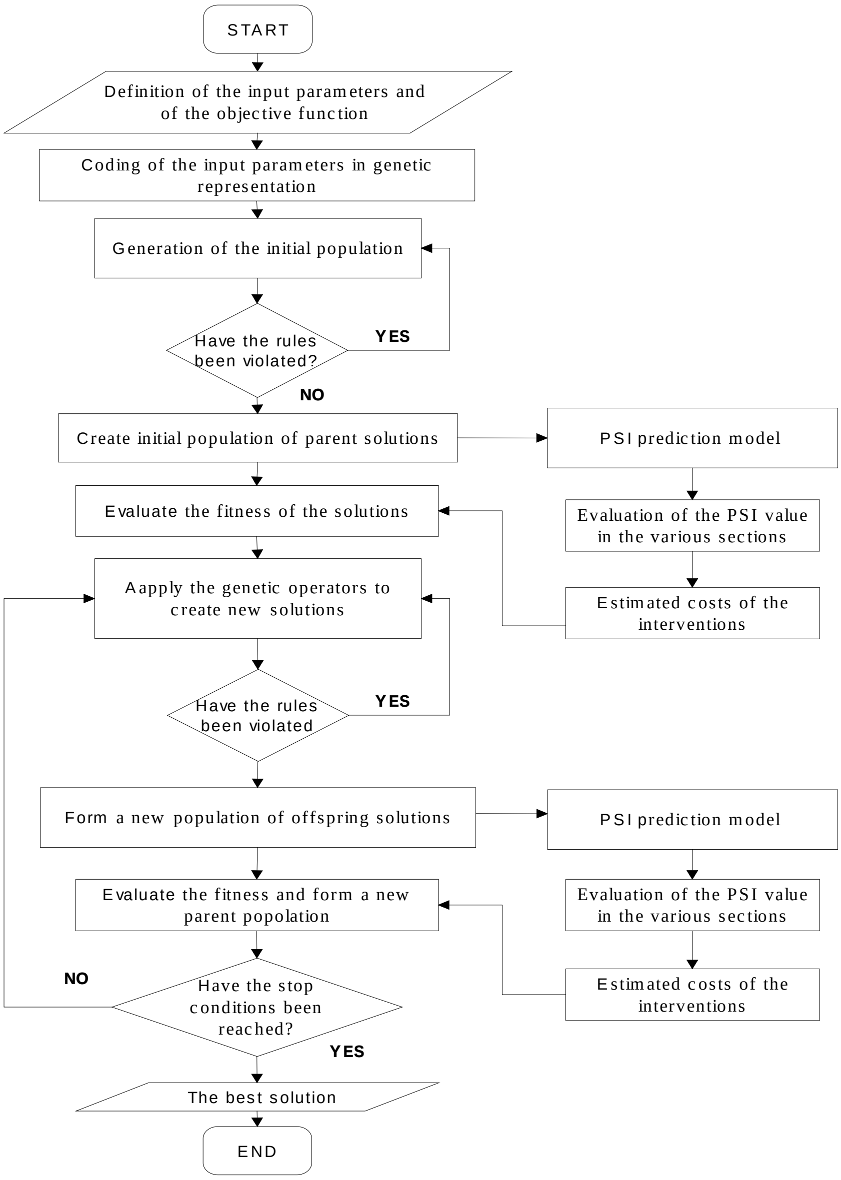

Figure 1: Flowchart of the procedure

CASE STUDY

The procedure was applied to A18 motorway, which represents one of the most important communication roads in Sicily and it is 77 km long.
A safety analysis carried out in the road work zones was used to define the homogeneous sections (Bosurgi et. Al. 2003). On the basis of the results obtained, 1 km was decided to be the optimal length.
Three interventions were considered.

- thin hot mix asphaltic concrete (HMA) overlay;
- seal coating;
- total reconstruction.

For each type of intervention the PSI values after maintenance intervention were evaluated using a study realized by Labi and Sinha (Labi and Sinha 2004). In particular:

- *thin HMA overlay*:

$$PJ = \frac{A}{B + C \cdot D^{IPC}}$$

where
PJ is the performance jump due to thin HMA overlay

IPC is the PSI value at time of maintenance
A, B, C and D are constants

- *Seal coating*:

$$PJ = A \cdot e^{-(IPC-B)^{C}}$$

where
PJ is the performance jump due to seal coating
IPC is the PSI value at time of maintenance
A, B and C are constants

- *Total reconstruction:*

$$PSI_j = PSI_{initial}$$

where
PSI_j is the PSI value after the maintenance intervention
$PSI_{initial}$ is the initial PSI value = 4,2

The successive phase consisted in the calibration of the problem to genetics. Each year of the programming period was mapped to a gene for each homogeneous section. The coded string structure of GA representation thus consisted of 770 genes, each carriageway being 77 km and having considered a five year programming period.
The identified interventions were numerically codified (Table 1).

Tab 1: Codification of Interventions

Coding number	Intervention
0	No intervention
1	HMA overlay
2	Seal coating
3	Total reconstruction

Therefore, the problem presented $4^{770} = 3.856 \cdot 10^{463}$ possible solutions.
The chosen population dimension was twice the size of a chromosome representing the single individuals and the genetic operators rates were fixed.
Once the genetic programming was finished, the objective function and the constraints were defined. In particular, the considered objective function was the average PSI value of the whole motorway; while the constraints were a available budget of 5,000,000.00 € and a minimum PSI value in the time equal to 3. Hypothetical PSI actual values were considered for the single homogeneous sections. The steps of the procedure for the single individual of each generation were the following:

1. The algorithm calculated a possible solution to the problem associating one of the codified values to the single genes;
2. The PSI values of the single homogeneous sections at the end of the programming period was calculated using the prediction model realized;
3. Each solution was checked against all the constraints to ensure that it was a possible solution.

The same procedure was carried out for all the individuals of each generation.
The genetic algorithm was stopped when variance of solution was equal to zero for one thousand generations. The GA solution to the problem is best presented in a table form as shown in Table 2.

Tab 2: Optimal Allocation of Interventions

Homogeneus section	Year					Homogeneus section	Year					Homogeneus section	Year				
	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5
1	0	2	0	0	0	53	0	0	0	0	0	105	0	2	0	0	0
2	0	0	0	3	0	54	0	1	0	0	0	106	0	0	0	0	0
3	0	0	0	0	0	55	0	0	0	0	0	107	1	0	0	0	0
4	2	0	0	0	0	56	0	0	0	0	0	108	0	0	0	0	0
5	0	0	0	0	3	57	0	0	1	0	0	109	0	0	2	0	0
6	0	0	0	0	0	58	0	0	0	0	0	110	0	0	0	0	0
7	1	0	0	0	0	59	0	0	0	0	0	111	0	0	0	0	0
8	0	0	0	0	0	60	0	0	0	0	0	112	0	1	0	0	0
9	0	0	0	0	0	61	0	1	0	0	0	113	0	0	0	0	0
10	0	0	0	0	0	62	0	0	0	0	0	114	0	0	2	0	0
11	0	3	0	0	0	63	0	0	0	0	0	115	0	0	1	0	0
12	0	0	0	0	0	64	0	0	1	0	0	116	0	0	0	0	0
13	0	0	0	0	0	65	0	0	0	0	0	117	0	0	0	1	0
14	0	0	0	0	0	66	0	0	0	0	0	118	2	0	0	0	0
15	0	0	0	0	0	67	0	0	0	0	0	119	0	0	0	0	0
16	0	0	0	0	0	68	0	0	0	0	0	120	0	0	0	0	0
17	0	0	0	0	0	69	0	0	0	0	0	121	0	0	0	0	0
18	0	0	0	0	0	70	0	0	0	0	2	122	2	0	0	0	0
19	0	0	2	0	0	71	1	0	0	0	0	123	0	1	0	0	0
20	0	0	0	0	0	72	0	0	0	2	0	124	0	0	0	0	0
21	0	0	0	1	0	73	0	0	0	0	0	125	0	0	0	0	0
22	0	1	0	0	0	74	0	0	0	0	0	126	0	0	0	0	0
23	0	0	0	0	0	75	0	1	0	0	0	127	0	0	0	0	0
24	0	0	0	0	0	76	0	0	0	0	0	128	1	0	0	0	0
25	0	1	0	0	0	77	0	0	1	0	0	129	0	0	1	0	0
26	2	0	0	0	0	78	0	0	0	0	0	130	0	0	0	0	0
27	0	0	0	0	0	79	0	0	0	0	0	131	1	0	0	0	0
28	1	0	0	0	0	80	0	0	0	0	0	132	0	0	0	0	0
29	0	0	0	0	3	81	0	0	0	0	0	133	0	0	0	0	0
30	0	0	0	0	0	82	0	0	0	0	0	134	0	0	0	0	0
31	0	0	0	0	0	83	0	0	2	0	0	135	2	0	0	0	0
32	0	0	2	0	0	84	0	0	0	0	0	136	0	0	1	0	0
33	0	0	0	0	0	85	1	0	0	0	0	137	0	0	0	0	0
34	0	0	1	0	0	86	0	0	2	0	0	138	0	0	0	0	0
35	0	0	0	0	0	87	0	0	0	0	0	139	1	0	0	0	0
36	0	0	0	0	0	88	0	0	0	0	0	140	0	0	1	0	0
37	1	0	0	0	0	89	0	0	0	0	0	141	0	2	0	0	0
38	0	0	0	0	0	90	0	0	0	3	0	142	0	0	0	0	0
39	0	0	1	0	0	91	0	1	0	0	0	143	1	0	0	0	0
40	0	0	0	0	0	92	0	0	0	0	0	144	0	0	0	0	0
41	0	0	0	0	0	93	0	0	2	0	0	145	0	0	0	0	0
42	1	0	0	0	0	94	0	0	0	1	0	146	1	0	0	0	0
43	0	0	0	0	0	95	1	0	0	0	0	147	0	0	0	0	0
44	0	0	0	0	0	96	0	0	0	0	0	148	0	0	2	0	0
45	0	0	0	0	0	97	0	0	0	0	0	149	0	0	0	0	0
46	0	1	0	0	0	98	0	0	0	1	0	150	0	0	0	0	0
47	0	0	0	1	0	99	1	0	0	0	0	151	0	0	0	0	0
48	0	0	2	0	0	100	0	0	2	0	0	152	0	0	0	1	0
49	0	0	0	1	0	101	0	0	0	0	0	153	0	0	0	0	0
50	0	0	0	0	0	102	3	0	0	0	0	154	0	0	0	0	0
51	0	0	0	0	0	103	0	0	0	0	0						
52	0	0	0	3	0	104	0	0	0	2	0						

CONCLUSIONS

This paper has developed a GA-based procedure to solve multiyear pavement maintenance optimization.
The procedure has allowed to highlight the potentiality of GAs for solving this complex road problematic. In fact, the robust search characteristics and multiple-solution handling ability of GAs are well suited for optimization analysis.
The procedure was applied to a real-word situation of A18 motorway in Sicily (Italy).
The obtained results have highlighted that the procedure represents an efficient approach to obtain one of optimal solutions in a very big space of possible solutions in sufficiently short periods of time.
The model could be extended to other components of the motorway and other pavement deterioration model could complete the model. It would be also possible to analyse more than one objective or constraint.

REFERENCES

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS (1993), *AASHTO Guide for Design of Pavement Structures*, Washington, D.C.

BOSURGI, G., D'ANDREA, A. and TRIFIRÒ, F. (2003), "Fattori di interazione cantieri-sicurezza stradale: l'esperienza della A18 (Me-Ct)", *Proceedings of the 14th Convegno Tecnico ACI "Sicurezza stradale ed uso delle infrastrutture",* ACI, Rome, Italy.

BOSURGI, G. and TRIFIRÒ, F. (2005a), "Multiyear pavement resurfacing optimization by artificial neural networks and genetic algorithms", *Proceedings of the 5th International Conference on Road & Airfield Pavement Technology*, International Committee on Road and Airfield Pavement Technology ICPT 2005, Seoul, Korea.

BOSURGI, G. and TRIFIRÒ, F. (2005b). "A hybrid approach for pavement maintenance management of an Italian motorway". *Proceedings of the International Conference on Computing in Civil Engineering*, ASCE, Cancun, Mexico

CHEU, R.L., WANG, Y. and FWA, T. F. (2004), "Genetic algorithm-simulation methodology for pavement maintenance scheduling", *Computer-Aided Civil and Infrastructure Engineering*, n°19, pp. 446-455.
CHOOTINAN, P. and CHEN, A. (2002), "Pavement maintenance programming using a stochastic simulation based genetic algorithm approach". *Proceedings of the 81st Annual Meeting of the Transportation Research Board*, Transportation Research Board, Washington.
CHOU, E.Y.J. and TACK, J.N. (2002), "Multiyear pavement repair scheduling optimization by pre-constrained genetic algorithm". *Proceedings of the 81st Annual Meeting of the Transportation Research Board*, Transportation Research Board, Washington.
FWA, T.F., CHAN, W.T. and HOQUE, K.Z. (2000), "Multiobjective optimization for pavement maintenance programming", *Journal of Transportation Engineering*, September-October 2000.
FWA, T.F., CHAN, W.T., LIU, Y. (2002a), "Priority weighting factors for pavement maintenance management", *Proceedings of the 81st Annual Meeting of the Transportation Research Board*, Transportation Research Board, Washington.
FWA, T.F., WANG Y. and CHEU, R.L. (2002b) Highway maintenance scheduling using genetic algorithm with microscopic traffic simulation. *Proceedings of the 81st Annual Meeting of the Transportation Research Board*, Transportation Research Board, Washington.
LABI, S and SINHA, K.C. (2004), "Cost and effectiveness models for selected preventive maintenance treatments", *Proceedings of the 83rd Annual Meeting of the Transportation Research Board*, Transportation Research Board, Washington.
LEE, C., CHEN C.F., HUANG, S. and HSU, C (2002), "Application of neural network for selection of airport rigid pavement maintenance strategies", *Proceedings of the 81st Annual Meeting of the Transportation Research Board*, Transportation Research Board, Washington.