ARRANGEMENT OF PAVEMENT MAINTENANCE ACTIVITIES USING GAS

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ABSTRACT

A new pavement management system (PMS) is applied to achieve the optimal pavement maintenance and rehabilitation (M&R) strategy for a highway network using genetic algorithms (GAs). Optimal M&R strategy is a set of pavement activities that both minimise the maintenance cost of a highway network and maximise the pavement condition of the road sections on the network during a certain planning period. NSGA-II, a multi-objective GA, is employed to perform pavement maintenance optimisation because of its robust search capabilities and constraint handling method that deal with the multi-objective and multi-constrained optimisation problems. In the proposed approach, a deterministic pavement age gain models is utilised for evaluating the evolution of pavement condition over time because of its simplicity of application. The proposed PMS is applied to a case study network that consists of different kinds of road sections. The results obtained indicate that the model is a valuable toolbox for pavement engineers.

KEYWORDS: Pavement Management System (PMS), Maintenance and Rehabilitation strategy, Genetic Algorithms (GAs), NSGA-II, Pavement age gain model

1. INTRODUCTION

In the presence of aging and deteriorating highway networks and inadequate budgets, it is of substantial importance for highways agency to preserve and enhance highway networks in a cost-effective way. Consequently, pavement management systems (PMS) have been developed to optimise maintenance decisions at both the network level and project level in order to achieve pavement performance requirements considering the applicable financial and technical constraints. Two main components are involved in a PMS: (1) the pavement deterioration model used to predict pavement performance; and (2) the technique used to determine the maintenance and rehabilitation (M&R) strategy for the road sections on the highway network.

The pavement deterioration model incorporated in a PMS can be either deterministic or probabilistic. Deterministic models utilise regression relationships to illustrate the pavement degradation process, which express the pavement performance in detailed and quantitative terms, with reference to the various pavement surface distresses that characterise the pavement condition, such as functional performance indices, i.e. Present Serviceability Index (PSI) and Pavement Condition Index (PCI) (Kay, Mahoney et al. 1993, Hall and Correa Munoz 1999), individual pavement distress indices, i.e. cracking and rutting, and some aggregate models, the Highway Design and Maintenance Standards model (HDM-III), the Highway Development and Management model (HDM-4) and the Australian Road Research Board model (ARRB) (W.D.O 1987, Martin 1998, Jain, Aggarwal et al. 2005).

Genetic Algorithms (GAs) have been widely applied to solve the optimisation problems, which were proposed by John Holland at the University of Michigan and applied as a computational technique in 1975 (Holand 1975). GAs are developed based on the survival-of-the-fittest concept of Darwinian evolution. Goldberg (1989) constructed the initial framework for GAs, known as the binary-coded genetic algorithm (BGA), and exhibited its robustness of optimisation and search. During the last two decades GAs have been widely studied and experimented, and significant contributions have been achieved within pavement management engineering (Chan, Fwa et al. 1994, Fwa, Tan et al. 1994, Ferreira, Picado-Santos et al. 2002, Bosurgi and Trifirò 2005, Morcous and Lounis 2005). GAs are attractive to pavement engineers because of their robust search capabilities and ease of implementation. Furthermore, GAs are applicable to solve multi-objective optimisation problems. During the last few years multi-objective genetic algorithms (MOGAs) were successfully applied to a large amount of pavement maintenance scheduling problems (Fwa, Chan et al. 2000, MBWANA 2001, Abaza and Ashur 2009). Recently, many different MOGAs have been proposed, among which the improved non-dominated sorting genetic algorithm (NSGA-II) is recognised as one of the most advanced method for solving multi-objective problems (Deb, Pratap et al. 2002, Konak, Coit et al. 2006).

This paper provides a new PMS that is developed by integrating a pavement age gain model and NSGA-II, where the pavement age gain model is used to evaluate pavement conditions over the planning period and NSGA-II is applied to perform maintenance optimisation. One underlying assumption is that the pavement condition after maintenance cannot be better than the initial pavement condition.

The objective of this paper is to provide an approach that uses NSGA-II in conjunction with the deterministic pavement age gain model for optimising pavement M&R strategy. The proposed approach is anticipated to preserve and enhance the existing highway network in a more cost-effective way.

2. DETERMINISTIC OPTIMISATION MODEL

This paper presents a road section based optimisation model to determine the optimal M&R strategy for a highway network in the planning period using NSGA-II. The proposed PMS aims to minimise the total agency cost and maximise the remaining pavement life of a highway network over a given planning period. Road sections between junctions are the decision making units to which maintenance actions are applied. This model employs the age gain to indicate the improvement of road sections resulting from M&R actions (Abaza and Ashur 2009). In addition, integer encoding is deployed to define various maintenance action possibilities. This coding method reduces the length of the chromosome compared to the more commonly used binary encoding of variables.

2.1 Deterministic pavement age gain model

The deterministic pavement age gain model was firstly proposed by Abaza and Ashur (2009), which uses the expected age gain associated with the M&R actions as the pavement improvement indicator. In this paper, five maintenance actions are considered. The maintenance cost and duration associated with each maintenance action is shown in **Error! Reference source not found.** (DfT 1997).

TABLE 1 Maintenance duration and cost for each type of maintenance action

M&R	Single carriageway (S2)		Dual 2 lane carriageway (D2AP)		Dual 3 lane motorway (D3M)	
Type	**Duration (days)**	**Cost (£'000s)**	**Duration (days)**	**Cost (£'000s)**	**Duration (days)**	**Cost (£'000s)**
Do nothing (0)	0	0	0	0	0	0
Patching (1)	2	50	3	100	4	140
Surface dressing (2)	4	70	5	140	6	170
Resurfacing (3)	8	200	14	550	20	900
Overlay (4)	16	320	23	820	33	1350

1. Costs and days are for 1km of road, that is, both carriageways.

Instead of using pavement condition rating index (PCR) (Abaza and Ashur 2009), the remaining pavement life for each road section is classified to indicate the pavement condition, so that the consistency with the pavement improvement indicator can be ensured, as shown in **Error! Reference source not found.**. The age gain is characterised by the pavement condition of the road section, given in **Error! Reference source not found.** (DfT 1997):

TABLE 2 Expected ages associated with pavement maintenance actions versus remaining pavement life

Remaining pavement life (years)	Pavement condition	Expected age gain (years)				
		(0)	**(1)**	**(2)**	**(3)**	**(4)**
>6	0	0	2	5	7	10
(4,6]	1	0	2	3	7	10
(2,4]	2	0	1	3	6	9
(0,2]	3	0	0	1	6	9

2.2 Classification of road sections

The proposed formulation of the maintenance optimisation problem groups road sections on a highway network according to similar properties, such as road classes, traffic categories, and climatic regions, which govern the pavement performance. By this means, all individuals from the same group are assumed to have the same performance characteristics and should be studied in a similar manner. In this paper, climatic conditions are not considered, as the road sections on a relatively small-sized highway network belong to the same climatic region. The classification of road sections is illustrated in **Error! Reference source not found.** (DfT 1997):

TABLE 3 Road section types

Road section group	Road class	Traffic flow (000s)	Initial/Maximum Pavement life (years)
1	S2	5-15	10
2	S2	15-20	8
3	D2AP	10-20	10
4	D2AP	20-30	9
5	D2AP	30-40	8
6	D3M	20-30	11
7	D3M	30-40	10
8	D3M	40-80	9

1. Flows are opening year Annual Average Daily Traffic (AADT).

It can be seen that 8 types of road sections are investigated in this study, including 2 types for Single carriageway (S2), 3 types for Dual 2-lane all-purpose carriageway (D2AP) and 3 types for Dual 3-lane motorway (D3M). Moreover, the initial pavement life for each type is also provided in **Error! Reference source not found.**.

2.3 Model formulation

As stated above, the two objectives of the PMS, presented in this paper, are to minimize the pavement maintenance cost and maximize the remaining pavement life of all the road sections on the network, which are formulated as follows:

$$Min\sum_{n=1}^{N}\sum_{t=1}^{T}\frac{1}{(1+d)^{t}}C_{n,t} \qquad n=1,...N;t=1,...T \tag{1}$$

$$Max\sum_{n=1}^{N}rpl_{n,T}\times L_{n} \qquad n=1,...N;t=1,...T \tag{2}$$

Where

$C_{n,t}$ - maintenance cost for road section group n at year t

$rpl_{n,T}$ - remaining pavement life for road section group n at year T

L_n- the total length of road sections that belong to group n

N- number of road section groups

T- planning horizon

d- discount rate

The discount rate is used to transform costs and benefits arising in different years to their present value. A discount rate of 0.035 is adopted in this paper (DfT 2004).

The evolution of the remaining pavement life for road section i at year t is evaluated as:

$$rpl_t(i) = rpl_{t-1}(i) + ag_{t,i}[m][k] - 1 \tag{3}$$

$$\text{If } rpl_t(i) > pl(i),\ rpl_t(i) = pl(i) \tag{4^a}$$

Where

$rpl_t(i)$- remaining pavement life for road section *i* at year *t*

m- pavement condition of road section *i* at year *t*, i.e. 0,1,2 and 3, according to **Error! Reference source not found.**

k- maintenance action performed in road section *i* at year *t*

$ag_{t,i}[m][k]$- age gain associated with the maintenance action performed on road section *i* at year *t* , according to Table 2

pl(i)- initial pavement life for road section *i*

Equation (3^a) indicates that the pavement condition of road section after maintenance cannot be better than the initial condition. The constraints of the model are stated below:

$$rpl_t(i) \geq rpl_{\min} \tag{5}$$

$$\sum_{n=1}^{N} \frac{1}{(1+d)^t} C_{n,t} < B_t \tag{6}$$

Where B_t is the budget for year *T*, £'000.

The first constraint is that the remaining pavement life for each road section group n cannot be smaller than the minimum remaining pavement life. The second constraint is the budget constraint, where the maintenance cost on the whole network at year t cannot exceed the available budget. Further constraints can be included, for example, the number of major M&R actions for the whole network/individual road sections per year cannot exceed a set threshold.

2.4 Method for model solution

In pavement engineering, there is often more than one objective that needs to be taken into account, and multiple objectives, that are often conflicting, have significant different impacts on the resulting M&R strategy.In this paper, NSGA-II is employed to perform the optimisation (Deb, Pratap et al. 2002), which is developed based on Goldberg's non-dominated sorting procedure and sharing approach (Srinivas and Deb 1994).

3. APPLICATION OF THE DETERMINISTIC PMS

The developed deterministic PMS is used to plan the maintenance of a newly constructed road network during a planning horizon T of 20 years. For the illustration purpose, an example network that consists of 4 road sections is analysed, which is shown in **Error! Reference source not found.**. The network is composed of a motorway (AB), a dual carriageway (CD), and two single carriageways (BC and AD). Each section is 1 km long.

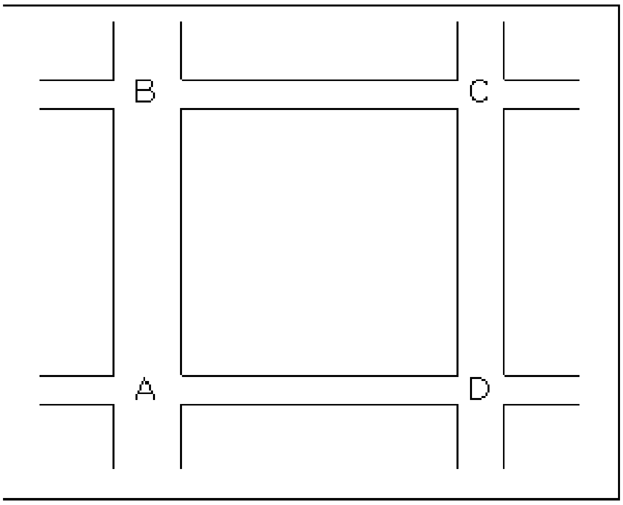

FIGURE 1 An example road network

The pavement condition of the road sections on the network is depicted in **Error! Reference source not found.**:

TABLE 4 Pavement condition for the example network

Road section	*Road section group*	*Initial pavement life (years)*
AB	6	11
BC	1	10
CD	3	10
AD	2	8

As there are 4 road sections on the network, 80 decision variables are used in this problem. As shown in Figure 2, the decision variable Int represents the maintenance action implemented on road section n at year t. The decision string structure for road section n is represented by:

I_{n1}	I_{n2}	I_{n3}	I_{n4}	I_{n5}	I_{n6}	I_{n7}	I_{n8}	...	I_{n15}	I_{n16}	I_{n17}	I_{n18}	I_{n19}	I_{n20}

FIGURE 2 The part of chromosome for road section n

3.1 Objectives and constraints

As stated in Section 2.3, two objective functions are considered, which are formulated as:

$$Min\sum_{n=1}^{4}\sum_{t=1}^{20}\frac{1}{(1+d)^t}C_{n,t} \tag{1}$$

$$Max\sum_{n=1}^{4} rpl_{4,20}\times L_n \tag{2}$$

and the constraints are evaluated as:

$$rpl_t(i)\geq 3 \tag{3}$$

$$\sum_{n=1}^{n}\frac{1}{(1+d)^t}C_{n,t} < 2000 \tag{4}$$

The minimum remaining pavement life is defined, say 3 years, so that the serviceability of pavements could be ensured, and the available annual budget is £2,000,000.

3.2 GA parameters

There are four main GA parameters to consider: the population size (P), the maximum number of simulation generations (M), the crossover rate (pc) and the mutation rate (pm). As 80 variables need to be optimised, the population size is set to 500. Based on NSGA-II, an analysis was conducted to investigate the effect of changing GA parameter values. A limited set of values for each GA parameter was selected as follows:

p_c: 0.6, 0.7, 0.8, 0.9
p_m: 0.001, 0.01, 0.1
M: 5000
P: 500

NSGA-II is used to determine the optimal Pareto frontiers using different combinations of crossover and mutation rates. **Error! Reference source not found.** is used to analyse the effect of mutation rates on the optimisation results when specific crossover rates are chosen.

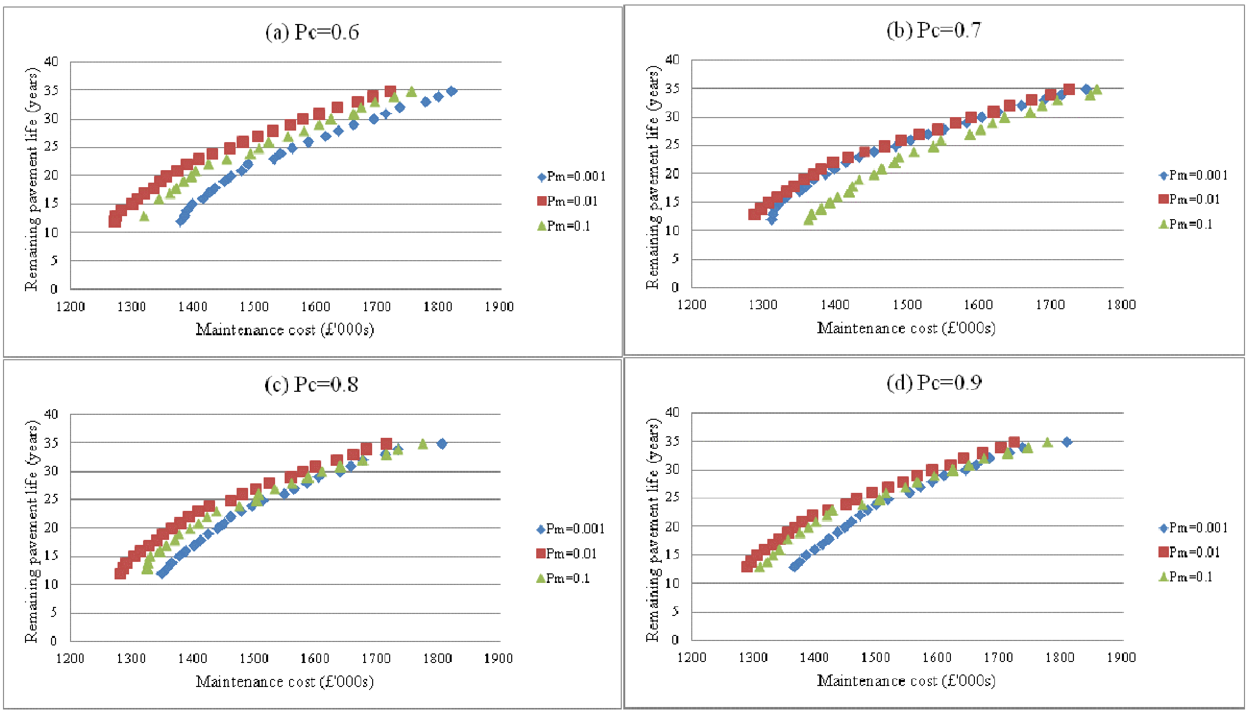

FIGURE 3 Optimum Pareto frontier for different mutation rates under each crossover rate

The results show that the mutation rate 0.01 lead to a better performance. This is because when the mutation rate is too high, the offspring solutions cannot maintain some good genes of their parents. While for the lower mutation rate, some helpful genes may never be explored. **Error! Reference source not found.** shows how the crossover rate influences the optimisation process when the mutation rate is 0.01.

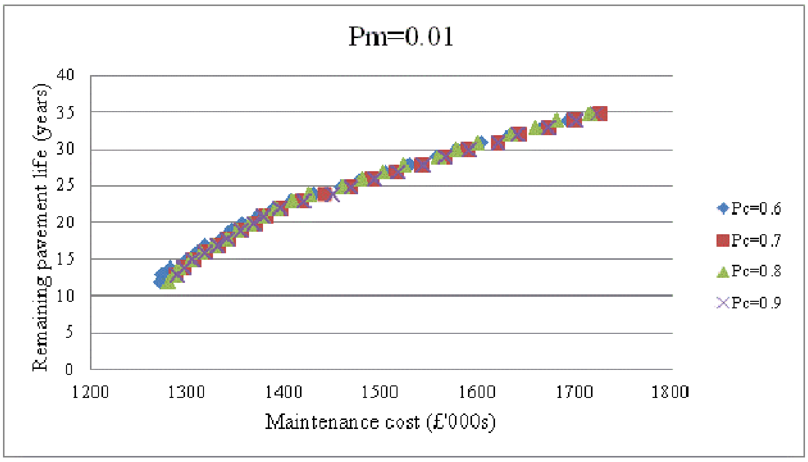

FIGURE 4 Optimum Pareto frontier for different crossover rates when Pm=0.01

Very similar optimal Pareto frontiers are obtained for each combination of the crossover and mutation rates in Figure 4. In order to consume less computational effort, the optimal crossover rate is chosen as 0.6. Therefore, the crossover rate of 0.6 and the mutation rate of 0.01 are applied in this part of the study.

3.3 Optimal Pareto solution

Based on the same GA parameter values as Section 3.3, NSGA-II (Deb, Pratap et al. 2002) is employed to achieve the optimal M&R strategy, and the resulting optimal Pareto frontier after a different maximum number of generations is illustrated in **Error! Reference source not found.**.

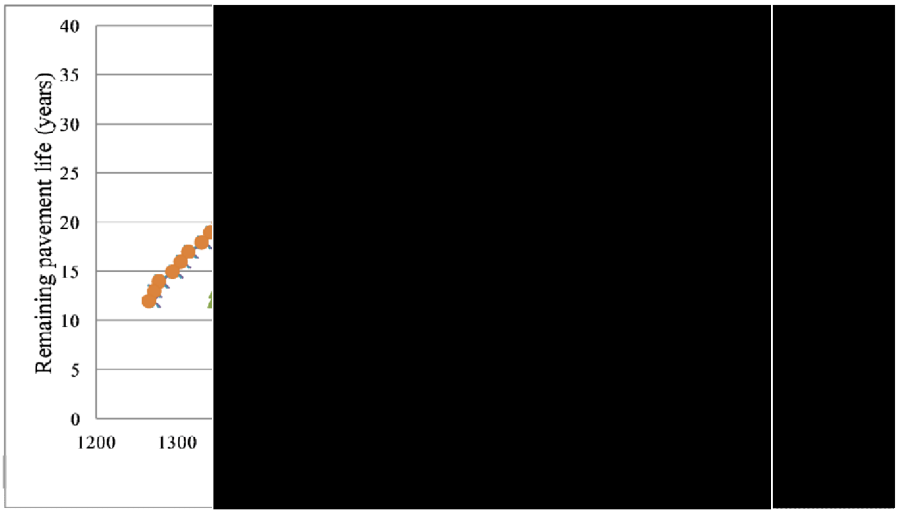

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FIGURE 5 The optimal Pareto frontier

The optimal Pareto frontier obtained is approaching the real Pareto frontier with increasing simulation generations. The results demonstrate that the optimal Pareto frontier is achieved at generation 5000, which cannot be improved significantly with further iterations.

The next step of the analysis is to normalise the obtained optimal Pareto frontier. The normalised distance for each non-dominated solution is calculated in terms of its objective function values. A normalised objective function value is achieved over a range of 0-100 for each objective based on the following mapping rules (Fwa, Chan et al. 2000):

$$O_N(i,x)=\frac{O(i,x)-O(i,\min)}{O(i,\max)-O(i,\min)}\times 100 \tag{5}$$

Where

$O_N(i,x)$ - the normalised parameter value of objective *i* for solution *x*

$O(i,x)$ - the actual value of objective *i* for solution *x*

$O(i,\max)$ - the maximum parameter value of objective *i* for non-dominated solutions

$O(i, \min)$ - the minimum parameter value of objective *i* for non-dominated solutions

For this optimisation problem, $O(1, \min) = £1{,}264{,}076$ and $O(1, \max) = £1{,}707{,}796$ for the objective of minimising maintenance cost; $O(2, \min) = 12$ years and $O(2, \max) = 35$ years for the objective of maximising remaining pavement life. The purpose of this mapping approach is to describe the two objective parameters in a single space.

The final step is to identify the solution that has the smallest Euclidean distance, dk, from ($O_N(1, \min), O_N(2, \max)$), represented by:

$$d_k = \sqrt{[O_N(1,x) - O_N(1,\min)]^2 + [O_N(2,x) - O_N(2,\max)]^2} \qquad (6)$$

The optimal solution based on the shortest normalised distance is determined as maintenance cost of £1,418,291 and total remaining pavement life of 24 years, chosen from the optimal Pareto solution set within the space of £1,264,076-£1,707,796 for maintenance cost, and 12-35 years remaining pavement life for the network. The resulting optimal Pareto solution is described in **Error! Reference source not found.**:

TABLE 5 The optimal M&R strategy

Road section	*Maintenance scheduling during the planning horizon T (20 years)*																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
AB	0	0	0	0	2	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0
BC	0	0	0	0	0	0	0	2	0	0	2	0	0	2	0	0	2	1	1	2
CD	0	0	0	0	0	0	0	2	0	0	2	0	0	2	0	0	2	0	0	2
AD	0	0	0	0	0	2	0	0	2	0	0	2	0	0	2	0	0	2	1	1

Examining **Error! Reference source not found.**, the maintenance plan for each road section on the network is provided. For road section AB, three maintenance actions are implemented over 20 years, i.e. three surface dressing (2) actions in years 5, 9 and 13. No resurfacing (3) or overlay (4) is carried out.

4. CONCLUSION AND FUTURE WORK

This paper presents a new approach to assign maintenance actions on a highway network. For the proposed PMS, a deterministic pavement age gain model is deployed to evaluate and forecast pavement condition, and NSGA-II is used to resolve the computational complexity of the maintenance optimisation problem. The formulation of the optimisation problem aims to both minimise the maintenance cost and maximise the pavement condition of a highway network over a given planning period. In this formulation, a road section group is employed as a decision making unit for the optimisation model, from which the road sections are given the same treatment. In this manner, less computational effort is required.

The developed deterministic PMS is applied to a simple road network. A set of GA parameters are compared to find the optimal combination that lead to the best Pareto solution set. With each additional simulation of generations, the optimal Pareto frontier generated is approaching the real Pareto frontier. Afterwards, the resulting optimal Pareto frontier is normalised, so that the balance between the involved objectives is established. This application indicated the feasibility, capability, and efficiency of using NSGA-II in conjunction with the deterministic pavement age gain model.

With the increase of highway network geometry, the computational effort for GAs increases exponentially. In this paper, NSGA-II is applied as the optimisation method which has proven itself to be sufficient enough for constrained multi-objective problems. However, more constraints can be added to the optimisation model, such as limitation of the use of surface dressing on motorways, and forcing structural maintenance on heavily trafficked roads (at least once during the life cycle). In addition, other advanced GAs and hybrid heuristic techniques can be implemented, as they have the feature of retaining the advantages of GAs, but prominently improve their searching ability and computational efficiency in achieving the global optimal.

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