PAVEMENT DESIGN AND MAINTENANCE VIA GENETIC ALGORITHMS

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ABSTRACT

Pavement design and maintenance are particularly complex and articulate processes, aimed at individualizing the pavement structural composition by means of an integrated analysis of various aspects, among which, the combination of materials and the maintenance and building strategies. Pavement design is obtained through an optimization problem, which is the result of the objectives that are to be achieved and of constraints that might affect the final result.

In view of a large number of variables, this process becomes exceedingly complicated to manage, so much so that the traditional approaches are not always adequate.

An important contribution has been given in recent years by the artificial intelligence techniques which have been more and more often applied to solve the problems relative to the road field. Genetic algorithms have, in particular, shown a great applicability for multivariable optimization analysis.

In this paper, genetic algorithms have been used in an optimization procedure to design and maintenance flexible pavements.

The procedure was applied to the A18 motorway (ME-CT) through a database of the infrastructure opportunely set up by the Authors.

Keywords: pavement design, pavement management, maintenance, genetic algorithms

1. INTRODUCTION

Pavement design is a fundamental part of the whole design of a road infrastructure; indeed, the high cost of the materials that make up the pavement courses considerably influences the entire cost of the whole infrastructure.

Cost does not only refer to that of building but also to that relative to the maintenance activity, that, compared to other components of the road system, for pavement is rather high.

However it is not enough to estimate the cost for road agency but it is also necessary to calculate that relative to the users in order to reckon not only the strictly economical characteristics linked to the pavement management, but also those of comfort and satisfaction of the users.

Design decisions must thus be correlated to the use conditions of the infrastructures and above all to the budget available.

The initial structural composition must thus be drawn from not only the best combination of materials but also from construction and maintenance strategies.

Thus the design decisions must be derived from the analysis of an optimization problem that results in a final solution obtained through an integrated decision that contemplates the design parameters and the maintenance activity to be carried out in the course of the years (Tighe et al. 2004).

Various Authors have already tackled this research program using different procedures (Abaza 2002, Lin et al. 2004, Mamlouk et al. 2000, Sanchez-Silva 2005). Genetic algorithms in particular have been applied both for programming maintenance activities for yearly or multi-yearly periods (Bosurgi and Trifirò 2005a, 2005b, 2005c, Chou and Tack 2002, Henderson and Fu 2004, Fwa et al. 1994a, 1994b, 1994c, Fwa et al. 1998a, 1998b, Fwa et al. 2000, Fwa et al. 2002, Cheu et al. 2004), and for pavement design (Tsai et al.2004, Hadi and Arfiadi 2001, Liu et al. 2003).

In this paper a procedure based on the genetic algorithms has been set up in order to establish the pavement design by resolving an optimization problem that considers the design parameters and the maintenance activity to be carried out in the course of the years

In particular the effectiveness/total cost ratio was chosen as the objective function, imposing two constraints, one economical, the other technical.

The procedure was applied to the A18 (ME-CT) motorway which is one of the most important road in Sicily.

2. GENETIC ALGORITHMS

Genetic algorithms (GAs) are complex adaptive procedures aimed at resolving problems of operative research and optimization based on the principles that regulate the natural evolution of the species (Holland 1975).

The GAs use a direct analogy with the behaviour of nature. They work with a population of individuals each of which represents a possible solution to the particular problem.

Each individual has its own characteristics and specific properties, shown externally and visible, that make up the phenotype.

It is the phenotype that indicates the possibilities and limits of the interaction of the individual with the environment in which it lives. But the phenotype is mostly determined by the invisible genetic patrimony or genotype, made up of the genes that are the fundamental units of the chromosomes. In general, a characteristic phenotype corresponds to each chromosome. Thus the survival of the individuals with the most suitable characteristics signifies the survival of the most suitable chromosomes.

A set of individuals that share the same genotype makes up a population. The concept of natural selection is fundamental and is often synthesized in the expression "the survival of the fittest", originally used by Darwin to indicate the ability of the individuals to survive to the reproductive stage and transmit their genes to the successive generation.

Indeed, not all individuals of a certain species adapt themselves with the same efficacy to the environment in which they live; the term "fitness" is used in order to express the degree of adaptability, that quantifies the degree of adaptability of an individual to a certain environment..

The greater the fitness of an individual, the greater is its adaptation to its environment.

The best individuals thus have the possibility to reproduce by "cross-breeding" with other individuals of the population, producing new descendants that share some characteristics of each parent. The less suitable individuals have lesser probability to reproduce and thus die out. In particular, the following genetic operators are applied to create the individuals of the new generations (Koza 1992):

- *Reproduction*: It consists in recopying an element of the present population in a new population representing the successive generation. This operator is used to increase in the population the presence of elements with a higher and thus more promising physicity. The fixed generational gap is the fraction of individuals that does not go on to the successive generations; it proves to be particularly important during reproduction.
- *Cross-over*: Once two individuals or parent strings are fixed, two elements of the new generation are created, exchanging substrings of random length with a prefixed probability. This probability is called cross-over rate and can assume values in the range 0-1; it should usually be set at a high value. The crossover is used to recombine the genetic information belonging to different parents, so that the best characteristics can thus be transferred to the strings of the new generation;
- *Mutation*: Having obtained a string, a randomly-chosen gene is modified and the new element thus obtained is inserted in the new generation. This pertains to a single value of a string whose value is changed with a prefixed probability called mutation rate. It can have values ranging between 0 and 1 and should generally be very low in order to avoid that the algorithm fails to converge to the solution but that at the same time can investigate spaces different to those identified during the generations.

Application of the above-mentioned operators defines a new population of individuals. This new generation contains a higher proportion of the characteristics possessed by the promising individuals of the previous generation. In this way, after many generations, the good characteristics being mixed and exchanged with other good characteristics are propagated to all the population. The more promising areas of the research space are explored by favouring coupling between the most suitable individuals.

If the GA has been well set up, the population converges to an optimal solution to the problem.

The properties of the genetic algorithms make them very appropriate to solve optimization problems:

- at every step, a pool of possible solutions, and not a single one, can be considered contemporaneously; this allows a simultaneous identification and exploration of different directions;
- Probabilistic rules can be used to generate new solutions from the initial ones, thus allowing the introduction of permutations to avoid that the analysis is influenced by local minims;
- At each step it is possible to select the best solutions comparing the values of the objective functions of the various generated solutions.
- The research process is not based on gradients and the derivability, convexity or other particular properties are not necessary.

3. PROPOSED METHODOLOGY

The objective of the proposed procedure consists in determining the thickness to be assigned to the pavement courses, in view of the maintenance works to be performed in a prefixed programming period. The procedure is as follows:

- Setting up of an opportunely-organized database, as regards the infrastructure containing the data relative to the road geometry, the traffic, the characteristics of the materials and climatic conditions.
- Definition of the range of the thickness to be assigned to the various pavement courses, choosing the intervals on the basis of the characteristics of the materials and the typology of infrastructure;
- Setting up of a prediction model for the functional characteristics of the pavement to evaluate and monitor the pavement’s conditions. In this case, the Present Serviceability Index (PSI) was used as indicator of the pavement’s condition;
- Choice of the objective function (maximization of the effectiveness/total cost ratio) and constraints (economical and technical)
- Definition and programming of the genetic algorithm.

3.1 Setting up of a database

The first step necessary to establish any procedure for maintenance management consists in preparing an opportunely-organized database relative to the infrastructure to be analyzed.

In this specific case the following data were collected:

- historical and actual traffic data;
- environmental data;
- climatic data
- data relative to the pavement’s conditions.

3.2 Definition of the thickness range

It is necessary to identify the materials and the range of thickness suitable for the various courses depending on the type of pavement being studied.

In our case, it was decided to analyze flexible pavements made up of a surface and binder course in bituminous concrete, a base course in bituminous mixture and a subbase course in granular mixture. In relation to the various courses the procedure searched for the solution within a fixed range of values.

3.3 PSI prediction model

To define the PSI prediction model a procedure was established that applies an incremental analysis starting from the American Association of State Highway and Transportation Officials (AASHTO) design equation for flexible pavements (AASHTO 1993):

$$\log_{10}(W_{80}) = Z_R \cdot S_0 + 9.36\log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\dfrac{\Delta PSI}{PSI_{iniz} - 1.5}\right)}{0.4 + \dfrac{1094}{(SN+1)^{5.19}}} + 2.32\log_{10}(M_r) - 8.07$$

Where:

W_{80} is the number of 80 kN equivalent single axle load (ESAL) applications estimated for a selected design period and design lane;

Z_R is the standard normal deviate for a specified reliability level;

S_0 is the combined standard error of the traffic prediction and performance prediction;

ΔPSI is the difference between the initial and terminal PSI value;

SN is the design structural number indicative of the total required pavement thickness;

M_R is the subgrade resilient module expressed in pounds per square inch;

From the previous equation, it is possible to extrapolate the PSI value at varying times:

$$PSI = PSI_i - (4.2-1.5)\cdot 10^{\left[\left(0.4+\frac{1094}{(SN+1)^{5.19}}\right)\cdot\left(-Z_R\cdot S_0 - 9.36\cdot\log_{10}(SN+1) + 0.2 - 2.32\cdot\log_{10}(M_r) + 8.07 + \log_{10}(W_{18})\right)\right]}$$

In this equation W_{80} is the only unknown. Hypothesizing that W_{80} increases linearly with time the following temporal transformation becomes possible:

$$\Delta T_{i,i+1} = \frac{\Delta W_{i,i+1}}{W_T} T$$

Where:

$\Delta W_{i,i+1}$ is the estimated incremental change in load applications;

$\Delta T_{i,i+1}$ is the incremental time interval;

W_T is the total number of 80 kN ESAL applications estimated over a design life of T years.

Thus, when the data on the pavement's condition are insufficient or lacking, the proposed procedure furnishes a simple instrument to predict the pavement's condition.

3.4 Effectiveness estimate model of the maintenance work

Three maintenance works were considered: seal coating, overlay and reconstruction.

To define the effects of these works in terms of PSI increment in the absence of direct data, some models were established by monitoring for three consecutive years the conditions of some sections of various pavements in Indiana (Labi and Sinha 2004).

In particular, the PSI performance jump was calculated with the following expressions:

$$\text{SEALCOATING} \qquad PJ = A \cdot EXP\left(-\left(IPC - B\right)^{C}\right)$$

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

where
PJ is the PSI performance jump
A, B, C and D are constants
IPC is the PSI value before the maintenance work.

Finally, in the case of a complete pavement reconstruction, the PSI value was fixed as equal to the initial value.

3.5 Analysis of the pavement life cycle cost

According to the most recent concepts, the overall life cycle cost is considered as made up of two components: the road agency cost and the user cost.

The road agency cost is the sum of the initial cost of building (Tab.1) and of the cost of the possible maintenance works (Tab.2) carried out during the analysis period (Hall et al. 2003, Ozbay et al. 2003).

Table 1 Cost for the Pavement Courses

Pavement courses	**Cost (Euro/m^3)**
Surface course	116
Binder course	102
Base course	84
Subbase course	15.8

Table 2 Cost for the Maintenance Works

Maintenance work	Cost (Euro/m^2)
Seal Coating	2
Overlay HMA (2cm)	5.4

The so-called salvage value of the pavement at the end of the analysis period was taken into account within the road agency cost. In fact, at the end of the analyzed period, the pavement still has a certain value that can either be recuperated after demolition if the material is recycled, or by performing further maintenance works that make the pavement serviceable.

The residual value of the latest maintenance activity applied to the pavement was thus estimated, in view of the portion of life consumed with respect to that expected from the treatment.

$$SV = \left(1 - \frac{L_A}{L_E}\right) \cdot C$$

where
C is the cost of the latest maintenance work;
SV is the residual value;
L_A is the life portion consumed in the course of the years
L_E is the life expectancy of the maintenance work expressed in years (Table 3) (FHWA 1998).

Table 3 Life Expectancy of the Maintenance Works

Miantenance work	Life expectancy (years)	Closing days of the lane
Seal coating	3	15
Overlay	6	15
Reconstruction	10	40

The user cost instead include the cost of the delay and the operative cost of the vehicles.

The delay cost allows the economic reckoning of the greater time spent to cover a given section of the infrastructure because of the road work zones.

The value is calculated by multiplying the value in euro of a one-minute delay both of a car and of a truck (Table 4) by the total number of minutes delay accumulated in that section for these two categories of vehicles in the course of each year because of the road work zones. It is thus hypothesized that, because of maintenance work one lane is closed to traffic for a given number of days, causing a 30% speed reduction.

Table 4 **Value of a One-Minute Delay**

	Truck	Car
delay (Euro/min)	1	0.25

The operative cost of the vehicles (VOC) was reckoned by using the HDM-4 (HDM-4 1999) procedure, and is thus calculated as the sum of the cost of fuel, of lubrifycating oil, of consumed wheels and of vehicle maintenance.

The cost of the various items was included in one single value, by the method of the actual value, that consists in considering the values at the initial moment, that is at the moment of construction.

3.6 Objective function and constraints

The objective function considered is the maximization of the effectiveness/total cost ratio. This value is obtained by adding the effectiveness/cost ratio for the single tracts:

$$\frac{\text{effectiveness}}{\text{cost}} = \sum_{j=1}^{m} \sum_{i=1}^{n} \left(\frac{\left(\frac{\left(PSI_i + PSI_{i-1}\right)}{2} \cdot [i - (i-1)] \right)}{K_J \cdot H_j \cdot C_i \cdot \left(1 + R\right)^{-i}} \right)$$

Where n is the number of years programmed for maintenance activity, m is the number of the sections, K_j is the length of the section j, H_j is the width of the section j and R is the discount rate.

The effectiveness is calculated by evaluating the area subtended from the performance curve. The cost at the denominator of this ratio is the overall total cost of pavement, that is the sum of the road agency cost and the user cost (Wei and Tighe 2004, Nunoo et al. 2002).

Two constraints were considered in the procedure: economical and technical.

The economic constraint is a fixed budget limit for the road agency.

The technical constraint consists in imposing that PSI value should be ≥ 3 as required by AASHTO.

3.7 Programmed genetic algorithm

The first operation to be accomplished was the calibration of the problem in a genetic form.

In particular it was necessary to subdivide the infrastructure into sections; for the design for each section a gene was made to correspond to every pavement course. Besides, as regards maintenance, a gene was also established for every year of the maintenance programming period.

By means of this chromosome representation, it has been possible to reckon, for each segment, the thickness to be assigned to the pavement courses, and, at the same time the maintenance work to be performed for each year of the programming period.

The successive phase consisted in codifying the maintenance activity by associating a numeric value for each intervention.

Once the chromosome structure was individualized and the activity codified, the various models set up were associated and the fitness function was made to coincide with the defined objective function, that is the maximization of the effectiveness/cost ratio.

The parameters of the genetic algorithm were set up:

- the dimension of the population;
- probability of mutation, reproduction and crossover;
- generation gap.

In this case, considering the significant dimension of the problem, the dimension of the population was chosen to be fixed at twice that of the chromosome that represent the single individual.

Opportune genetic operations were carried out for every generation, producing new individuals and thus variety.

Once the planning and programming phases were concluded, the stop criteria were defined, that is, the choice of the moment in which the algorithm is considered to reach convergence. This was a very delicate decision, given the considerable complexity and dimension of the problem to be resolved.

It was decided to stop the algorithm when the percentage variation of the objective function proved to be less than 0.001% for a number of successive generation equal to 50,000. Figure

4. CASE STUDY

The described procedure was applied to manage the pavement design and maintenance of the A18 motorway for a period of 10 years.

This infrastructure is one of the most important motorway of the Sicilian road network; it is 77 km long and made up of two carriageways.

The whole infrastructure was subdivided into sections everyone identified between two successive motorway exits. There were 7 sections for each direction (14 in all). As already mentioned, a gene was associated to each section for every pavement course (4) and as many genes as the maintenance programming years (10).

14 genes were thus associated to each section.

The length of the chromosomes was thus equal to 196 genes (14 genes x 14 sections).

The genes relative to the design were codified in such a way as to have for the thickness of the courses an entire value included in the following intervals:

$$3 \leq \text{Surface course} \leq 6$$

$$5 \leq \text{Binder course} \leq 7$$

$$10 \leq \text{Base course} \leq 25$$

$$15 \leq \text{Subbase course} \leq 30$$

The different maintenance works were codified (Table 5).

Table 5 Coding of the Maintenance Works

Coding number	Maintenance work
0	No intervention
1	Seal coating
2	Overaly
3	Reconstruction

Successively, the activation probabilities of the various genetic operators were fixed:

- the cross-over rate was fixed to 0.9 to improve the convergence of the algorithm;
- the mutation rate was fixed at 0.1 to help the algorithm to convergence towards a solution and to investigate solution spaces different from those individualized during the generations.

As previously illustrated, the PSI prediction model was defined and was imposed a PSI initial value equal to 4.2.

The effectiveness models were associated to the maintenance activity, evaluating the effect of their application in terms of PSI performance jump.

Once the genetic programming was concluded, the objective function and constraints were fixed as previously described.

In particular, an available budget of 30,000,000 Euro was fixed as economic constraint and an average discount rate of 4% yearly; the technical constraint was imposed in such a way that the PSI should always remain above the minimum value equal to 3, fixed by the AASHTO.

The possible solutions were evaluated to point out the entity of the problem and the great difficulty in applying the traditional optimization techniques to identify the optimal solution.

Referring only to the pavement thickness, the problem is described by 4 solutions for surface course, 3 for the binder course, 16 for the base course and 16 for the subbase course for each of the 14 segments considered; this will be thus characterized by $(4+3+16+16)^{14}=1.88\cdot 10^{22}$ possible solutions. As for the maintenance activity, there are 4 possible solutions and 140 genes (14 segments x 10 year programming period) thus $4^{140}=1.94\cdot 10^{88}$ possible solutions.

The evaluation procedure of the solution for the single individual of the single generation is as follows:

- the genetic algorithm assesses a possible solution of the problem, associating one of the codified values to the single genes;
- the performance of the pavement is assessed on the basis of the values associated with the various genes, verifying whether the PSI value constraint has been respected; if not the solution is discarded.
- If the total cost assessed in view of the predicted works is higher that the maximum budget available, the solution is discarded or else taken into consideration as available.
- The effectiveness/cost ratio is reckoned

- The procedure remains unaltered for all the individuals of the generations and the genetic operators are applied on them.

Once the procedure has started, the objective function achieves its maximum value after 415,504 generations carried out in about 19 hours. One part of the initial generations of the algorithm does not respect the budget available, but as the generations progress, the algorithm adjusts itself and at the end, about 42.90% of the solutions obtained respect the economic constraint.

Instead, the technical constraint has proved to be much less selective as regards the PSI value, which is respected by about 89% of the solutions.

The best solution found involves a total cost of 29,998,572.91 €.

CONCLUSIONS

The procedure proposed in this paper allows pavement design and maintenance, permitting the determination of the thickness of the pavement courses, and the maintenance activity to be carried out during the analysis period; the objective is to maximize the pavement effectiveness at the same time keeping the cost within a prefixed budget.

The complex optimization problem has been resolved by means of an opportunely planned and programmed algorithm.

These innovative computer methods were chosen in order to fully exploit their considerable versatility and potentialities, in fact they are an important tool to find optimal solutions in a space, even enormous, of possible solutions in a sufficiently quick length of time.

The model has been applied to a real case, the A18 (ME-CT) motorway managed by the “Consorzio per le Autostrade Siciliane”.

The results have pointed out the convenience of using these managing procedures, that not only allow pavement design but also a correct programming of the maintenance activity

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