

# Optimisation of Pavement Maintenance and Renewal Activities

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## Abstract

Many professionals have some degree of unease about the method of solving the pavement maintenance and renewal planning problem and recognised this planning is a complex process. Especially, the difficulty arises when the project interaction effects are considered. This is because of the multi-directional and diversity nature of these project interactions. Generally, it is very difficult to formulate such interaction as an objective function or constrain.

Before the project interaction can be properly integrated into the optimisation process, maintenance projects are usually planed without being effectively coordinated with each other. The maintenance cost is treated as a constant, as such, the opportunity of reducing the maintenance cost, practically the indirect maintenance costs, such as the user cost at the roadwork sites, are lost.

An approach has been studied in this paper to introduce an alternative measure to integrate the project interaction (coordinating type) into the optimisation process. Traffic interaction and maintenance - condition interaction are considered to be in relation to the demand prediction and condition projection respectively. A pavement maintenance and renewal planning framework has been proposed. With the developed project interaction integration model, this framework supports the plans to be optimised in a state- temporal and interaction dimension.

Keywords: Asset Management, Pavement Maintenance and Renewal, Optimisation, multi - objective Analysis, Traffic Modelling, Prevalent deterioration Model.

## 1. INTRODUCTION

Asset management (AM) is defined by Austroads (2006, pg. 1) as follows:

‘A comprehensive and structured approach to the long-term provision and maintenance of physical road infrastructure using sound engineering, economic, business and environmental principle to facilitate the effective delivery of community benefits’.

In the AM context, planning the pavement maintenance and renewal includes setting up an ‘economic’ standard for investment, defining the level of service, and developing cost effective programs for the long term. However, if the budget is constrained, the task is to determine the timeframe of maintenance and the level of intervention to a road network to make the available budget to be spent more cost effective from a long-term view.

Let  $R^n$  denotes  $n$  dimension search space;  $S$  denotes the feasible solution universes in  $R^n$  or  $S \subset R^n$ ;  $F: S \rightarrow R$  be the objective functions, and  $X$  denotes the decision variable. The asset maintenance and renewal-planning problem can be stated as finding a vector  $X = (x_1, x_2, \dots, x_n)^T$  in  $S$  or  $X \in S$  to optimise the  $F(X)$ . Generally, the problem (without loss of generality we only consider the minimization case) can be defined as follows:

$$\underset{X \in S}{\text{Min}} F(X) \tag{1}$$

$$\begin{aligned} F(X) &= (f_1(X), f_2(X), \dots, f_p(X))^T \\ S &= \{X \mid g(X) \leq 0\} \\ g(X) &= (g_1(X), g_2(X), \dots, g_m(X))^T \\ X &= (x_1, x_2, \dots, x_n)^T \quad X \in S \subset R^n, \end{aligned} \tag{2}$$

where

$F(X)$  - the objective function vector  
 $g(X)$  - the constraint vector

The problem consists of  $n$  number of decision variables,  $m$  number of constraints and  $p$  number of objective Functions.

### 1.1. Planning Problem for Pavement Maintenance and Renewal Projects

Many professionals have some degree of unease about the method of solving this problem. It is generally recognised to be a complex process because the goals and constraints are usually incommensurable or competing against each other (Zeleny, 1998). The elements interact with each other; the workload and pavement condition usually subject to uncertainties and dynamic changes and the difficulty in evaluating the effectiveness of an alternative project program (Taplin et al., 2005). There are

trade-offs between pavement effect and its condition, between short term saving and long term cost effectiveness and between time and space in the networks.

With the help of advanced computers and software, such as Genetic Algorithm (GA), Particle Swarm Optimisation (PSO), the success of the planning largely relies on the planner's ability in structuring the problem.

The difficulty arises when the full interaction effects are taken into consideration in the process of structuring the problem because these interactions are multi-directional over a large amount of parts. It has been found difficult to structure them as an objective function or constrain.

These interactions may include project interaction, traffic interaction, and pavement condition -maintenance interaction. However, traffic interaction analysis considers the fact that improving road conditions change the pattern of network traffic. The condition improvement-maintenance interaction reflects that maintenance treatment improve road condition. Therefore, it would be reasonable to consider that these two types of interaction are relevant with the demand – forecasting and condition-predicting problem respectively rather than the optimisation problem.

Studying project interaction deals with the effects between projects in term of coordination. For example, taking advantages of joint maintenance and project alignment can reduce the maintenance costs (direct and indirect costs) and redo works. Researchers have found it is important to take into account the project interaction in the optimisation process (Brillet and Lepert, 2003).

## **1.2 Current Practice and Issues**

Normal practices structure the problem in state-temporal dimension. They seek to optimise the number of maintenance activities, cumulated level of intervention, time of maintenance and also set adequate priority to these more effective links or paths. All of these are essential factors and critically important for the success of the planning, however are incomplete. One of the major weaknesses of this approach is indicated by Sinha and Fwa (1993) that maintenance projects are planned without being effectively coordinated with each other.

Another issue arises when structuring the problem in the state-temporal dimension is that the maintenance cost is treated as a constant, in other words the optimising process blinds the indirect maintenance cost, such as the user cost at the roadwork sites.

In fact, maintenance cost includes direct and indirect maintenance cost in reality. User cost at the roadwork sites is an important element of the indirect cost. It is changeable if the projects can be properly coordinated. A full optimisation of a road maintenance program should take into account all the consequences of road works, including user cost at roadwork sites (Brillet and Lepert, 2003) . If the problem is structured in a state-temporal and interaction dimension and project interaction effects are considered, the maintenance cost becomes a variable. Reducing the indirect maintenance cost including the frequency of road works, their duration and their impact on traffic flow

(slowdowns and bottlenecks) will decrease the total delay experienced by users in their travels, and thus reduce the total economic cost of the maintenance programs.

The following example (Brillet and Lepert, 2003) shows the user costs at roadwork sites. On a dual carriageway road, the speed is limited to 110 km/h, and where traffic flow are up to 20,000 vehicles /day, a surface renewal must take place on 5 km during 10 days; this requires the closure of one carriageway, the other being exploited in both directions at a 70km/h speed limit. The direct cost of work is estimated at \$30/m<sup>2</sup>, that is \$1.2 M in total. The user cost at the roadwork sites is shown in Table 1.

Table 1. User cost at roadwork sites

Traffic situations	Traffic flow freely; the effect with a speed limit (70 km/h)	Half of the vehicles would undergo 15 minutes waiting, and would travel through the work site at 30km/h
User costs	\$ 68,500	430,000 \$ (more than 1/3 of the direct cost)

As a result of normal practice, the interaction issues have to be remedied in the operation planning or the implementation planning stage. At this stage, the considerations are usually taken from a short-term view and the adjustment cannot be large as this may damage the long-term optimum balance. As such, the optimisation of pavement maintenance and renewal plan is most likely to be not as good as it could be in the interaction dimension.

Therefore there is an opportunity to further optimise the program in the interaction dimension, thus allowing for the potential savings and benefits. The question raised here is how to structure the project interaction and how to integrate them into the decision space.

### 1.3. Objective

An approach has been studied in this paper to introduce an alternative measure to structure the project's interactions and then integrate them into the decision space. A pavement maintenance and renewal planning framework also has been proposed. With the developed project interaction pre-optimisation model, this framework supports to optimise the plan in a state- temporal and interaction dimension.

### 1.4. Paper Outline

The rest of the paper is organised as follows: Section 2 describes the strategies of structuring and integrating the project interaction into the planing process and the developed approach. Section 3 discusses the approaches of condition prediction and the demand model used in this framework. Section 4 presents the PSO Optimisation Model. A case study application is presented in Section 5. Further research and conclusions are given in final section.

## **2. THE PROPOSED INTERACTION PRE-OPTIMISATION MODEL**

Before getting into the details of the proposed model, two terms, ‘objects’ and ‘interaction similarity’ need to be clarified.

To deal with the problem defined in Equation 1 and 2, all roads in a planning network should be split into manageable long segment, such as 5 km to 10 km long. Each segment is regarded as a potential roadwork project on the road network.

There are several ways of project interactions such as geographical interaction, function interaction and logistic interaction. If interacted projects should ideally be maintained together such as joint maintenance or alignment, the interaction is defined as an interaction similarity. If the interacted projects should ideally be maintained separately, the relation is defined as a dissimilarity interaction.

### **2.1. The Suitability of the Proposed Approach**

The suitability of the proposed approach is considered to meet the following requirements and scenarios:

- As most of road authorities are responsible for thousand of kilometres of road, it is cumbersome to model individual segments as stated in HDM-4 Analytical Framework and Model Descriptions (Odoki and Kerali, 2000). The objects should be classified into homogeneous categories in modelling and maintenance scheduling process (Morcoux and Lounis., 2006, Lingars, 2001).
- Generally, the plan will be further adjusted in the operation and implementation planning process. At the optimisation stage, the interaction should be optimised in a broad sense to leave room for accommodating later adjustments.
- As stated in the introduction section, the project interactions are considered as a complex interrelationship in term of type, direction and the number of entities involved. It is difficult to standardise or formalise them interactions into objective functions or constraints. Therefore, alternative means should be considered.
- An optimal solution is achieved by balancing all factors considered in the problem space rather than individual factors. Individual factor including the interaction should not dominate others in a decision making process. So a suitable approach should be able to not only structure and integrate the project interaction but also balance all aspects of the problem to achieve the global optimization.
- As stated before, to the multi-constrain, multi-objective pavement maintenance and renewal optimisation problem, there is no single optimal solution but rather a set of alternative solutions or non-inferior solutions

(Gholaman et al., 2006). The ultimate solution should be selected from them based on human judgment. To find these non-inferior solutions is a computational complex process and usually helped by some sophisticated technologies, such as artificial intelligence. These technologies normally work in a systematic and automatic way. Therefore, such project interaction integrating methods would be more efficient if they are systematic and easily automatic processes.

Having the above considerations, this study proposes a two-stage approach to integrate the interaction dimension into the decision space. Firstly, the interaction relation is structured as an attribute of the objects and then applies a similarity analysis to group or split projects into different groups in accordance with their interaction attribute and other attributes. This process is a project interaction pre-optimization process. Secondly, these homogeneous project clusters are input into a global optimization model developed in this study to find the most competitive solution by trading-off all of the factors including project interaction.

## 2.2. Structuring the Interaction Relationship

Let the project to be organised in a table ( $U$ ). Its rows are labelled by objects ( $X$ ); columns are labelled by attributes ( $A$ ); and the entries of the table are attributes values ( $V$ ); the  $\rho$  presents the information function  $\rho: X \times A \rightarrow V$ . This table can be represented (Pawlak, 1982) as follows:

$$U = \langle X, A, V, \rho \rangle \quad (3)$$

To a given object  $x$  in the table, its value of attribute  $a$  is presented as:

$$\begin{aligned} \rho_x(a) &= \rho(x, a) \\ x &\in X \text{ and } a \in A. \end{aligned} \quad (4)$$

The interaction type should be defined in consultation with expert knowledge and in relation to a particular scenario. Suppose 8 types of interaction relation are indicated, and types 1, 2, 3 4 of interactions are interaction similarity, and type 5, 6 and 7 are interaction dissimilarity.

Let  $I \in A$  denote the interaction attribute,  $Ix_i$  denotes the interaction attribute of object  $x_i \in X$ ,  $n$  denotes the total amount of objects in the table ( $U$ ). The interaction similarity relations between object  $x_i$  and others in  $U$  can be defined as follows:

$$Interaction(x_i) = \begin{cases} Sim(x_i, x_j), & \text{if object } x_i \text{ and } x_j \text{ has 1, 2, 3 or 4 type relation} \\ Dis(x_i, x_j), & \text{if object } x_i \text{ and } x_j \text{ has 5, 6 or 7 type relation} \end{cases}$$

The interaction attribute for each project is structured as follows:

$$\begin{aligned} Ix_i &= (\{x_j \mid Sim(x_i, x_j) \in X\}, \{s_j \mid dis(x_i, x_j) \in X\}) \\ X_i &\in X, \quad X_j \in X \end{aligned} \quad (5)$$

$$\begin{aligned} 0 < i, j, \leq n \\ i \neq j \end{aligned}$$

Where  $i, j$ , are the unique identifying numbers of projects in the table or the set  $X$  .

### 2.3. Pre-optimisation

Given more opportunities for those interaction similarity projects to be maintained at a similar time, and avoiding the conflict between interaction dissimilarity projects, a pre-optimization operation is developed.

The pre-optimizing is realised by a hybrid classification – cluster model. It is the combination of the classification and cluster approach, and integrated with the Hamming Distance, Rough Cluster, Partition Algorithm and Hierarchical Agglomerative Algorithm.

The procedures include feature reduction, similarity analysis, classifying, approximation and clustering.

Feature deduction is the process of taking out the common attributes such as the climate attribute if the studied area is small, and climate effects on each segments are considered to be same; determining the most critical attributes (core attribute in short). The core attributes values must be identical in the same cluster, such as the pavement condition, age and structure. The remainder are judgment attributes.

The first step is to divide the entire projects table into  $n$  sub-table, in other words, to divide the super class into  $n$  classes ( $(U_c = (U_1, U_2, \dots, U_n) \in U, U = \bigcup_{c=1}^n U_c$  ). Then apply a similarity analysis to each class.

This similarity analysis goes through the following steps:

- Measure the similarity of a given attribute value
- Measure the similarity between projects
- Measure the similarity between clusters and re-clustering the existing clusters.

For details of the steps and equations refer to appendix A of this paper. Its procedure is shown in Figure 1.

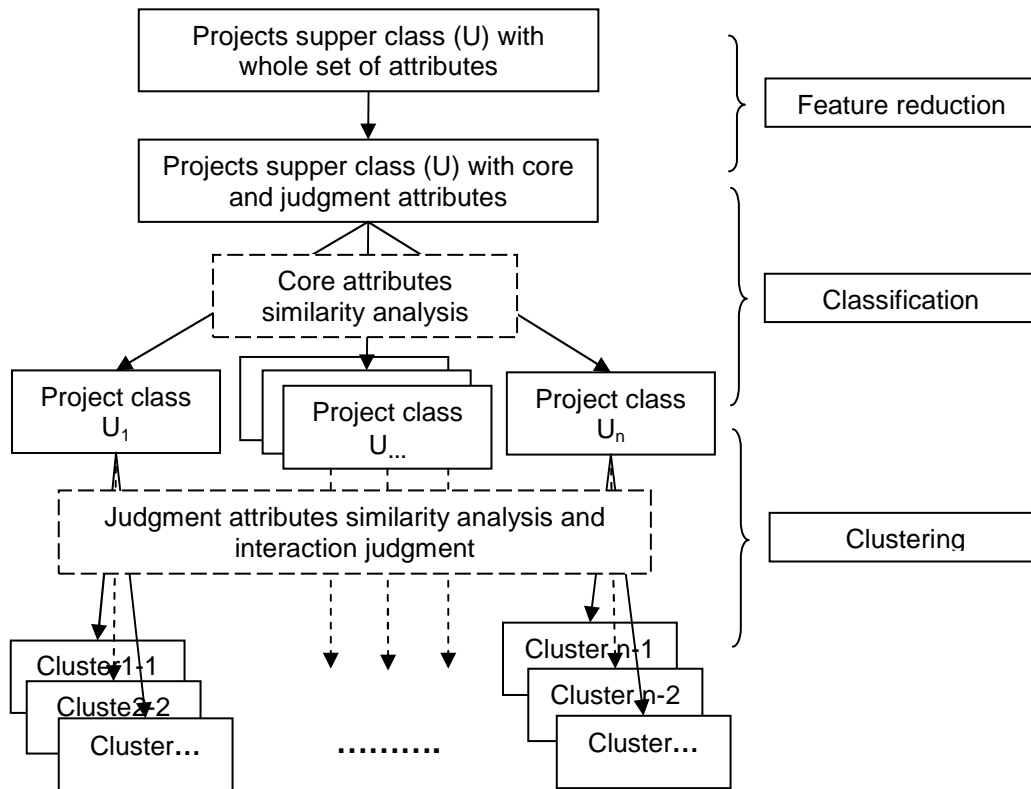


Figure 1. The procedure of the proposed pre-optimisation method

The outputs of this model are the clusters with the structured interaction similarity and dissimilarity relationship. These clusters have their own attributes similar to the project’s attributes, which describe their properties including the number of the projects in the cluster. These clusters are the input of the optimum model, which is a Particle Swarm Optimisation (PSO) based model.

### 3. PAVEMENT DETERIORATION AND DEMAND MODELS

The above interaction pre-optimisation model contributes one important input to the maintenance and renewal optimization, which is the project clusters with the structured project interaction relationships. The other required inputs of the optimisation model are the pavement condition and the traffic demand of the road network.

#### 3.1. Road Deterioration

Main factors influencing the road deterioration are considered to be the traffic loading, age, environmental effects, maintenance, pavement characteristics and their initial construction quality. Construction quality has rarely been used in models as it is not easily measurable (Han, 2002). Any road deterioration model with all or most of the factors including the maintenance effects, can be used in this framework. Preferably, the model has a similar structure with following concept equation:

$$Pavement\ condition = normal\ deterioration - the\ road\ condition\ improvement\ function\ relating\ to\ maintenance\ activities$$

A modified HDM3 model is used in this framework. The original model is a generalised HDM3 model developed by Han (2002), and the modification follows the concept of Chootinan et al (2006). Roughness is used as the dependent variable for measuring road deterioration.

The generalised HDM3 roughness aggregate model (Han, 2002) is:

$$R_t = [\alpha(DEF^{\gamma})(NE4)^{\nu} + \xi]e^{\beta t} \quad (6)$$

Where

NE4 - traffic loading measured by annual average cumulative equivalent standard axles (ESA's)

DEF - the falling weight deflection curvature (millimetres)

$\xi$  a special parameter to make up for lack of data on initial roughness

$t$  the age since construction or last reconstruction,  $t = t_{current} - t_{construction}$

$\gamma, \beta$  the parameters

$\beta = 0.016$  which is gained by looking up table of HDM3 model manu (Watanatada et al., 1987)

$\gamma = -5$  Standard

$\nu = 1$

The generalised incremental roughness model:

$$\Delta R_t = \alpha e^{\beta t} DEF^{\gamma} \Delta NE4 + (\beta \Delta t + \theta \text{ reseal} + \delta \Delta RM) R_t \quad (7)$$

Where

$\Delta R_t$  - increase in roughness over time  $\Delta t$  (m/km IRI)

DEF - falling weight deflectionmeter

$\Delta NE4$  \*- increasemental number of ESAs in period  $\Delta t$

Reseal - number of reseals in period  $\Delta t$

$\Delta RM$  - routine maintenance during the period  $\Delta t$

$\beta$  - age- environment coefficient

$\alpha, \gamma, \theta, \delta$  - parameters to be calibrated

\*  $\Delta NE4 = 365 \times 1.1 \times AADT / (\text{No. of lanes}) \times E \times C\% \times \Delta GF$

C - the percentage of heavy commercial vehicles

E - the estimated number of ESA's per commercial vehicle from Table E5 in the Pavement Design Manual (Austroads, 1992)

$\Delta GF$  - Traffic grow factor

Because the routine maintenance is considered as the base case in Han's 2002 study, as it is treated as a maintenance type in this study, and Equation 7 does not include the overlay, major rehabilitation option. Therefore, modification is required before using it in this study. As it is generally recognised, the modularised model has the

advantage of easy implementation and easy integration with external data. Therefore, original model is modified to the following form:

$$R_i = R_0 + \alpha e^{\beta t} DEF^\gamma \Delta NE4 + \beta \Delta R_0 - \sum_{i=1}^j p_i(x_i, y_i) \quad (8)$$

Where

$x_i$  - the treatment option

$y_i$  - the age when this treatment was applied

$p_i$  - the actual improvement in pavement condition ( roughness ) at year  $i$  as a result of applying treatment option  $m_i$

After the above modification, Equation 8 is modularised and ready for studying the effect of any maintenance option, and also capable of using external data, such as the data shown in Table 2.

Table 2. Treatment types and effect on pavement condition

Code	Treatment type	Unit cost (\$/m <sup>2</sup> )	Age of pavement applicable (< year)							
			20	19	16	13	10	7	4	1
0	–	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	Routine maintenance	0.20	0.000	0.000	0.000	0.225	0.225	0.450	0.450	0.450
2	Surface treatment	0.74	0.000	0.450	0.675	1.125	1.575	1.575	1.575	1.575
3	Overlay	4.67	0.000	0.900	1.575	1.800	1.800	1.800	1.800	1.800
4	Major rehabilitation	7.74	4.500	4.500	4.500	4.500	4.500	4.500	4.500	4.500

Source: (Chootinan et al., 2006)

The scale used in Table 2 is Present Serviceability Index (PSI). It is the statistical estimate of the Present Serviceability Rating (PSR) (Paterson, 1987). The conversion relationship between International Roughness Index (IRI) and PSI is presented by following equation (Paterson, 1987, pg. 36):

$$IRI = 5.5 \log_e (5.0 / PSI)$$

### 3.2. Demand Model

As discussed before, the goal of maintenance and renewal of the physical road network is to facilitate the effective delivery of community benefits. To estimate the benefits of expenditure, road traffic in relation with different benefits measurement, is an import factor. Therefore, a demand forecast is essential.

Most of the traffic forecast models can be used in this framework rang from a simple fixed growth rate model to a more sophisticated method such as the widely used four - step mode of either deterministic or stochastic based, depending on the particular scenario of the application. For example, if it is assumed that there is no congestion, which means the link costs are fixed and travellers always choose the shortest route. The deterministic model, such as All-or- nothing model may be selected, whereas, if the variability in driver's perceptions of costs are considered, the stochastic base model may be suitable.

In this framework, a direct demand and assignment model which combined Gravity and log Model, developed by Taplin et al (2005) and Han (2002), is used. However, it should be calibrated under each particular condition and practice.

$$F_i = \sum_{\forall r} \sum_{\forall s} \sum_{\forall k} \delta_i^k q_{rs} p_{rs}^k = \frac{\delta_i^k \alpha [\Omega P_r P_s]^\beta f(C_{rs}) e^{-\theta u_{rs}^k}}{\sum_{\forall k} e^{-\theta u_{rs}^k}} \quad (9)$$

where

$F_i$  - estimated traffic flow on link  $i$

$q_{rs}$  - trips between origin  $r$  and destination  $s$

$P_{rs}^k$  - proportion of trips on the route  $k$  between origin  $r$  and destination  $s$

$\delta_i^k$  - equal to 1 if link  $i$  is on route  $k$ , 0 otherwise

$\alpha$  - a scale parameter

$\Omega$  - tourism attraction factor,  $\Omega = \xi^\tau$  ( $\xi \geq 1$  parameter,  $\tau = 0$  either  $s$  or  $r$  is a recognized tourism destination,  $\tau = 1$  one of them is tourism destination,  $\tau = 2$  both  $r$   $s$  are tourism destination)

$P_r, P_s$  - the population of  $r$  and  $s$

$\beta$  - trip demand elasticity with respect to population product and GDP

$f(C_{rs})$  - the impedance function

$\theta$  - a separate parameter

$u_{rs}^k$  - travel cost of route  $k$  between origin  $r$  and destination  $s$

## 4. OPTIMISATION MODEL

The optimisation model is constructed based on Particle Swarm Optimisation. This model use an VEPSO (Schaffer, 1985) multi-objective technique to handle the multiple objective functions instead of the Weighted Aggregation Approach.

### 4.1. Particle Swarm Optimisation (PSO)

PSO introduced by Kennedy and Eberhart (1995) is one of the latest Evolutionary Algorithms (EA) technologies. Results of studies indicate that PSO is a good alternative to solve an optimization problem due to its easy implementation, usually faster convergence rates and competitive detective capability than other EAs (Kennedy and Eberhart, 2001, Parsopoulos and Vrahatis, 2002).

This is probably benefited from its one-way information design. In PSO only the global best solution (gbest) is published for every particle within a swarm and there is no communication between particles. More details of PSO can be found in these papers (Parsopoulos and Vrahatis, 2002, Kennedy and Eberhart, 1995, Kennedy and Eberhart, 2001).

The PSO procedure starts with an initial pool(s) of solutions represented as a swarm(s). Each solution in the pool is represented as particle. It iteratively evaluates the individuals in the pool for fitness. Each particle records its historic best solution (pbest) and the swarm tracks the best solution (gbest) over all particles. Each particle modifies the solution according to its own pbest, the gbest and a random function. The modification velocity and the new position of each particle are calculated by Equation

10 and 11 (Shi and Eberhart, 1998). The evaluation and modification process are repeated until the criterion for termination is satisfied.

$$v_{id}(t+1) = w v_{id}(t) + c_1 r_{1j}(t)(pbest_{id}(t) - x_{id}(t)) + c_2 r_2(t)(gbest_d(t) - x_{id}(t)) \quad (10)$$

$$x_{id}(t+1) = x_{id}(t) + v_{id}(t+1) \quad (11)$$

Where

$x_{id}$  - the current position of  $i^{th}$  particle in  $d$  dimension;

$v_{id}$  - the current velocity of  $i^{th}$  particle in  $d$  dimension;

$pbest_i$  - the best position of  $i^{th}$  particle achieved;

$gbest_d$  - the global best position of the swarm;

$r_{1j} = rand_1()$  and  $r_2 = rand_2()$  - the uniform random numbers in  $[0, 1]$ ;

$c_1$  and  $c_2$  - constants called acceleration coefficients.

In Equation 10,  $w$  is the inertia factor, which was introduced by Shi and Eberhart (1998). If  $w=1$ , Equation 10 and 11 are the standard PSO formulation. A large inertia weight facilitates wide ranging exploration, whereas a small one tends to facilitate the exploitation of the area nearby.

## 4.2. Multiple Objective Handling Approach

From the AVEPSO formulations (Parsopoulos et al., 2004), the proposed optimisation model directly uses the objective functions in evaluation of the candidate solutions in the searching process. In which more than one swarms are employed and the number of swarms depend on how many objective functions the problem has. Each swarm is exclusively evaluated with one of the objective functions. The  $gbest$  of one swarm will be used as the  $gbest$  of another swarm in the fitness evaluation process. The exchanging  $gbest$  among swarms is organised in a run-cycle way. The significant benefit of applying this approach is to avoid the bias in given a user-supplied weight to each objective function in the objective combining process of the widely used Weighted Aggregation Approach.

## 4.3. Procedure

The procedures of the optimisation model are as shown in Figure 2.

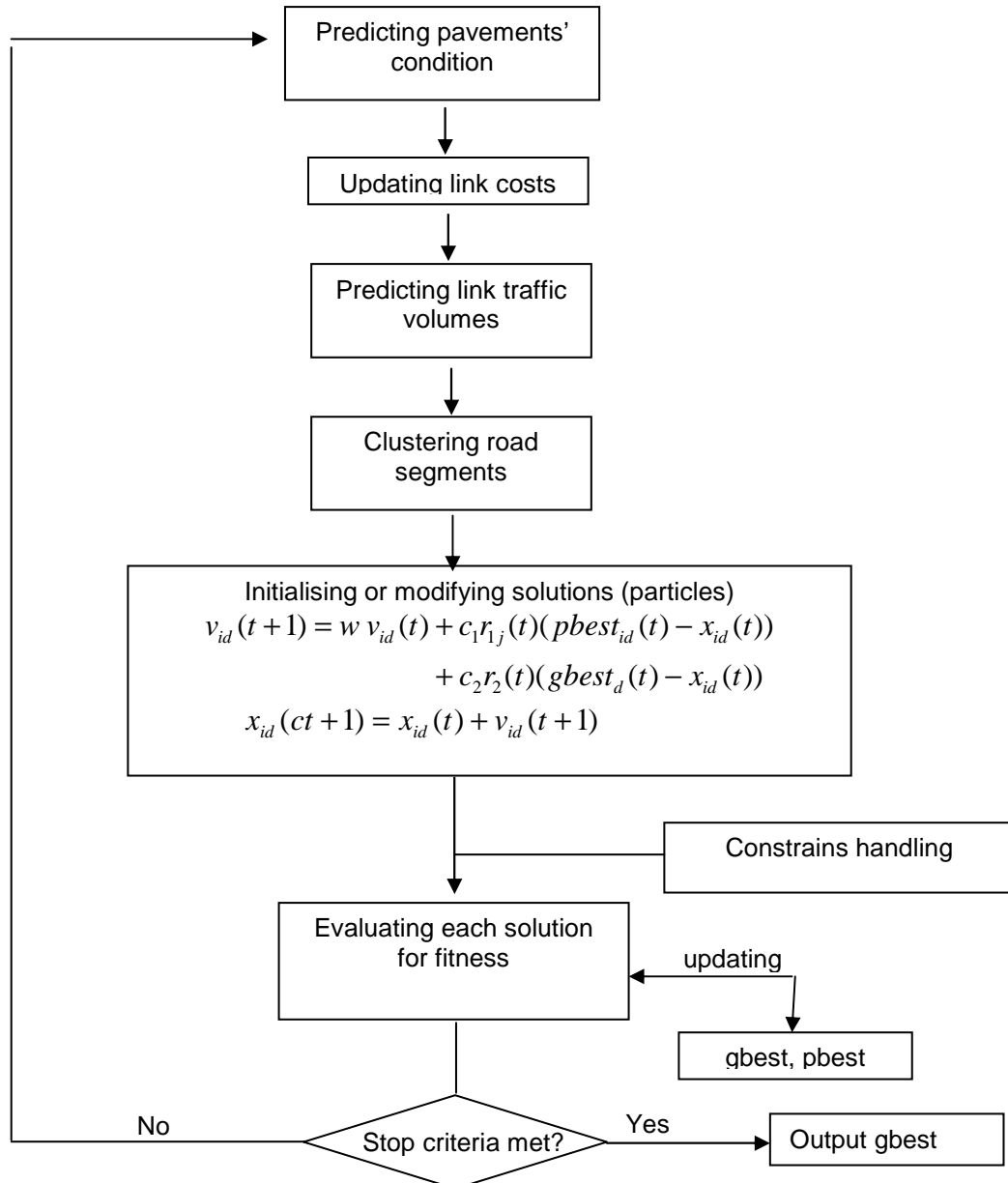


Figure 2. The procedures of the optimisation model

## 5. CASE STUDY APPLICATION

### 5.1. Road Network and Problem Specification

To illustrate the feasibility of the proposed method, a case study is conducted in this paper. The study is based on the rural network of South West Region of Western Australian as shown in Figure 3. The region occupies the south-west corner of the State and covers an area of 23,998 square kilometres. There are 140,846 people living in the region in 2005. The study network comprises the state roads in Roads 2025 Regional Road Development Strategy released during 1997, including 660 km of highway, 923 km main roads and local roads. Only the state and main roads are

considered in this study. The highway and main roads were split into 243 segments with 5-10 km long for each.

A long-term maintenance and renewal plan is studied with an assumed annual budget of \$17 m in order to maximise the expenditure effectiveness of the available budget.

With the planning period, although AM recommends focusing on the life time cost effective, in general, life cycle is considered over a finite horizon. In accordance with the International Infrastructure Management Manual (2002), 10 –20 year plans such as the cash-flow predictions for maintenance, rehabilitation and replacement, are usually regarded as a long-term plan. Therefore, a 15-year planning period is adopted in this study.

Maintenance options considered in this study are: route maintenance, reseal, overlay and major rehabilitation.



Figure 3. Road Network of South West Region, WA

## 5.2. Formulation of the Objective Functions and Constrains

$$\text{Minimise: } Z_1 = \sum_{t=1}^T \sum_{s=1}^S \frac{R_{ts} F_{ts}}{L_s} \quad (\text{Min: Roughness x vehicles / km}) \quad (12)$$

$$Z_2 = \sum_{t=1}^T \sum_{s=1}^S Co_{ts}(x_{si}) \quad (\text{Min: Maintenance costs}) \quad (13)$$

Where

$$F_{ti} = \sum_{\forall r} \sum_{\forall s} \sum_{\forall k} \delta_{ti}^k q_{rs} p_{rs}^k = \frac{\delta_{ti}^k \alpha [\Omega P_r P_s]^\beta f(C_{rs}) e^{-\theta u_{rs}^k}}{\sum_{\forall k} e^{-\theta u_{rs}^k}}$$

$$R_{st} = R_{s0} + \alpha e^{\beta t} DEF^\gamma \Delta NE4 + \beta \Delta R_{s0} - \sum_{i=1}^j p_{si}(x_{si}, y_{si})$$

Subject to:

- Each year expenditure  $\leq$  each year's budget

$$\sum_{s=1}^S Co_s(x_{st}) \leq B_t \quad \forall t, \forall s \quad (14)$$

- The expenditure of any project in one year should be less than 50% of the total annual budget, otherwise, applying large project profile (Qiu, 2000).

$$Co_{st} = f_{profile}(x_{st}), \quad \forall t, \forall s \quad (15)$$

$$f_{profile}(x_{st}) = \begin{cases} Co_{st}, & \text{if } Co_{st} \leq \frac{1}{2} B_t \\ \frac{1}{2} Co_{st}, & Co_{st+1} = \frac{1}{2} Co_{st}, \text{ if } \frac{1}{2} B_t \leq Co \leq B_t \\ 30\% B_t, & Co_{st+1} = 30\% B_t, Co_{st+2} = 40\%, \text{ if } Co_{st} \geq B_t \end{cases} \quad (16)$$

- The performance of any pavement assignment should meet the related minimum requirement (defined standards  $Q_s$ )

$$R_{st} \leq Q_s \quad (17)$$

- Maintenance option initialisation function (age, condition, interval between two major treatments)

$$x_{st} = f(y_{st}, R_{st}, Tu_{s(t,t-1)}), \quad x_{xt} \in \{0, 1, \dots, m\}, \quad \forall s, t. \quad (18)$$

( $Tu_{s(t,t-1)}$  - the time passed since last project,  $m$  maintenance option). This function is defined by applying the rules summarised in Table 3.

Table 3. Treatment initialization criteria and rules

Criteria	Age of pavement applicable	Codes	Treatment type	Minimum interval between treatments
		0	Routine maintenance	-
$2.3 < R \leq 3$	$< 16$	1	Reseal	-
$R > 3$	$< 19$	2	Overlay	-
$R > 7$ and other standards	$< 20$	3	Major rehabilitation	10 years

Extracted from (Taplin et al., 2005, Chootinan et al., 2006)

### 5.3. Projects Interaction

Two types of project interactions are selected in this study to illustrate the proposed approach, which are: the geographically closer pavement segments (route distance < 50 km), and the projects on the shortest (or cheapest) and the second shortest routes (the critical paths). The former is an example of the interaction similarity relationship, and the later are the example of interaction dissimilarity relationship. However, if data is available, other types of project interaction can also be included..

### 5.4. Defining and Structuring the Selected Interaction Relationships

Before applying the proposed method in section 2, it is necessary to define the selected interaction relationships. The road networks are continuous. For defining this geographically closer relationship, it is necessary to make the continuous road network discrete. This is accomplished by putting discrete points on links or paths over the road network. The geographically closer relationships are analysed by measuring the segments' relative distances along links to the corresponding discrete points.

The method of selecting the shortest path and the second shortest path:

- Select significant nodes on the road network to be assumed as the critical OD pairs, and centralise the rest of the nodes
- Identify the acceptable routes (no substantial backtracking) between each of these critical OD pairs by using STOCH algorithm (single-pass method) (Dial, 1971)
- Using the all-or-nothing assignment procedure, to select the 1<sup>st</sup> and 2<sup>nd</sup> best path or routes for each of these OD pears.

If two segments on the same path (either on the best path or on the 2<sup>nd</sup> best path, their relationship are defined to be interaction similarity. Otherwise, the relation between them is defined to be dissimilarity.

The above definition assumes that most of the trips occupy the 1<sup>st</sup> and 2<sup>nd</sup> best paths between OD. If both paths were disturbed by road works, extra user cost, such as travelling through a more expensive 3<sup>rd</sup> path would be introduced. Therefore, ideally, road works on the two paths at similar time should be avoided.

### 5.5. Representation of the Particles

$S$  denotes the number of road segments;  $Y$  denotes the year and the  $M$  denotes the type of treatment. Then, each solution or a particle is coded as follow:

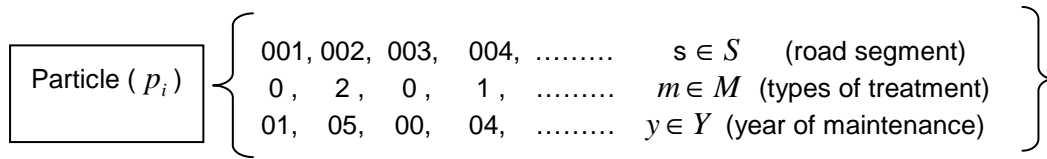


Figure 4. Coding particle using  $3 \times n$  metric approach

### 5.6. Results

15 Year pavement maintenance and renewal plans are developed using the development optimisation model with and without the project interaction pre-optimisation model.

Initial results show that the projects are coordinated in term of the selected interaction scenario, and considerable savings in the consequents cost of road works are achieved in the plans generated by the proposed approach as compared with that of base case. The model is also competitive in savings of computational time and resources. Details of results will be reported in a further paper.

### 6. CONCLUSION

Normal practice optimises pavement maintenance and renewal projects in a state-temporal dimension, which treats maintenance cost as a constant and blinds the project interaction effects as the project are planned without being effectively coordinated with each other.

Project interaction should be considered to stress the project coordination such as project alignment and joint in the optimisation process to reduce adverse effect on each other.

User costs at the roadwork sites are important and should be considered together with the number of maintenance activities, time of maintenance, level of intervention at the pavement and pavement's effects.

An alternative pavement maintenance and renewal plan framework has been proposed in this paper, including a project interaction pre-optimisation model. The framework supports to optimise the plan in a state-temporal and interaction dimension by taking into account the project interaction in the optimisation process. Moreover, it treats the maintenance cost as a variable, as such enabling optimisation of the user cost at the roadwork sites.

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## References

- Austrroads (1992) *Pavaement Design - A Guide to the Structure Design of Road Pavement*, The Kelvin Press, Sydeny.
- Austrroads (2006) *Guid to Asset Management Part 1: Introduction to Asset Management*, Austrroads, Sydney.
- Brillet, F. and Lepert, P. H. (2003) In *The XXIIInd PIARC World Road Congress* World Road Association-PIARC.
- Chootinan, P., Chen, A., Horrocks, M. R. and Bolling, D. (2006) *Transportation Research Part A*, **40**, 725 - 743.
- d'Amato, M. (2004) *Int. J. of Strategic Property Management* *Production Economics*, **8**, 205 - 217.
- Dial, R. B. (1971) *Transport Research*, **5**, 83-111.
- Gholaman, M. R., Ghomi, S. M. T. F. and Ghazanfari, M. (2006) *Computers and Industrial Engineering*, **51**, 26 - 43.
- Hamming, R. W. (1950) *The Bell System Technical Journal*, **29**, 147 - 160.
- Han, R. (2002) In *Department of Information Management and Marketing* The University of Western Australia, Perth.
- Kennedy, J. and Eberhart, R. (1995) In *4th IEEE Int. Conf. on Neural Networks* (Ed, IEEE) Piscataway, NJ,, pp. 1942 -1948.
- Kennedy, J. and Eberhart, R. C. (2001) *Swarm Intelligence*, Morgan Kaufmann Publishers.
- Lingars, P. (2001) *Journal of Intelligent Informaion Systems*, **16**, 215 - 228.
- Morcous, G. and Lounis., Z. (2006) *Canadian Journal of Civil Engineering*, **33**, 756 - 765.
- Nieimen, J. (1998) *Foundation Information*, **11**, 289 - 296.
- NZ National Asset Management Steering (NAMS) Group and the Institute of Public Works Engineering of Australia (IPWEA) (2002) *International infrastructure management manual*, Thames, N.Z. : Association of Local Government Engineering N.Z.
- Odoki, J. B. and Kerali, H. G. R. (2000) *HDM-4 Analytical Framework and Model Descriptions*, World Bank Association.
- Parsopoulos, K. E., Tasoulis, D. K. and Vrahatis, M. N. (2004) *Proceedings of the IASTED International Conference. Applied Informatics*, 823-828.
- Parsopoulos, K. E. and Varhatis, M. N. (2002) In *The 2002 ACM Symposium on Applied Computing (SAC 2002)*, pp. 603?07.
- Parsopoulos, K. E. and Vrahatis, M. N. (2002) In *Proceedings of the 2nd Euro-International Symposium on Computational Intelligence* (Ed, al., V. K. e.) Kosice Slovakia, pp. 214 ?220.
- Paterson, W. D. O. (1987) *Road Deterioration and Maintenance Effects*, The Johns Hopkins University Press, Baltimore.
- Pawlak, Z. (1982) *Int. J. of Computer and Information Science*, **11**, 341- 355.
- Pawlak, Z. and Skowron, A. (2007) *Information Sciences*, **177**, 28.
- Qiu, M. (2000) In *School of Information Management* University of western Australia.
- Schaffer, J. D. (1985) In *In tonational Conference on GA and Their Applications* Pittshurgh, PA, pp. 93-100.
- Shi, Y. and Eberhart, R. (1998) In *IEEE Int. conf. on Evolutionary Computation* (Ed, IEEE) Piscataway.
- Sinha, K. C. and Fwa, T. F. (1993) *Transport Research Record*, **826**, 5-8.

- Taplin, J. H. E., Qiu, M., Salim, V. K. and Han, R. (2005) *Cost- Benefit Analysis and Evolutionary Computing*, Edward Elgar Publish, Inc., Northampton.
- Watanatada, T., Harral, C. G., William, P. D. O., Dhareshear, A. M., Bhandari, A. and Tsunokawa, K. (1987) *The Highway Design and Maintenance Standards Model*, The John Hopking University Press, Baltimore.

## Appendix A

### Details of the formulation and procedure of the proposed clustering method

#### 1. Measuring the similarity according to the continuous value

Objects in a cluster are similar rather than identical. If some difference in the values of a given attribute is within the tolerance value, they should be clustered into the same cluster; this refers to the tolerance indiscernibility relation (d'Amato, 2004, Nieimen, 1998). The degree of the indiscernibility can be calculated by the following equation:

$$De\_Ind_a(x, y) = \frac{\max(0, \min(\rho_x(a), \rho_y(a)) + Th_a - \max(\rho_x(a), \rho_y(a)))}{Th_a} \quad (\text{A1})$$

$$x \in X, \quad y \in X, \quad a \in A \text{ and } Th_a > 0$$

Where,  $Th_a$  is the tolerance value determined subjectively (e.g. expert judgment), and  $De\_Ind_a(x, y)$  is the degree of indiscernibility between objects  $x, y$  with respect to the value of attribute  $a$ , then the similarity or  $Sim_a(x, y)$  between two objects or  $x, y$  with respect to the value of attribute  $a$  is calculated by following equation:

$$Sim_a(x, y) = \begin{cases} 0 \text{ (false)} & \text{if } 0 \leq De\_Ind_a(x, y) < F_a \\ 1 \text{ (true)} & \text{if } F_a \leq De\_Ind_a(x, y) \end{cases} \quad (\text{A2})$$

$$x \neq y, \quad x \in X, \quad y \in X, \quad a \in A$$

Where,  $F_a$  denotes the degree of freedom (determined subjectively).

#### 2. Measuring the similarity between projects

Hamming distance is a widely used similarity measuring approach for nominal attributes (Hamming, 1950). This model uses a modified Humming distance formulation, which is the combination of tolerance function and Humming distance to measure the similarity between asset objects as follows:

$$d_H(x, y) = \frac{1}{p} \sum_{i=1}^p \delta(\rho_x(a_i), \rho_y(a_i))$$

$$\delta(\rho_x(a_i), \rho_y(a_i)) = \begin{cases} 1 & \text{if } \rho_x(a_i) = \rho_y(a_i), \quad a_i \in A_N \\ 1 & \text{if } Sim_{a_i}(x, y) = 1 \quad a_i \in A_V \\ 0 & \text{otherwise} \end{cases} \quad (\text{A3})$$

$$x \in X, \quad y \in X$$

$$A_N \in A, \quad A_V \in A \text{ and } A \cap B = \emptyset$$

Where,  $d_H(x, y)$  is the tolerance Humming distance between object  $x$  and  $y$ .  $\rho_x(a_i)$  denotes  $i^{th}$  attribute's value of object  $x$ ;  $\rho_y(a_i)$  denotes  $i^{th}$  attribute's value of object  $y$ ;  $p$  is the total attribute of each object in the table;  $A_N$  denotes the subset of nominal attributes on the set  $A$ ;  $A_V$  denotes subset of number attributes. The tolerance equivalence function  $Sim_{ai}(x, y)$  refers to Equation A1.

### 3. Measuring the similarity between clusters

After the above similarity analysis, the objects in each class will be clustered into clusters or the up approximation sets  $(R(R_1, R_2, \dots, R_n))$ , but their boundaries are not clearly defined, they may overlap each other. Further merging operation and reassigning elements among clusters are needed based on the concept of rough approximation.

Let  $R_i \in R$  and  $R_j \in R$ , and  $R \in U_c$  (classified class in according to core attribute), the similarity of  $R_i$  to other cluster  $R_j$  is given by following rough inclusion function (Pawlak and Skowron, 2007):

$$Sim_R(R_i, R_j) = \frac{card(R_i \cap R_j)}{Card(R_i)} \quad \begin{matrix} R_i \neq \phi \\ i \neq j \end{matrix} \quad (A4)$$

The new approximation of each the first equivalences  $R_i$  with the similarity threshold value  $Th_b$  is given by the following equation:

$$\tilde{R}_i(x_i) = \left\{ x_j \mid x_j \in \bigcup \left\{ x_j \mid Sim_R(R_i, R_j) \geq Th_b \right\} \right\} \quad (A5)$$

$$\forall i, j \quad 1 \leq i \leq n-1, \quad i+1 < j \leq n$$

To describe in words: if upper approximation  $R_i$  is similar to  $R_j$  ( $Sim_R(R_i, R_j) \geq Th_b$ ), then replace the elements of  $R_i$  by the union of elements of all similar  $R_j$ .

This approximating are repeated until no changes occur in each approximation set.