Application of System Dynamics to Pavement Maintenance Optimisation

Keith T Linard

Senior Lecturer, University of New South Wales, AUSTRALIA
(Australian Defence Force Academy)
k-linard@adfa.edu.au

ABSTRACT: *Most pavement maintenance management systems tend to be either non-analytical databases or statistical correlation models. However, pavement maintenance is part of a complex system (comprising the road pavement, the environment, diverse users, the maintenance authority and Local/State/Federal Governments) that has significant feedbacks, making it a suitable field for system dynamics enquiry.*

This paper discusses a system dynamics based pavement management model developed at the Australian Defence Force Academy. The paper discusses briefly the extension of this model to incorporate political feedback and also system optimisation using genetic algorithm techniques.

Keywords: Pavement maintenance management; pavement life cycle costing; transport economics; economic evaluation; system dynamics; genetic algorithm optimisation.

INTRODUCTION

With the public sector reforms of the past decade, Road Authorities have had major functions trimmed, outsourced or simply chopped. Probably more than most areas of Government, road asset managers are being required to work 'smarter'. The 'outsourcees', road maintenance companies, are under a twin squeeze - to win maintenance management contracts in a very competitive environment and to satisfy shareholders concerned with return on investment. Both road asset managers and maintenance contractors require tools to assist in 'whole-of-life' cost optimisation in respect of road maintenance.

Over the past two decades two approaches to computer based pavement management system (PMS) have gained widespread use. The first approach is a database PMS, which catalogues the current state of pavements and facilitates budget decision-making. The database PMS has no predictive capability, provides no guidance on alternative policy levers and little guidance on the implications of choices. The second approach utilises sophisticated statistical correlation modelling based on data relating to diverse factors including pavement type, environment, vehicle loadings, vehicle usage, maintenance and rehabilitation patterns. The World Bank's HDM-III model set the conceptual pattern for this approach (Hoban 1988). These models are applied in a predictive sense, based on the assumption that the identified correlations will persist into the future. They are widely used for highway planning and top level budgetary planning but, despite urging from Federal Government agencies (BTE 1990), have found little favour at the Local Government level, where database PMS are more common.

Particularly at Local Government level, politics is important, alongside economics and pavement engineering, when issues of pavement conditions arise. This focuses attention on another set of stakeholders, the road users, whose input to the maintenance decision process operates within the much fuzzier and qualitative political environment, and whose desire for quality roads is balanced by their desire for other public goods and/or lower taxes. 'Hard systems' operational research tools, such as HDM-III, are not suited to this environment.

There is a need for analytical and decision support tools for road asset managers which can address both the 'hard' quantitative dimensions and the 'soft' qualitative dimensions. This is a focus of the system dynamics modelling research at ADFA.

OF HARD SYSTEMS, SOFT SYSTEMS AND SYSTEM DYNAMICS …

Within the diverse systems disciplines the distinction between 'hard' and 'soft' systems is important to the understanding the value added of system dynamics modelling techniques.

Hard systems are characterised by:

- clear and unambiguous objectives;
- widespread agreement with the objectives;
- high degree of agreements on the facts; and
- high degree of knowledge concerning the principles of operation.

In such situations the technical decision paradigm is optimisation and traditional operations research techniques have a good track record in such contexts.

Soft systems, on the other hand are characterised by:

- multiple objectives which may be fuzzy or conflicting;
- multiple stakeholders who may have multiple and/or conflicting interests;
- no clear agreement on the objectives; and
- complex inter-relationships between system elements which may not be well understood or which may even be subject to dispute between competent professionals.

In soft systems, human rather than technical issues dominate, and *the paradigm is one of mutual learning between client, project team and diverse stakeholders*. An example of a soft systems problem would be that of urban accessibility. To the highway engineer a freeway may seem an obvious solution. Some house owners might agree, at least when caught in peak hour traffic … provided the road is located in someone else's backyard. Others may be concerned about environmental issues and support public transport solutions. Yet others may consider the problem to be one of work place location - bring the jobs to the people rather than vice versa. Whilst economists might argue that the 'real problem' is the lack of an appropriate road pricing strategy.

ROAD MAINTENANCE AND SYSTEM DYNAMICS

At first glance, the maintenance of roads might seem to be a classic 'hard system'

- the objectives are clear and unambiguous - *pavements should be safe & smooth*;
- there is widespread agreement with the objectives - *there is no 'pothole protection society' or 'save the roughness' campaign;*
- high degree of agreements on the facts - *both engineers and the public can agree on what constitutes a rough driving surface, and understand that maintenance reduces roughness;* and
- high degree of knowledge concerning the principles of operation - *at the least, this is one field where the public will defer to engineering competence.*

However, it's not that simple. Pavement roughness is the consequence, inter alia, of trade-offs between routine maintenance decisions, pavement reconstruction, as well as decisions relating to overall network investment, which influences traffic intensity on particular road links. Each of these areas is subject to political debate at all levels of Government. Investment decisions in road system development, maintenance and rehabilitation based on short term budgetary considerations can have very significant implications for diverse social goals, especially in the rural Local Government sphere (NAASRA 1984).

System dynamics is particularly useful in understanding the linkages between the qualitative and the quantitative aspects of road asset management. System dynamics modelling employs a set of techniques that allow both quantitative and a realistic representation of variables that are typically perceived to be qualitative.

The development of the initial system dynamics road maintenance model

Preliminary work on the application of system dynamics modelling to road maintenance management was undertaken by the author in the early 1990's at ADFA. The current model grew out of joint research with the Australian Road Research Board (ARRB) aimed at developing an EXCEL spreadsheet based life-cycle costing decision support tool. More specifically it grew out of two concerns.

First, whilst the client specified the use of EXCEL spreadsheet, the complexity of the spreadsheet structure made it yet another 'black box' … it appeared so complex that visibility of assumptions and relationships was lost and client confidence in the resultant output was problematic.

Secondly, the model did not readily permit the introduction of more qualitative (political) feedback resulting from resource allocation decisions.

Structure of the model

The Powersim model is in five parts:

- a roughness progression module;
- a rehabilitation module, (a function of periodic reconstruction);
- a vehicle operating costs module;
- a net present value module; and
- political feedback module.

The technical engineering part of the model does not purport to introduce any new insights into the engineering relationships. These are totally based on ARRB research into roughness and vehicle operating costs (Martin 1995). However, as discussed below, an early fruit of the modelling was uncovering a flaw in the econometric modelling in published ARRB research. The political feedback module is still highly speculative at this stage, based on student research with one rural Shire council (Jackson 1997). It is only touched on briefly in his paper.

<u>Key User Definable Parameter</u>

Discount rate (% per annum, typically in range 6% - 12%)

<u>Other Parameters Which User Can Fine Tune</u>

Av AADT (annual average daily traffic)
% Heavy Vehicles
Initial SNCo (pavement strength parameter))
Initial Ro (road roughness parameter)
AvR_PCo (road roughness post rehabilitation work)
QCF (regional road work quality control factor)
Av Thornthwaite Factor (climatic / soils parameter)
Av Rise & Fall (of road in metre / kilometre)
Av Curvature (of road in degrees / kilometre)
Max annual rehabilitation expenditure (policy and planning parameter)
Max annual maintenance expenditure (policy and planning parameter)
Max road roughness (policy parameter, impacting on user satisfaction and hence on political feedback)

The model in Figure 1 incorporates a full economic evaluation capability and, through the use of arrays (the double line around the stocks and auxiliaries denote array variables) addresses up to 400 road segments.

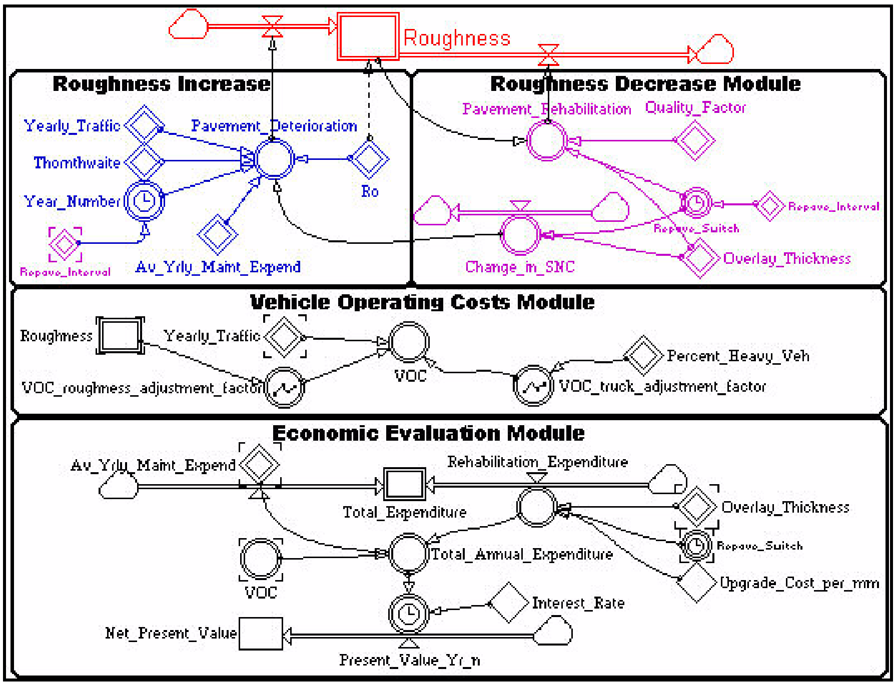

Figure 1: System Dynamics Pavement Maintenance Model Structure

Initial data input is via dynamic data exchange (DDE) linkage with a road maintenance database built in EXCEL spreadsheet. This has the advantage of being able to utilise existing data systems which are common in Local Government. Output from a simulation can similarly be transferred to a database PMS.

The model has a user friendly ‘front-end’ to allow for ‘what if’ analyses of alternative maintenance strategies, for example, lower annual maintenance plus more frequent major rehabilitation versus high annual maintenance and less frequent rehabilitation. This is illustrated in Figure 2.

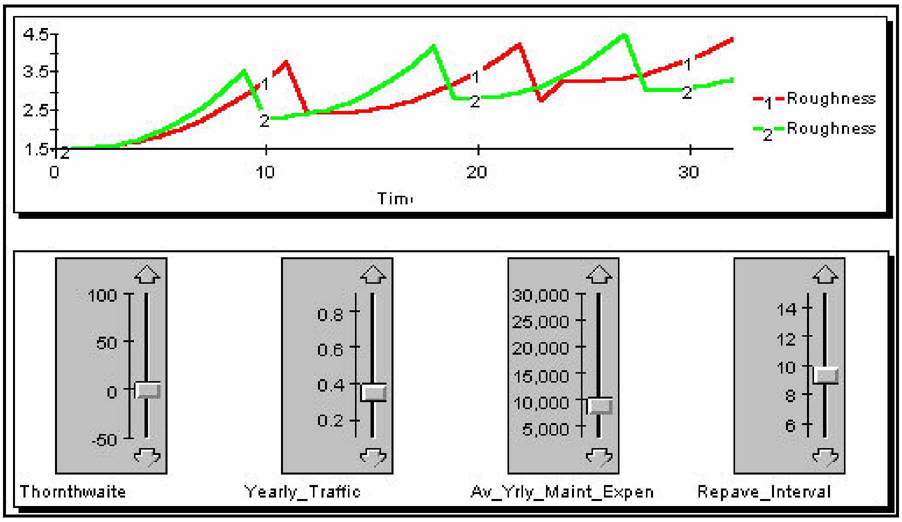

Figure 2: User friendly front-end for sensitivity analysis

Other output reports include Net Present Value results and a 'Political Sensitivity Index', the latter based on the judgement of Local Government staff (Jackson 1977) about the level of complaints from rate payers for given levels of road roughness. One finding from using the model with Local Government staff was that economic evaluation seems to be less significant than using road maintenance expenditure as a counter-cyclical measure. That is, road expenditure tends to be used to address seasonal unemployment. This further emphasised the 'soft' nature of the problem, and is guiding further development of the model as a broader social planning tool.

Identification of Errors in Published Econometric Modelling

The initial model was built using relationships from published ARRB econometric studies. The model, depicted in Figure 3, produced plausible results when run within normal limits. However, extreme conditions tests produced 'impossible' results. The stock-flow diagram below immediately made visible a fallacy in model structure not been picked up by the referees of the ARRB research or by its many subsequent professional users. Translating the fruits of the econometric modelling to system dynamics terminology, road structural number (SNC), a representation of the pavement strength, was a stock with an inflow but no outflow. This implied that road strength increased with each reconstruction without limit, somewhat in conflict with soils science! This led to a revision and reissue of the relevant ARRB research report.

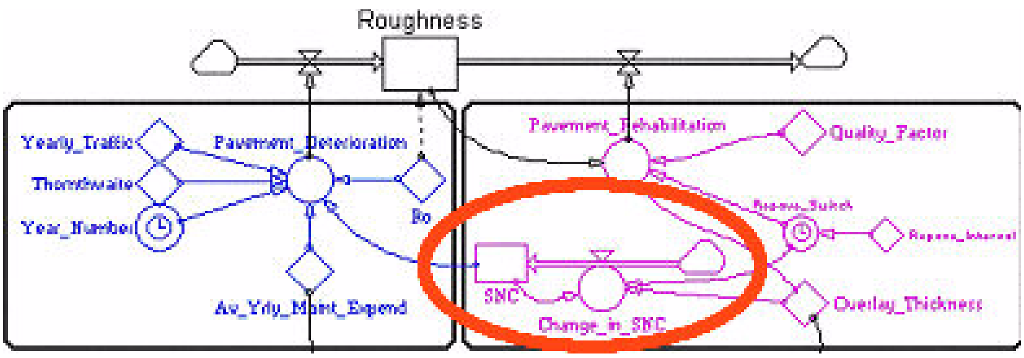

Figure 3: Initial maintenance model structure

Overview of Optimisation

Given the number of input variables and the range of possible values, 'what-if' analysis has only limited value for analysing maintenance strategies across networks. Effectively there are an infinite number of positions for the various decision levers, with no intuitive way of getting "good" initial settings. In such situations, some form of optimisation capability is essential; even if all that can be claimed is that the resultant "optimum" is simply a good place to start "what-ifing".

The genetic algorithm search procedure, which is now integrated into the Powersim system dynamics software, is based (conceptually) on the Darwinian principles of survival of the fittest. Optimisation is achieved through the emulation of biological evolution, and terms such as population, reproduction, genes, chromosomes, and mutation have been borrowed from this natural process to describe the genetic algorithm method.

The algorithm initially generates a population consisting of a predefined (user declared) number of randomly generated solutions. The 'altitudes' ('z' coordinate value) of each possible solution are compared, with those solutions that have higher altitudes (that is, 'fitter' solutions), retained for the recombination process. Recombination involves the random pairing of these retained solutions. Each pair then exchanges 'x' or 'y' coordinate values (known as the crossover process) to produce another two sets of coordinates. In this way, the original pair are considered to be parents and the newly generated coordinate sets are the children or offspring. The new generation formed by the children from each of the mating pairs is then assessed for fitness and manipulated in the same way that their parents were. This process continues for a fixed number of iterations or until a certain tolerance within the desired outcome is achieved (as defined by the user).

Applying genetic algorithms to the optimisation of maintenance outlays

In the road maintenance optimisation problem, the optimisation objective is to identify the maintenance strategies which minimise the Net Present Value (NPV) for the road system. The principle decision levers available in the model to achieve this are:

- Average annual maintenance expenditure per lane km
  - ⇒ Expenditure may vary (realistically) from $300 to $30,000
- Average rehabilitation interval
  - ⇒ Interval may range from 8 to 16 years
- Average rehabilitation thickness
  - ⇒ Thickness may range from 20mm to 100mm

In addition there are a variety of constraints, including upper limits on the amount of road expenditure per road category and aggregate overall expenditure.

The algorithm selects an initial population consisting of randomly generated values for the range variables. The Powersim model then runs and the objective function values (ie NPV) resulting from the initial set of population members is determined and returned to the genetic algorithm. After a number of iterations, the genetic algorithm determines the fittest members of the initial population in accordance with how close the resulting objective functions are to the desired objective function. Offspring are generated. These offspring then form the new population of range variables. When the specified stopping criteria have been met, the genetic algorithm returns the values of range variables, which best achieved the desired objective function (maximum NPV). The entire process is shown schematically in Figure 4.

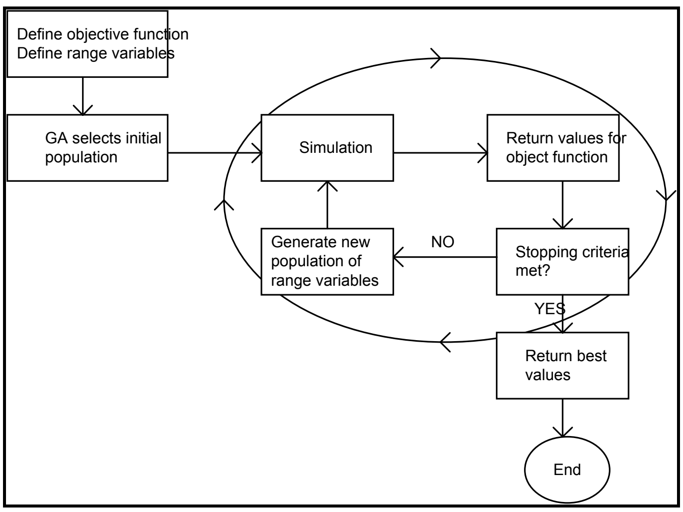

Figure 4: Genetic Algorithm Optimisation Process

The output of the optimisation process is a schedule which suggests, for each road segment, the average annual maintenance expenditure, the average number of years to next reconstruction and the degree of reconstruction. Given the many simplifications in the model this "optimum" is simply to be viewed as a good group of parameter settings from which to start further what-if analysis.

Model Limitations

At present the model generates a "user barometer", a crude indicator of satisfaction by rural Local Government ratepayers of their road system. This is simply based on a 10 point scale developed in one rural Shire. This political feedback is presented to the user along with net present value data. Further research is clearly required to refine such a measure.

A second shortcoming is that, especially in rural Local Government, work programming in practice takes account of location. Thus road maintenance may be done on a lower priority road, simply because the maintenance gang is in that locality. Resolution of this shortcoming in the model is being examined.

CONCLUSIONS

This paper has discussed the application of two new technologies to the management of the road maintenance asset, system dynamics modelling and genetic algorithm optimisation. From the work thus far the following advantages can be claimed for SDM over more traditional statistical correlation modelling:

- The graphical interface makes apparent the relationships between key variables (this was instrumental in identifying a major mistake in published research);
- "Soft" (qualitative) data, which is important in the decision making, can be readily incorporated into the model;
- The model readily integrates with database type pavement management systems, significantly enhancing their potential for scenario analysis;
- The genetic algorithm optimisation capability of the Powersim software enables the user to have confidence in identifying "good plausible settings" of the model parameters, from which subsequent "what-if" analysis can proceed.

Further work is required into:

- incorporation of qualitative 'social and political' feedback mechanisms;
- incorporation of work practice parameters into the prioritisation function.

REFERENCES

BTE (1990), Pavement Management: Development of a Life Cycle Costing Technique. Bureau of Transport Economics Occasional Paper 100, AGPS, Canberra.

Cumming, IR (1991), Relevance of System Dynamics Modelling to Road Pavement Maintenance. MEngSc Project Report, University of New South Wales (ADFA).

Hoban, C (1988), The Highway Design and Maintenance Model HDM-III: An Introduction. Australian Road Research Board 14th Conference.

Jackson, J. (1997), A Predictive Pavement Management System for an Urban Road Network. Thesis submitted for 4th Year Bachelor of Civil Engineering Degree, University of New South Wales.

Martin, Tim (1995), An Assessment of the Influence of Maintenance Expenditure on Arterial Road Conditions (Working Paper), Australian Road Research Board.

NAASRA (1984), The NAASRA Roads Study – 1984 Report of the Australian Road Network, National Association of Australian State Road Authorities.