Implementing Innovative Ideas in Structural Engineering and Project Management
Edited by Saha, S., Zhang, Y., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-1-7

ASSET LEVELS OF SERVICE-BASED DECISION SUPPORT SYSTEM FOR MUNICIPAL INFRASTRUCTURE INVESTMENT: A FRAMEWORK

VISHAL SHARMA[1] and MOHAMED AL-HUSSEIN[2]

[1]*Northern Alberta Institute of Technology (NAIT), Edmonton, Canada*
[2]*Hole School of Construction, University of Alberta, Edmonton, Canada*

The most significant challenge facing municipalities today is a shortage of funds required to upgrade or expand aging infrastructure. A chronic lack of funding impairs a municipality's ability to maintain desired infrastructure levels of service. Over the last decade, municipalities in Canada have faced the pressures of increased complexities in infrastructure asset management decision making, which to some extent is attributed to cost escalation, increasing demand, and interdependencies between infrastructure networks. This paper presents a framework to develop an asset levels of service (ALOS)-based decision support system for municipal infrastructure funding investments. This paper focuses primarily on the allocation of funds in the maintenance, rehabilitation, and repair (MR&R) of municipal networks based on ALOS, future demand, and network interdependencies.

Keywords: Utility functions, Multiobjective analysis, Analytical techniques, ALOS, MR&R, Municipal networks.

1 INTRODUCTION

Municipal infrastructure inventory includes “the physical assets developed and used by a municipality to support its community’s social and economic activities” (City of Edmonton 2006). In any municipality, typical infrastructure assets are found in transportation networks (e.g., roads, bridges, walkways, and transit), protection services (e.g., fire, police and emergency medical services), community services (e.g., parks, recreation, cultural and community services, and amenities), general government services (e.g., civic buildings, and information technology), and utility networks (e.g., water supply, sanitary sewerage, storm drainage, flood control, and solid-waste management).

Although asset management systems have existed for decades (Golabi et al. 1982, Thompson et al. 1987), the infrastructure deficit, defined as the difference between existing funding and required funding to maintain the network levels of service (LOS) at optimum or expected levels, has emerged as one of the major challenges to infrastructure management in Canada and worldwide. Traditionally, infrastructure decision making has been undertaken by cost-benefit analyses (Georgi 1973, Loucks et al. 1981, Taylor et al. 1992), but the vulnerability of this approach becomes obvious when non-tangible benefits are measured. Today's infrastructure networks create new and complex patterns of interaction among each other as well as with the natural systems they affect (Allenby 2004). This interaction is such that the degree of a network's maintenance and rehabilitation will have a significant effect on the performance of the dependent networks.

Users play an integral role in determining the asset levels of service (ALOS) of infrastructure networks. The objective of this paper is to present the framework for a web-based ALOS-based decision support system, known as OPTIsys, which provides the basis of optimal resource allocation for the maintenance, repair, and rehabilitation (MR&R) of transportation networks. It also accounts for any increase in the utility of ALOS, network interdependencies, and future growth. The research methodology can be modified and used for investment decision making with respect to other municipal infrastructure networks – such as water supply, sanitary sewage and waste management. Application of OPTIsys will be demonstrated for optimal resource allocation in the MR&R of urban roads in this paper. The research methodology has been implemented in the following four phases:

2 QUANTIFICATION OF ASSET LEVELS OF SERVICE (ALOS)

ALOS can be defined as the integration of the LOS for all users of a given asset. For example, taking an urban road as an asset, ALOS will represent the cumulative expected LOS for vehicle users, bicyclists, and pedestrians. LOS is represented as an index that measures the quality of service provided by an infrastructure network (FCM and NRC 2003). The challenge lies in reaching integrated LOS, or ALOS, which can be used in the decision-making process due to user interdependencies and the selection of appropriate quantitative techniques (Sharma et al. 2008).

To determine the ALOS, proposed methodology uses a combination of quantitative and qualitative tools. Quantitative parameters impacting the ALOS have been captured by use of empirical models. Qualitative parameters such as user's willingness to pay, safety and environmental acceptability are captured using tools such as Analytical Hierarchy Process (AHP).

The ALOS quantification process begins with the study and analysis of existing LOS determination models for the selected infrastructure network (in this case, urban road networks). The objective is to identify suitable LOS-determination models that can be adapted to a particular municipal network context with minimal changes. Expert and user input were obtained, in the context of the City of Edmonton, and coupled with data from the literature review to identify the qualitative factors affecting ALOS. AHP was then used to quantify the impact of the identified qualitative factors on the ALOS. The outcome of this research phase yielded a single-index ALOS which accounted for the aggregated LOS for various users of the network. Detailed methodology and example of ALOS calculation for urban road networks has been presented in Sharma et al. (2008). The quantified ALOS value from this phase has been incorporated into OPTIsys for optimal funding allocation.

3 ASSESSMENT OF MULTIATTRIBUTE UTILITY FUNCTIONS FOR INVESTMENT DECISIONS

Each MR&R decision impacts the ALOS of the assets. When making decisions about MR&R, the increase in the utility of ALOS is a more relevant measure than the absolute change in ALOS. For example, the overlay of road surfaces will have more utility or value if applied to a road with a poor roughness index as opposed to a road with a good roughness index. Phase II involves the application of the multiattribute utility theory to quantify the multiattribute utility of investment decision.

The methodology involves the identification of interdependencies, and attributes affecting the multiattribute utility. Attributes included in this research are: (1) increase in ALOS; (2) the physical deterioration of an asset; (3) future demands on an asset; and (4) the improvement of dependent infrastructures (in this case emergency medical services). An utility function is derived for each attribute affecting the impact factors listed above. AHP is used to decide the relative importance of each utility function while considering the impact of interdependencies between the attributes. Based on workshops with City of Edmonton personnel, multiattribute-utility of Asset Levels of Service (U-ALOS) has been calculated for urban roads, which is given by Eq. (1):

$$\text{U-ALOS} = 0.332u(\text{ALOS}) + 0.214u(\text{NHG}) + 0.31u(\text{IRI}) + 0.141u(\text{EMS}) \qquad (1)$$

Where:

(1) U-ALOS = Multiattribute Utility of Asset Levels of Service of the road section due to given MR&R treatment;

(2) u(ALOS) = Utility of increased Asset Levels of service of the road section due to given MR&R treatment;

(3) u(NGR) = Utility change of a road section due to projected future neighborhood growth rate of area where the road section is located;

(4) u(IRI) = Utility of increased International Roughness Index of the road section due to given MR&R treatment;

(5) u(EMS) = Utility of increased Emergency Services rating of the road section due to given MR&R treatment.

4 MULTIOBJECTIVE DECISION MODEL FORMULATION AND OPTIMIZATION

Infrastructure MR&R funding allocation decision making is multiobjective in nature. Decisions are based on multiple and often competing objectives. This phase involveed the development of a multiobjective funding allocation model. To determine the relative importance of the objective functions, the AHP method was employed. Genetic algorithms were then used to solve the multiobjective optimization model.

The model incorporated two time-periods: analysis period, and planning (or budget) period. The analysis period represents the number of years for which the selected road sections are evaluated. The planning period is the number of years the budget or resources are available. Let $\mathbf{B} = \{B_1, B_2, ...B_{t'} ..., B_T\}$ be the set of budgets available during the planning or budget period *(1,2,…t',…T')* which can be allocated to a vector of candidates **(x)**. Let **P** = {*1,2,…,p,…,P*} be the P-dimensional vector of treatments which can be applied to the road sections **(x)**.

4.1 Objective 1: Maximization of the Multiattribute Utility of Investment

$$\text{Max } Z_1(\mathbf{x}) = \sum_{i=1}^{n}\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{t'=1}^{T'} \text{MAU-ID}_{ipt}\ \alpha_{ipt'} \tag{2}$$

Subject to the following constraints:

(1) Multiattribute Utility of the investment decision should lie between 0 and 1 (i.e. $0 \leq \text{MAU-ID}_{ipt} \leq 1$)

(2) The minimum acceptable value for ALOS is 4.5 (i.e., $ALOS \leq 4.5$)

Where:

(1) MAU-ID_{ipt} is multiattribute utility of applying the treatment (maintenance or repair) *p* to x_i candidate in time period *t*; *i = 1,2,…,n; p = 1,2,…,P; t = 1,2,…,T;*

(2) $\alpha_{ipt'}$ = 0 or 1 for every treatment (maintenance or repair) *p = 1,2,…,P* applied project x_i; *i = 1,2,…, n* in time period *t' = 1,2,…,T'.*

The utility of any selected treatment, MAU-ID_{ipt}, will decrease over the analysis period due to physical deterioration based on Eq. (4).

4.2 Objective 2: Minimization of Budget Idleness (or Maximization of Budget Utilization)

After normalization, the second objective function, Z2, can be expressed as:

$$\text{Max } Z_2(\mathbf{x}) = \sum_{t'=1}^{T'} \frac{\sum_{i=1}^{n}\sum_{p=1}^{P} a_{ipt'}\alpha_{ipt'}}{B_{t'}}, \tag{3}$$

Where:

(1) $a_{ipt'}$ = the cost incurred on road section *(i)* due to selection of treatment *(p)* in the year *t'*;

(2) $\alpha_{ipt'}$ = 0 or 1 for every treatment *(p)* applied to candidate (x_i) in the time period *t'*;

(3) $B_{t'}$ = the amount of budget available in the year *t'*, for *i = 1,2,…,n; p = 1,2,…,P; t' = 1,2,…,T'.*

Subject to the following constraints:

(1) The total amount of the available budget should be greater than or equal to the total amount of the allocated budget: $\sum_{t'=1}^{T}\left(B' - \sum_{i=1}^{n}\sum_{p=1}^{P} a_{ipt'} \cdot \alpha_{ipt'}\right) \geq 0$

(2) Non-negativity constraint for every project *i*, resource *k* and time period *t'*: $a_{ikt'} \geq 0$

MAU-ID is the primary asset performance measure used in this research. Hence, it is crucial to quantify the decrease in MAU-ID with respect to time. In this research, it is assumed that the deterioration of MAU-ID is directly proportional to the deterioration of IRI. Based on Canadian Long Term Pavement Performance (C-LTPP) study data, Raymond et al. (2002) investigated the impacts of various alternative rehabilitation treatments on pavement roughness progression. Raymond et al. (2002) proposed a simplified version of the model to quantify the deterioration based on International Roughness Index (IRI) as illustrated in Eq. (4):

$$PD = \begin{pmatrix} 0.160 - 0.00120OT + 0.000578PC - 0.0000805FI \\ +0.00147DP + 0.0000000223ESAL_8 \end{pmatrix}^3 \tag{4}$$

Where:

(1) *PD* = the rate of pavement deterioration (IRI/year);

(2) *OT* = the overlay thickness (mm);

(3) *PC* = the prior cracking (m/150 m);

(4) *FI* = the annual freezing index (^{o}C.d);

(5) *DP* = the annual number of days with precipitation; and

(6) $ESAL_8$ = the accumulated equivalent single axle loads after eight years.

5 WEB-BASED DECISION SUPPORT SYSTEM DEVELOPMENT: OPTIsys

A web-based decision support system, known as OPTIsys, has been developed for optimal funding allocation for the MR&R of urban roads. OPTIsys integrates all the developed mathematical models and implements the research methodology in the World Wide Web. A central asset-information repository (Asset Database) was developed in MS Access. The developed application, OPTIsys, allows the user to make MR&R decisions in an interactive way.

6 CONCLUSION

This paper presented an integrated framework for ALOS-based decision support systems for municipal infrastructure network investments. The proposed framework was based on the fact that ALOS should be one of the main criteria for municipal infrastructure investments. Other parameters which were incorporated for municipal infrastructure investment decision making were the physical deterioration of assets, future growth, and the impact on dependent infrastructure networks. The proposed framework focused on funding allocation for the MR&R of municipal networks. The framework is applicable to municipal infrastructure networks, excluding other assets such as buildings, parks, etc. Application of the proposed framework was demonstrated on the MR&R of urban roads. OPTIsys will enable infrastructure departments to maintain operational capability of the network in compliance with the targeted LOS. Overall, municipalities will be able to reduce the infrastructure deficit while maximizing economic returns.

References

Allenby, B.R., Infrastructure in the Anthropocene: Example of Information and Communication Technology, *Journal of Infrastructure Systems*, Special Issue: Sustainable Development and Infrastructure Systems, pp. 79-86, 2004.

City of Edmonton, Infrastructure Investment Needs, Office of Infrastructure, City of Edmonton, 2006.

FCM and NRC, *Developing Levels of Service*, Federation of Canadian Municipalities and National Research Council, 2003.

Georgi, H., *Cost-Benefit Analysis and Public Investment in Transportation: A Survey*, Butterworths, London, 1973.

Golabi, K., Kulkarni R. and Way, G.B., *A statewide pavement management system, Interfaces*, Vol. 12, pp. 5-12, 1982.

Loucks, D.P., Stedinger, J.R. and Haith, D.A., *Water Resource Systems Planning and Analysis*, Prentice-Hall, Englewood Cliffs, N.J., U.S.A, 1981.

Raymond, C., Tighe, S., Haas, R. and Rothenburg, L., Development of Canadian Asphalt Pavement Deterioration Models to Benchmark Performance, *Canadian Journal of Civil Engineering*, Vol. 30, no. 4, pp. 637-643, 2002.

Sharma, V., Al-Hussein, M., Safouhi, H. and Bouferguène, A., Municipal Infrastructure Asset Levels of Service Assessment for Investment Decisions Using Analytic Hierarchy Process, *Journal of Infrastructure Systems*, Vol. 14, No. 3, 2008.

Taylor, D.B., Hofseth, K.D., Shabman, L.A. and Moser, D.A., Moving Toward a Probability-Based Risk Analysis of the Benefits and costs of Major Rehabilitation Projects, *Proc., Risk-Based Decision Making in Water Resources V*, ASCE, New York, pp. 148– 173, 1992.

Thompson, P.D., Newman, L.A., Miettinen, M. and Talvitie, A. (1987), A Micro-Computer Markov Dynamic Programming System for Pavement Management in Finland, *Proc., Second North American Conference on Managing Pavements*, Toronto, ON, Vol. 2, pp. 2.242-2.252, 1987.