



NRC Publications Archive Archives des publications du CNRC

Multi-objective optimisation of asset maintenance management

Kyle, B. R.; Lounis, Z.; Vanier, D. J.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=f59f34d1-1517-4e28-a93e-5ab889261e3e>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=f59f34d1-1517-4e28-a93e-5ab889261e3e>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.





NRC - CNRC

Multi-objective optimisation of asset maintenance management

Kyle, B.R.; Lounis, Z.; Vanier, D.J.

NRCC-45160

A version of this paper is published in / Une version de ce document se trouve dans:
9th International Conference on Computing in Civil and Building Engineering, Taipei, Taiwan, April 3-5, 2002, v. 1 of 2, pp. 701-706

www.nrc.ca/irc/ircpubs



MULTI-OBJECTIVE OPTIMISATION OF ASSET MAINTENANCE MANAGEMENT

B. R. Kyle¹, Z. Lounis² and D. J. Vanier²

¹*Facility Life-cycle Management, Technology, AES, Real Property Services, Public Works
and Government Services Canada, Hull, Québec, Canada*

brian.kyle@pwgsc.gc.ca

²*Urban Infrastructure Rehabilitation, Institute for Research in Construction,
National Research Council of Canada, Ottawa, Ontario, Canada*

zoubir.lounis@nrc.ca, dana.vanier@nrc.ca

Abstract

Asset managers are faced with the necessity to reduce total life-cycle costs of their facilities as well as to improve their physical condition and long-term performance while considering the relative consequences of their failure. This paper presents a systematic decision-making approach for asset maintenance management that combines a stochastic Markovian performance prediction model with a multi-objective optimisation method to determine the optimal allocation of funds and prioritisation of assets for maintenance, repair and replacement. The maintenance optimisation is formulated as a multi-stage and multi-objective optimisation problem where the simultaneous satisfaction of several conflicting objectives, including minimisation of maintenance costs, maximisation of condition and performance, and minimisation of risk (weighted consequence) of failure, is sought. Compromise programming is used to determine the optimal ranking of deteriorated assets in terms of their priority for repair or replacement, by achieving a satisfactory trade-off between the competing / conflicting objectives. In addition, the paper examines the benefits of this approach as compared to the traditional maintenance prioritisation and management practices.

Introduction

A significant portion of the funds expended each year in the construction industry is for asset management and more particularly for maintenance management. A review of recent Canadian construction statistics shows that \$8.5 billion is spent annually for repairs and maintenance of buildings (Vanier 1998); this is well below the recommended maintenance expenditure levels (NACUBO, 1990). Asset managers are tasked to manage their properties in the most efficient manner over the entire service life of their facilities. The basic asset management objectives are: (a) to provide the required functionality, and (b) to optimise economic benefit throughout the asset service life. This must be done while considering various design and as-built conditions, operations and maintenance procedures, environmental performance requirements, as well as continuous redefinition of function. Effective decision-support systems are required to assist asset managers in taking appropriate and timely actions relative to the possible maintenance, repair or replace scenarios. The development and adoption of a network-level life-cycle maintenance management system will yield improved performance and reliability, reduced life-cycle costs, and extended service life. The main components of the system proposed in this paper are: (a) condition assessment of components and systems; (b) prediction of future performance and remaining service life of building elements using stochastic Markovian models; and (c) multi-objective maintenance optimisation of maintenance by considering multiple conflicting objectives.

A comparative example is provided to view the benefits of this approach relative to conventional maintenance prioritisation practices.

Computerised Asset Maintenance Management

The maintenance management system described here was developed as part of the Building Envelope Life Cycle Asset Management (BELCAM) project (Lounis *et al*, 1999). The proposed BELCAM management system consists of many subsystems as depicted in Fig. 1. The principal constituents of the proposed maintenance management system are: (a) asset condition and performance assessment; (b) service life prediction; (c) assessment of consequences of failure; and (d) maintenance optimisation.

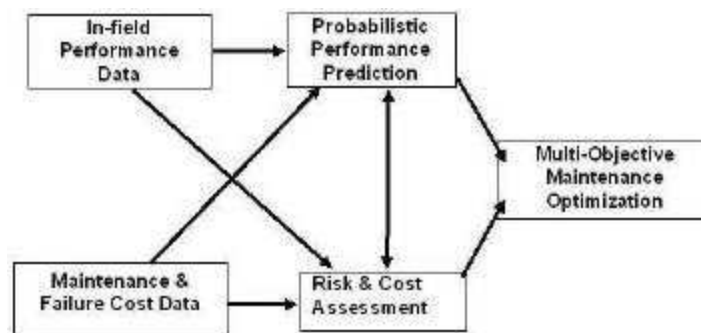


Fig. 1: Maintenance management system

For the purposes of this examination, the condition of components and systems is represented by discrete condition ratings obtained by mapping the assessed damage levels to a 1 to 7 rating scale (1-failed to 7-excellent condition). These condition assessment techniques have been applied for various infrastructure systems including bridges, pavements, etc. (Bailey *et al*, 1990).

The condition and performance of components and systems deteriorate with time as a result of environmental degradation factors, traffic loading, inadequate maintenance and poor workmanship. Considerable uncertainty and variability are associated with the performance of components resulting from the uncertainty and variability in the environmental factors, quality of workmanship and level of maintenance. Hence, a probabilistic model, specifically a discrete Markov chain that captures both the time-dependence and randomness of the system performance is used to assess the current condition and predict the future condition.

The performance predictions are combined with a system assessment model to evaluate the probabilities of failure of different components and entire system taking into account the correlation between different components and failure modes. The consequences of failure can be evaluated from available cost data on maintenance, repair and replacement (MR&R), and the cost of failure, which depend on the type of building and occupancy. Failure refers to the loss of functionality and loss of serviceability. Consequence (or risk) of failure is obtained by multiplying the cost of failure by its associated probability of failure.

The maintenance management system described in this paper combines a stochastic Markovian performance prediction model with a multi-objective optimisation procedure to determine the optimal prioritisation of assets for maintenance, repair and replacement, and the optimal allocation of funds. The proposed approach is based on the following interrelated subsystems: (a) a standardised framework for collecting and processing data; (b) probabilistic models for condition and performance prediction as well as risk assessment; and (c) multi-

objective optimisation procedure for decision making under conflicting objectives (Lounis & Vanier, 2000). The following sections briefly describe the latter two of these subsystems.

Probabilistic Modelling of Performance

The underlying assumption of the first-order Markov chain model is that the probability of a component being in a particular condition is governed solely by its present state and not on the entire stress history. The development of the Markovian model requires historical performance data at two or more points in time. If the probability of a component decaying by more than one condition rating in one time period is assumed negligible, the modelling of the deterioration process is greatly simplified (Lounis *et al*, 1999) through the use of unit-jump Markov Chain.

The proposed model enables the forecast of future performance of systems throughout their entire service lives. The performance of components and systems is dependent upon several explanatory variables, including age, environmental conditions, material type, quality of work executed and materials used as well as the amount and quality of maintenance. In order to ensure the validity of the Markov chain model, it may be necessary to develop transition probability matrices for components and systems according to their classification with regard to these explanatory variables. These prediction models can be continuously improved using the Bayesian-updating technique, as additional performance data become available.

Systems are comprised of multiple components with multiple failure modes that can be modelled as a hybrid system comprised of a combination of subsystems in series and parallel. The probability of failure of each component is time-variant and increases with time due to the time-dependent degradation of its performance. The probability of failure can be determined using systems reliability approach taking into account the correlation between different components and failure modes. In addition, the corresponding risk of failure of the system may be evaluated once the consequences of failure are established.

Multi-objective Maintenance Optimisation

The proposed multi-objective maintenance optimisation is based upon compromise programming method (Lounis & Cohn, 1995), where the simultaneous satisfaction of conflicting objectives is considered. The conflicting nature of maintenance is illustrated in Fig. 2 for two objectives, namely MR&R costs and risk of failure. Figure 2 shows that system failure is at a minimum when maintenance costs are at the highest. An owner or manager is willing to assume some risk of failure in order to reduce the MR&R costs: the objective is to find the best "trade-off" point.

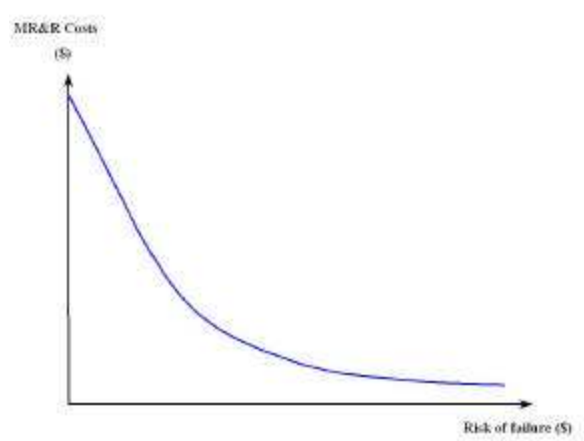


Fig. 2: Illustration of conflicting objectives

At the network-level of maintenance management, critical decision-making involves the optimal selection or prioritisation of projects that require immediate MR&R. This is not, generally, a straightforward task. The maintenance management problem is multi-objective in nature, and requires the determination of the optimal maintenance strategy that achieves the best trade-off between the different conflicting objectives. For example, maintenance

optimisation may include the following three objectives: (a) minimisation of MR&R costs (f_1); (b) maximisation of network performance (f_2); and (c) minimisation of risk of failure (f_3) (Lounis & Cohn, 1995).

Multi-Objective Optimisation and Pareto Optimality Concept

For single-objective optimisation problems, the notion of optimality is easily defined as the minimum (or maximum) value of some given objective function that is sought. However, the notion of optimality in multi-objective optimisation problems is not that obvious. In general, there is no single optimal (or superior) solution that simultaneously yields a minimum (or maximum) for all objective functions. The “*Pareto optimum concept*” is adopted as the solution to the multi-objective maintenance optimisation problem. A solution is said to be a Pareto optimum, if and only if there exists no solution in the feasible domain that may yield an improvement of some objective function without worsening at least another objective function (Lounis & Cohn, 1993, Lounis & Cohn, 1995). Typically in a multi-objective optimisation problem, there are several Pareto optima, and the issue is to select the solution that is the best compromise between all competing objectives. Such a solution is referred to as “satisficing” solution (Koski, 1984) and yields the minimum distance from a set of Pareto optima to the so-called “ideal solution” of \bar{x}^* . The ideal solution is defined as that that yields simultaneously extreme (minimum or maximum) values for all objectives. It does not exist (non-feasible), but is introduced as a target. In general, the ideal solution is associated with the following “ideal vector objective \mathbf{f}^* ”:

$$\mathbf{f}^*(\mathbf{x}) = [\min f_1(x) \quad \min f_2(x) \quad \dots \quad \min f_m(x)]^T \quad (1)$$

The ideal vector objective is the one that yields simultaneously minimum maintenance cost, maximum network condition, and minimum consequence of failure. Therefore, the satisficing solution is the one that minimises the distance from the “ideal” and non-feasible solution to the Pareto optima set. The distance measure used is the family of normalised and weighted L_p metrics, the satisficing solution yields a minimum for the following L_p metric function:

$$\min L_p(x) = \min_{x \in \Omega} \left[\sum_{i=1}^m w_i \left| \frac{f_i(x) - \min f_i(x)}{\max f_i(x) - \min f_i(x)} \right|^p \right]^{1/p} \quad (1 \leq p \leq \infty) \quad (2)$$

in which w_i are the weights associated with the corresponding objective functions f ($i=1,2,\dots,m$).

The weighting of the maintenance objectives depends on the attitude of the decision-maker towards the consequences of failure, economy, and network reliability. This L_p metric function indicates how close the satisficing solution is to the ideal solution. The value of p indicates the type of distance. If $p \geq 2$, then greater weight is given to larger deviations in the metric function. L_2 represents the Euclidean metric function. For the example presented in this paper, L_2 is adopted as a priority index for the establishment of the optimal ranking in terms of the MR&R requirements by considering simultaneously the cost, consequence of failure and network condition.

Prioritisation practices

Scenarios for MR&R prioritisation in network or portfolio asset management have traditionally followed either age-based or condition-based approaches. In infrequent cases where the age-condition-deterioration relationships are adequately understood, MR&R resources are allocated by applying subjective restorative intervention. Condition-based management, on the other hand, sets priorities dependent upon asset condition ratings.

Consequence (or risk)-based maintenance assigns priorities relative to the potential risk that failure represents to the network. Dependent upon the diversity of the asset base, there may be additional benefit in applying asset-specific levels of minimum condition. This is done to reflect the relative significance (or potential risk of failure) of individual assets to the network. Resource and maintenance allocations and execution are often decided by blending these approaches. This typically has taken the form of a non-systematic consideration of minimum asset condition requirements, “regular” maintenance levels and subjective quantification of relative asset importance.

Illustrative Example

In order to assess the impact of various prioritisation procedures upon the maintenance plans and expenditures, the multi-objective optimisation approach presented in this paper is compared with age-based, condition-based and consequence-based prioritisation methods. The three approaches are applied to the maintenance management of a network of roofs on buildings with different occupancies. As illustrated in Fig. 3, 5 roofs of the network are divided into 10 sections. Assume that maintenance is considered for the sections with condition ratings of 3 or less and that the annual maintenance budget is limited to \$270,000. The data on the ages, condition ratings, consequences of failure, and maintenance cost for the 7 roof sections are summarised in Table 1. The total MR&R cost for the seven critical sections is \$520,000, roughly twice the allocated budget.

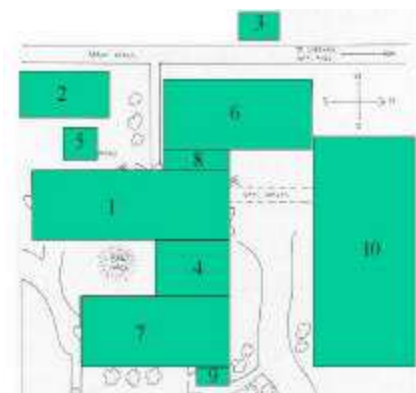


Fig 3: Roofing network

Table 1: Influencing parameters for prioritisation

Section Number	Age (years)	Cond. (f_1)	Cost (f_2) (\$1,000)	Conseq. (f_3) (\$1,000)
1	36	1	100	50
2	30	2	75	20
3	23	3	35	10
4	40	3	75	30
5	18	2	60	10
6	32	1	90	20
7	38	2	85	20

Single-objective ranking

The age-based prioritisation assigns MR&R activities to the roof sections purely on the basis of age, therefore producing a priority ranking as follows: Section 4, 7, 1, 6, 2, 3, then 5.

A condition-based approach must also consider the MR&R cost for setting the priorities due to the limited budget. Therefore for every condition rating group the priorities must be assigned relative to remaining funds; for this assessment the lowest priced MR&R activities at a given condition rating were given precedence for budget allocation. The rankings are: Section 6, 1, 5, 2, 7, 3, then 4.

Similarly for the consequence-based rankings, with no consideration to the probability of failure (or condition), the sections with lowest priced MR&R costs were given priority. The preferred order of execution would be: Section 1, 4, 2, 7, 6, 3, then 5.

Fig. 4(a) displays the single-objective rankings obtained for each of the subject roof sections.

Multi-objective optimisation

In applying the multi-objective optimisation the values from Table 1 are associated to the “ideal” (non-feasible) roof section with the following vector objective $\mathbf{f}^* = [f_{1\min} \ f_{2\min} \ f_{3\max}]^T = [1 \ 35,000 \ 50,000]^T$. This means that the first section for MR&R is the one that has minimum condition rating, minimum cost, and maximum consequence of failure. However, the objective is to select those sections that are the closest to this so-called “ideal solution”. Using the Euclidean metric (Eq. 2) and assuming equal weights for the three objectives, the satisficing solution that yields $\min L_2(x)$ is found to be Section 1. From Table 2, and Fig.4(b), the optimal ranking of roof sections in terms of priority for MR&R is as follows: Section 1, 2, 6, 5, 4, 7, and 3, as illustrated in Fig. 4(b).

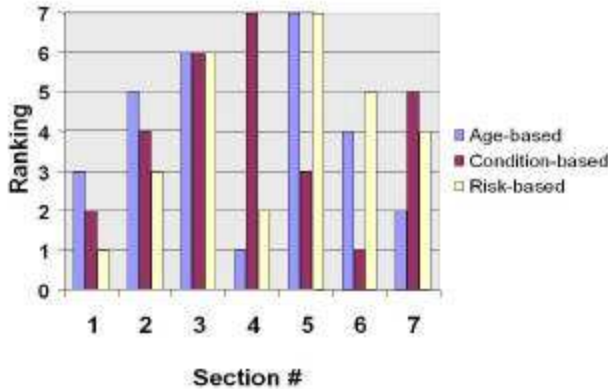


Fig. 4(a): Priority ranking for age-based, condition-based and consequence-based

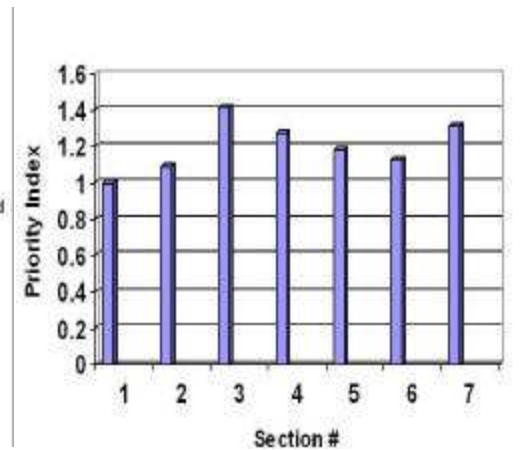


Fig. 4(b): Multi-objective-based maintenance prioritisation

Table 2: Euclidean metric-based priority indexes for MR&R of deteriorated roof sections

Section No.	1	2	3	4	5	6	7
$L_2(x)$	1.00	1.09	1.41	1.28	1.18	1.13	1.31

Summary and Discussion

Fig. 4 presents the rankings for each of the considered prioritisation schemes. As expected, there are noticeable differences between the priorities established as well as the MR&R expenditures relative to the available budget. Age-based allocations would lead to MR&R action on Sections 4, 7 and 1 for a total cost of \$260,000; without repairing Section 6 (condition rating of 1). Condition-based rankings would see Sections 6, 1 and 5 being repaired for \$250,000; a creative variant of this method would select Section 2 over 5 in order to use more of the available budget (\$265,000 vs. \$250,000). The consequence-based approach recommends action on Sections 1, 4 and 2 for a total of \$250,000; if however the third allotment is made to roof Section 6 rather than Section 2 the total cost rises to \$265,000. The multi-objective optimisation has found a balance between the competing requirements as well as the above ranking and recommends that with the given a budget of \$270,000 for the current year, Sections 1, 2, and 6 should be scheduled for MR&R at a total cost of \$265,000.

Visualisation

A two-dimensional, graphical prototype tool, christened Visualizer, was developed to demonstrate maintenance prioritisation and decision support capabilities for roofing management (Kyle *et al.* 2002). The Visualizer package is capable of calculating and displaying the existing data from condition assessment surveys and the future effects resulting

from planned maintenance and restorative actions. The projections that can be displayed include costs, condition, remaining service life, and consequences of failure. Figure 5 presents the Visualizer displays for the network example described above. Multi-objective ratings for condition, cost and consequence are illustrated in Fig. 5(a); whereas condition and cost ratings are depicted in Fig. 5(b). Figure 5 illustrates the different priorities for different asset managers: -- one asset manager can rank a building with a high priority (Section at top left of images in Fig. 5) when another manager ranks it lower, and *visa versa* (Section at top centre in Fig. 5).

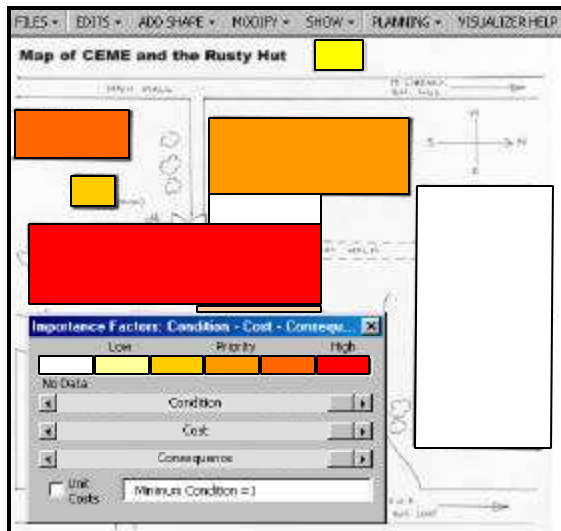


Fig. 5(a): Display of multi-objective data

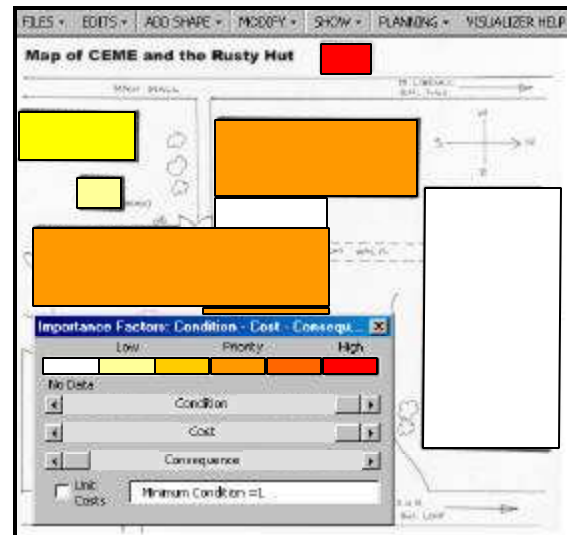


Fig. 5(b): Display of Condition and Cost

Conclusions

A multi-objective and stochastic system, integrating probabilistic performance prediction and risk assessment models within a multi-objective optimisation approach is an effective toolbox for network-level maintenance management. The multi-objective maintenance optimisation seeks to satisfy several conflicting objectives: e.g. minimisation of maintenance costs, minimisation of consequence of failure, and maximisation of network. The compromise programming method is used to determine the optimal ranking in terms of priority for maintenance, repair and replacement. Discrete Markov chains are used to model the performance of roofing components that account for their time-dependence, and uncertainty. The decision support tools proposed in this paper will assist building managers in predicting the remaining service life and will allow them to optimise their maintenance expenditures.

Recommendation

To apply procedures to optimise MR&R strategies within a finite or short term planning horizon followed by an optimisation within a longer planning horizon. This task will be achieved through the combination of the dynamic programming method with the proposed multi-objective optimisation approach. Continued research and standardisation in the field of data visualisation relative to the key aspects of information storage and flow.

References

Bailey, D.M, Brotherson, D.E., Tobiasson, W & Knehans., A. , 1990, *ROOFER: An Engineered Management System (EMS) for Bituminous Built-up Roofs*, *USACERL Technical Report M90/04*.

- Koski, J., Multiobjective Optimization in Structural Design, In *New Directions in Optimum Structural Design*, eds. Atrek et al., Wiley, New York, 1984, pp. 483-503.
- Kyle, B.R., Vanier, D.J., Kosovac B., Froese T.M., & Lounis Z. 2002, 'Visualizer: An Interactive, Graphical, Decision-Support Tool for Service Life Prediction for Asset Managers', Submitted to Proc. 9th International Conference on Durability of Building Materials and Components, Brisbane Convention & Exhibition Centre, Australia, 17-20 March.
- Lounis, Z., & Cohn, M.Z., 1993, Multiobjective Optimization of Prestressed Concrete Structures, *ASCE J. of Struct. Engrg.*, **119**(3), pp. 794-808.
- Lounis, Z., & Cohn, M.Z., 1995, An Engineering Approach to Multicriteria Optimization of Highway Bridges, *J. of Microcomputers in Civ. Engrg.*, **10**(4), pp. 233-238.
- Lounis, Z., & Vanier, D.J., 1998, Optimization of Bridge Maintenance Management Using Markovian Models, *Proc. 5th International Conference on Short and Medium Span Bridges*, Calgary, Vol. 2, pp. 1045-1053.
- Lounis, Z.; Vanier, D.J., 2000, "A Multiobjective and Stochastic System for Building Maintenance Management," *Journal of Computer-Aided Civil and Infrastructure Engineering*, 15, (5), pp. 320-329, September 01.
- Lounis, Z., Vanier, D.J., Lacasse, M.A & Kyle, B.R., 1999, Decision-Support System for Service Life Asset Management: The BELCAM Project, Proc.8th International Conference on Durability of Building Materials and Components, Vancouver, 30 May - 3 June, vol. 2, pp. 1223-1234.
- NACUBO (1990) *Managing the Facilities Portfolio*, National Association of College and University Business Officers, Washington, DC, 100p.
- Vanier D.J. (1998), "Product Modeling: Helping Life Cycle Analysis of Roofing Systems", *The Life Cycle of Construction IT Innovations: Technology Transfer from Research to Practice*, Stockholm, Sweden, pp. 423-435.