Advances in Computational & Experimental Engineering & Science

Life-Cycle Cost Analysis System for Infrastructure Management

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Summary

Life cycle cost analysis (LCCA) is a key component of the infrastructure management process, and it is used extensively to support network-level and project-level decisions. This paper presents an infrastructure LCCA system called **L**ife**CCA**S (Life-Cycle Costs Analysis System) that can consider construction costs, maintenance and rehabilitation costs, user costs, and the residual value of infrastructures. The LCCA system uses genetic algorithms to support infrastructure management decisions.

Infrastructure Management Systems

Public and private agencies have always tried to maintain their infrastructure assets in good and serviceable condition at a minimum cost; therefore, they practiced infrastructure management. However, as most of the nation's infrastructure systems reached maturity and the demands placed on them started to rapidly increase in the mid-1960s, infrastructure agencies started to focus on a systems approach for infrastructure management. This process has lead to today's Asset Management concept. The process started with the development of pavement management systems (PMS), continued with bridge management systems (BMS) and infrastructure management systems (IMS), and has recently evolved into asset management[1,2]. One milestone in the development of engineering management systems is the concept of integrated infrastructure management systems. An infrastructure management system is defined as the operational package that enables the systematic, coordinated planning and programming of investments or expenditures, design, construction, maintenance, rehabilitation, renovation, operation, and in-service evaluation of physical facilities. The system includes methods, procedures, data, software, policies, and decision means necessary for providing and maintaining infrastructure at a level of service acceptable to the public or owners.

Many infrastructure management agencies conduct mathematical optimization to generate programs and budgets that are consistent with their performance goals and financial constrains. Linear programming is the most commonly used technique. Nonlinear, integer, dynamic, and multicriteria programming have also been used[3]. In particular, genetic algorithms provide an efficient heuristic for finding "good" solutions for difficult optimization problems (such as those dealt with in pavement management). This technique has been used for pavement management project-level analysis[4],

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network-level pavement maintenance and rehabilitation programming[5,6], bridge deck rehabilitation projects selection[7], and bridge maintenance optimization[8]. Genetic algorithms are particularly efficient for finding optimum or, at least, near-optimum solutions in large solution spaces, whose size is beyond the capability of mathematical optimization techniques.

Life-cycle cost analysis is a decision-support tool commonly used to account for all costs associated with a certain investment. The Federal Highway Administration (FHWA) has encouraged and, in some cases, mandated the use of LCCA in analyzing all major investment decisions mainly at the project level[9]. LCCA has been used for several different types of infrastructure assets. For example, it was used for building structures with the objective of minimizing maintenance costs under such conditions as carbonation should not reach reinforcing steel until the end of service life and constraints of budget and service life[10]. It was also used for evaluating different maintenance strategies for building walls with service life periods of 35 and 60 years[11].

Infrastructure Life-Cycle Costs Analysis System

This paper presents an infrastructure LCCA system called **L**ife**CCA**S (Life-Cycle Costs Analysis System). The system has been implemented in a computer program. To conduct an LCCA analysis, the infrastructure manager must define and load all the components of the system (Figure 1), the objective of the analysis, the data and the models about the infrastructure components, and the constraints that the system must guarantee. The results of the system's application to a set of infrastructure assets are the "optimal" maintenance and rehabilitation (M&R) program, the corresponding costs throughout the life of the facility, and the predicted structural and functional quality of the various infrastructure assets.

Case Study

To illustrate the application of the **L**ife**CCA**S system, it was applied to the road network of Coimbra, which consists of 254 sections. In this example, the objective is to determine an M&R strategy that minimizes the total discounted costs involved in the M&R actions carried out in the pavements of a given road network over a given planning time-span, while keeping pavements above given quality standards. **L**ife**CCA**S applies all the treatments specified at different times and selects the combination of M&R projects that minimizes the total transportation cost using genetic algorithms. Pavement sections are the decision-making units to which M&R actions apply. For the definition of long-term (20-year) M&R strategies for all the pavements of the road network, three different M&R policies were considered:

- Policy I: corrective-only policy involving the simplest M&R actions;
- Policy II: agency costs optimization approach (corrective-preventive) involving all possible M&R actions;

- Policy III: total costs (agency costs, user costs and residual value of pavements) optimization approach (corrective-preventive) involving all possible M&R actions.

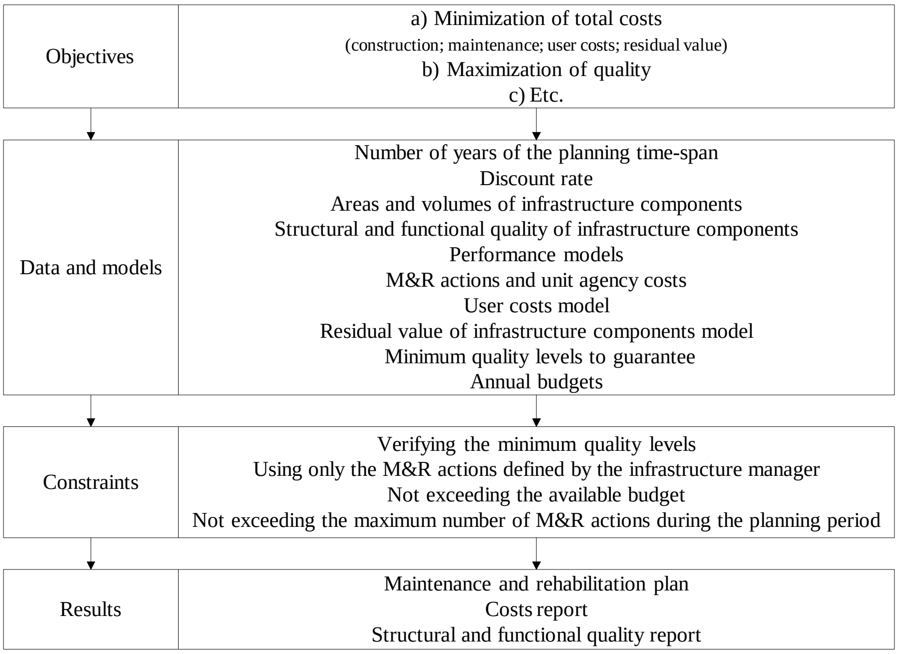

Figure 1 – LifeCCAS components

The pavement performance model used in this example is the one used in the AASHTO flexible pavement design method[12]. This design method for pavement structures is the most widely used in North America and is probably the most widely used in the world[13]. The basic design equation used for flexible pavements is formulated as follows[12]:

$$\log_{10}(W_{18_t}) = Z_R \times S_0 + 9.36 \times \log_{10}(SN_t + 1) - 0.20 + \frac{\log_{10}\left[\dfrac{\Delta PSI_t}{4.2 - 1.5}\right]}{0.40 + \dfrac{1094}{(SN_t + 1)^{5.19}}} + \quad (1)$$

$$+ 2.32 \times \log_{10}(M_{R_t}) - 8.07$$

Where: W_{18} is the number of 18-kip equivalent single axle load applications estimated for a selected design period and design lane; Z_R is the standard normal deviate; S_0 is the combined standard error of the traffic prediction and performance prediction; ΔPSI is the difference between the initial or present serviceability index (P_0) and the terminal serviceability index (P_t); SN_t is the structural number indicative of the total required pavement thickness and is given by equation (2); M_R is the subgrade resilient modulus (pounds per square inch); C_n^e is the structural coefficient of layer n; C_n^d is the drainage coefficient of layer n; and H_n is the thickness of layer n (mm).

$$SN_t = \sum_{n=1}^{N} H_n \times C_n^e \times C_n^d \tag{2}$$

In this study, vehicle operation costs and the residual value of pavements were calculated using equation (3) and equation (4), respectively.

$$VOC_t = 0.39904 - 0.03871 \cdot PSI_t + 0.00709 \cdot PSI_t^2 - 0.00042 \cdot PSI_t^3 \tag{3}$$

$$V_{s,T+1} = C_{s,rehab} \cdot \frac{PSI_{s,T+1} - 2.5}{PSI_{s,rehab} - 2.5} \tag{4}$$

Where: $C_{s,rehab}$ is the cost of the last rehabilitation action applied in pavement section s; $PSI_{s,rehab}$ is the PSI value after the application of the rehabilitation action in pavement section s.

Part of the results obtained with the application of the **L**ife**CCA**S system is summarized in Table 2 and Figure 2, only for pavement section number 26. This road section has the following attributes: length = 1000 m; width = 10 m; sub-grade CBR = 10%; thickness of bound layers = 0.25 m; thickness of granular layer = 0.20 m; structural number = 4.4; age of pavements = 4; annual average daily traffic = 3000; annual average daily heavy traffic = 300; annual growth average tax = 0.02; truck factor = 3.0; PSI = 3.76.

For example, if policy I was adopted, the first intervention on the section would only occur in planning year 6 (because the warning level for the PSI, the value 2.5, would be reached this year), and would consist of M&R action 2. If policy III was adopted, the first intervention would be heavier (M&R action 3 instead of 2) and would be applied earlier (planning year 5 instead of 6). Following the preventive application of M&R action 3, no intervention would be needed on the section in the next thirteen years. Figure 2 describes the evolution of PSI in the same pavement section as a consequence of the M&R actions applied there.

Table 2 – M&R actions for pavement section 26 under policies I, II and III

Policy	PSI_0	Year																			
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
I	3.76	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	2	1	1
II	3.76	1	1	1	1	1	1	4	1	1	1	1	1	1	1	1	1	1	1	1	1
III	3.76	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	2

Legend: 1 - Routine maintenance; 2 - Asphalt concrete layer (5 cm);
3 - Two asphalt concrete layers (5+5 cm); 4 - Two asphalt concrete layers (5+8 cm)

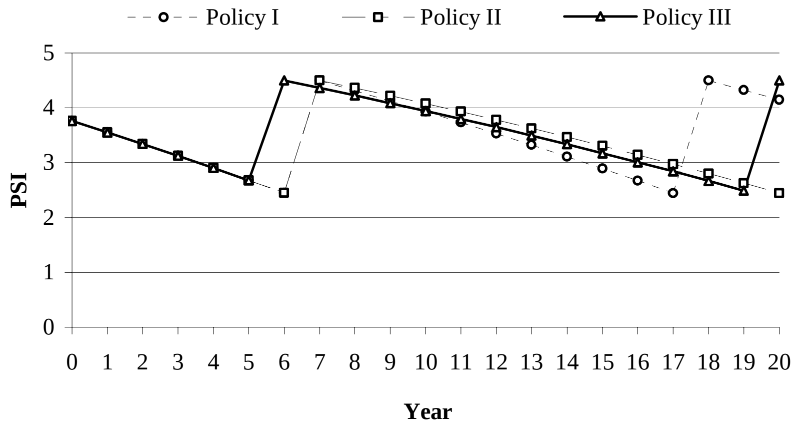

Figure 2 – Evolution of PSI for pavement section 26 under policies I, II and III

Conclusions

The applications presented in this paper show that genetic algorithms provide a very efficient heuristic for optimizing the M&R program for a network of pavements. Planned enhancements for the **L**ife**CCA**S system include the incorporation of other user costs, the potential use of other soft computing techniques, and its application to other types of infrastructures assets. The use of consistent LCCA procedures for different kinds of infrastructure assets (e.g., pavements, bridges, signs, and tunnels) is expected to greatly facilitate the holistic integration of the decision-making process for asset management.

Acknowledgments

The writers are grateful to Fundação para a Ciência e a Tecnologia for the financial support provided to this study through Grant POCTI/ECM/46461/2002, ‘‘A Deterministic Segment-Linked Pavement Management System.’’

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