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NRCC-51170


May 11, 2008

A version of this document is published in / Une version de ce document se trouve dans: 11th International Conference on the Durability of Building Materials and Components, Istanbul, Turkey, May 11-14, 2008, pp. 1-9
Optimization of the Building Maintenance Management Process Using a Markovian Model

Michael A. Lacasse¹
Brian Kyle²
Aurélie Talon³
Daniel Boissier⁴
Thibaut Hilly¹
Khaled Abdulghani¹

Theme Number: T72

ABSTRACT

Building managers are increasingly faced with having to maintain their building assets more efficiently whilst reducing the short and long-term cost of maintenance and rehabilitation. Several different systems employing a Markovian approach have been adapted to the bridge structure domain; fewer in the domain of buildings. The present paper describes a parallel approach to maintenance management used in bridge structures but adapted to the maintenance of building facades. The maintenance of several components of a concrete panel façade system is considered in the context of both yearly and longer-term maintenance planning. The significance of different components in relation to others in the system is determined by first conducting a Failure Mode Effect and Criticality Analysis (FMECA) on all façade components. The FMECA permits developing a component criticality index from which their relative importance is assigned amongst the different façade components. An optimization of different possible maintenance actions are considered in relation to the cost of specified actions to or replacement of components based on a multi-objective index. This index provides a means of relating competing maintenance objectives; that of controlling maintenance intervention costs and maintaining component condition ratings. It provides yearly maintenance costs of individual components for a given wall system over a long-term horizon that spans the life of the façade system.

KEYWORDS

building facade, building maintenance, component deterioration, failure mode analysis maintenance optimization

1. National Research Council Canada, Institute for Research in Construction, Ottawa, Canada K1A0R6, Phone +1 613 993 9715, Fax +1 613 954 5984; Michael.Lacasse@nrc-cnrc.gc.ca; Khaled.Abdulghani@nrc-cnrc.gc.ca
2. Public Works and Government Services Canada, 11 Laurier Street, Gatineau, Canada K1A 0S5; Phone: +1 819 956 3420; Fax: +1 819 956 3400; brian.kyle@pwgsc.gc.ca
3. CEMAGREF, Unité Ouvrages Hydrau liques et Hydrologie, 3275 route Cézanne - CS40061, 13182 Aix en Provence Cedex 5; Phone +33 4 42 66 99 80; Aurelie.Talon@cemagref.fr
4. Polytech’ Clermont-Ferrand - Department of Civil Engineering, 24 Avenue des Landais, BP 206, Aubière, France 63174; Phone +33 473407525; Fax +33 473407494; daniel.boissier@cust.univ-bpclermont.fr
1 INTRODUCTION

Building managers are increasingly faced with having to maintain their building assets more efficiently whilst reducing the short and long-term cost of maintenance and rehabilitation. In the domain of construction infrastructure, there exist several examples of infrastructure maintenance that employ the Markovian approach; examples can be found in the domain of roadway pavements [Nesbitt et al 1993; Durango-Cohen and Mandanat 2006], storm water sewerage works [Micevski et al 2002] and several related to the bridge structure domain [Cesare et al. 1994; Morcous et al. 2003; Morcous and Lounis 2006; Robelin and Mandanat 2007]. However there are fewer examples of the Markovian approach used in the domain of buildings although some useful examples include the work of Van Winden and Dekker (1998), Lounis and Vanier [2000] and that of Augenbroe and Park [2002].

Approaches to Maintenance Management of Building Components

The Markov-based decision model for rationalising building maintenance, developed by Van Winden and Dekker (1998) was used at the strategic level for the planning of maintenance for buildings owned by a building society. The value of the model as a management instrument in estimating and allocating maintenance budgets was demonstrated in a pilot case of four (4) building elements, namely: masonry, pointing, window frames and painting. Modelling the deterioration of these components permitted determining the maintenance policy that ensured a specified average quality level at minimal cost. The intent of the study was to provide some estimate of life cycle costs to the building and as such, the study provides useful information related to methods of establishing cost matrices. However, there appears to be some missing information related to the allocation of costs.

Lounis and Vanier [2000] describe the development of a roofing maintenance management system that integrates an existing condition assessment module (i.e. Roofer; [Bailey 1990]), and performance prediction based on a Markovian model, with a multi-objective optimization scheme. The maintenance optimization includes the determination of the optimal allocation of funds and prioritization of roofs for maintenance, repair and replacement that satisfy: (i) minimization of maintenance and repair costs; (ii) maximization roof performance; and (iii) minimization of risk of failure. Compromise programming is used to solve the optimization problem and the system purports to provide building managers an effective decision support system that identifies optimal projects for repair and replacement whilst achieving satisfactory trade-offs between conflicting maintenance objectives.

Augenbroe and Park [2002] suggest that the building maintenance problem can be formulated as a Markov decision process. They indicate that the discrete Markov chain model aptly describes both the time-dependence and randomness of building system performance and thus can be used for systematic decisions regarding replacements of building components that affect the scope of yearly maintenance activities. Such an approach permits comparison of various maintenance policies on resulting maintenance costs and building quality. The authors also suggest that this approach gives insight into the relation between yearly maintenance costs and the quality of the building, both on short as well as a long term.

The present paper describes a parallel approach to the maintenance management of bridge desks initially postulated by Lounis and Vanier [1998] and on which the work of Lounis and Vanier [2000] on roofing was developed, of which a broader overview of the roofing project is provided by Kyle et al. [2002]. In this instance, these approaches have been adapted to the maintenance management of buildings facades and have also drawn upon the more recent work of Morcous et al. [2003] and Morcous and Lounis [2006].

2 PROPOSED MARKOVIAN-BASED, BUILDING FAÇADE MAINTENANCE MANAGEMENT (BMM)

The Markovian-based, building façade maintenance management (BMM) model permits the optimization of maintenance planning, and introduces software that permits a user to initiate building maintenance actions. The intent was to provide building managers who are faced with having to maintain their buildings assets more efficiently, with a tool that could reduce the short and long-term costs of maintenance and rehabilitation. In essence, the BMM software can either optimize maintenance planning actions based on an expected maintenance budget or determine the budget required to maintain the façade to a minimum acceptable level of performance. A schematic of the primary components of the software is given in Figure 1. The façade was first considered in development of the BMM software given that it is a significant element of the building envelope and of the building itself.

Consider for example, the maintenance of several components of a concrete panel façade system in the context of both yearly and longer-term maintenance planning. The significance of different components in relation to others in the system is determined by first conducting a Failure Mode Effect and Criticality Analysis (FMECA) on all façade components. This permits developing a component criticality index from which their relative importance is assigned amongst the different façade components. An optimization of different possible maintenance actions can then be considered in relation to the cost of specified actions to or replacement of components. However, a means of relating competing maintenance objectives is required that controls maintenance intervention costs whilst maintaining component condition ratings.

3 OVERVIEW OF FMECA IN THE CONTEXT OF MAINTENANCE MANAGEMENT

Of the several parts of which is comprised the BMM model, one of the key components is Failure Mode Effects and Criticality Analysis (FMECA) and performance analysis of the façade and related components; the several steps of this process are provided in Figure 2. The first step consists of developing a façade component criticality index that is based on outcomes of a FMECA. This permits determining the relative importance assigned amongst the different façade components, as proposed by Talon [2006].

Given that building managers do not necessarily dispose of unlimited budgets for maintenance actions, only the most critical set of components are further analyzed by simulation of the deterioration process. These simulations reflect the change in condition state of façade components and thus the degree of overall deterioration over time. The different condition states are necessarily defined thereby ensuring that it is possible to observe symptoms of these conditions during an inspection. The condition state vector \( \mathbf{D}_t \), given in Figure 2, provides information on current condition; each element in this vector having \( S \) condition states, represents the estimated percentage of all like components in a particular condition state after time \( t \), for which \( t \) is expressed in transition periods, or e.g., periods between inspection. The likelihood of a component remaining or changing state at given inspection intervals provides the transition probabilities \( \mathbf{P}^{(t)} \), that is, probability of changing (or not) condition

from state $i$ to a lower state $j$, and for which the corresponding transition probability matrix ($P$) is obtained. Such a matrix ($S \times S$), shown in Figure 2, permits estimating the service life of components, or assembly of components, through an analysis using the Markovian model. Given the present condition vector of a component ($D_t$), the future condition vector ($D_{t+n}$) can be obtained as: $D_{t+n} = D_t \times P^n$, where $n$, is the number transition periods in the future.

### 4 MANAGEMENT OF COMPONENT CONDITION STATE USING A MARKOVIAN METHOD

There are different maintenance actions that maintenance managers can take over the course of managing the façade component condition state. For example, the component might be repaired such that its condition can be maintained or it might be completely replaced. If repaired, consideration should be given to how amenable to repair the component. Can the component be repaired more than once? Then again, can the component be repaired indefinitely? Provided a component is readily accessible then repair is likely possible. However, it is unlikely that any building façade component can be repaired indefinitely so then repairs should be considered as actions capable of retarding the degradation process but ultimately not preventing the need for replacement at some time in the future. Hence a repair action undertaken on a component typically would not renew the component to its original condition state but the action would improve its condition to a stated higher level.

If, however, the component were replaced then its condition state would be renewed to that of a new component. A typical example of components in a building façade more likely replaced as opposed to repaired would be the insulated glass (IG) component of a window. The IG unit is either, functioning adequately (i.e. IG unit is transparent, and still holds an inert gas between glass lites), or its seal has failed and the unit is now clouded, as is evident by the presence of moisture on the interior glass lites.

As well, it may be decided that no maintenance action be taken, in which case the loss in performance over time would continue at the rate prescribed by the deterioration process.

For each of these actions (described as a maintenance vector, $M_{ct}$), including the no maintenance action, there exist transition matrices that reflect the action taken (i.e. $P_{ct}$) and associated with each of these a cost for repair or replacement, and perhaps in some cases, a cost for no action as well ($C_{ct}$). The general stages in the maintenance action approach are provided schematically in Figure 3. Once the consequences of maintenance actions are established, one can then consider optimization of maintenance actions.

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**Figure 2 - Description of performance analyses and development of Markov condition state matrices for service life estimation.**
### 5 Optimization of Maintenance Actions

An optimization of different possible maintenance actions considers three scenarios that relate aggregated component condition rating (ACCR) to a desired or available maintenance budget. These scenarios include:

- Maximization of component condition rating for a given annual maintenance budget.
- Minimizing the maintenance budget for a targeted condition state (aggregated condition state for all components)
- Use of multi-objective index when neither the budget is neither defined nor is the expected condition state – a compromise solution between maximisation of the budget and minimisation of the condition state over time.

The aggregated component condition rating (AACR) is derived from the knowledge of the number of “sections” in any given condition state at a given time, a section being defined as a measurable part or portion of the entire set of sections that together form the representative “mass” for a given component type. As illustrated in Figure 4, at any given time, \( t \), component sections will be in their respective conditions state.

The multi-objective index (MOI), obtained from Morcous and Lounis [2006], with evaluation criteria, \( i \), a set of criteria, \( m \), and assuming the solution metric with \( p = 1 \), is given by:

\[
MOI(x) = \sum_{i=1}^{m} w_i \cdot \left[ \frac{f_i(x) - \min f_i(x)}{\max f_i(x) - \min f_i(x)} \right]
\]

Where, \( w_i \) is the weight given to criteria \( i \), \( f_i(x) \) the value of objective function, and \( \max f_i(x) \) and \( \min f_i(x) \) the maximum and minimum values of the same function respectively. The choice of \( p \) indicates all deviations from the ideal solution are considered in direct proportion to their magnitudes Lounis and Vanier [2000]. If it is assumed that the competing objectives are budgeted maintenance cost and AACR (i.e. \( m = 2 \)), then this index provides a means of relating competing maintenance objectives; that of controlling maintenance intervention costs and maintaining component condition ratings.

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**Figure 3**: Description of maintenance analysis – possible choice of maintenance actions, associated maintenance vector, transition matrix and cost matrix
If a building maintenance manager is aware of the expected annual budget or has made the necessary provision for acquiring the requisite funds to conduct a proper maintenance program then in this case, the maintenance strategy is to maximize the overall component condition rating. Essentially, the manager has interest to maximize the gains afforded by a given annual maintenance budget allocation.

Another scenario is one where the building manager may know the overall component condition rating to attain, or maintain, but wishes to minimise the budgetary requirements. Whereas a more likely scenario, as in the third case, is one in which the manager may not as yet have defined budgetary requirements and as well, is not aware of the average aggregate condition state under which he should be operating the facility beyond minimum acceptable levels. Indeed, the building manager may require some insight into the most cost effective maintenance he can expect over a longer-term horizon and still operate the facility above a minimum acceptable condition state.

This is a case where a compromise is to be reached between two competing objectives: maintaining a minimum acceptable AACR in relation to the yearly maintenance budget. The intent is to determine the highest achievable AACR for any given yearly maintenance budget. As such, a multi-objective index (MOI) approach is used that is based on: the degree of criticality of amongst components; number of components being considered; condition state vector; relative importance brought to the budget in relation to the building condition state; and the AACR, and limiting values for ACCR (i.e. $\text{ACCR}_{\text{min}}$ and $\text{ACCR}_{\text{max}}$).

In respect to the limiting values for AACR, these values are selected by the building manager to better manage the maintenance process. For example, it is unlikely that a new window unit should require replacement in its initial years of use; likewise one would expect that a failed unit would be replaced. Hence, the manager can set limits on minimum and maximum values of ACCR for each façade component. For example, the building manager can determine that if the AACR of the components lies between “new condition” (e.g. state 6) and an “average” condition (e.g. state 4), then no action to consider replacing the unit should be taken. Whereas a repair could be requisitioned should the components be considered in the poor, urgent or critical states (e.g. condition states 3, 2, 1 resp.). The determination of such limits thus permits the building manager to establish a policy of when actions should be taken and indeed the system could be used to determine how such policies might affect overall maintenance costs.

A summary of the three different maintenance scenarios is given in Figure 5. In essence, the façade BMM system provides yearly maintenance costs of individual components for a given wall system over a long-term horizon that spans the life of the façade system.
6 SUMMARY

A building façade maintenance management system is proposed that considers the effect of different maintenance options on the overall cost of maintenance over a yearly and longer time scale. Performance predictions in respect to component condition state are based on a one-step Markovian model. An optimization of different possible maintenance actions are considered in relation to the cost of specified actions to, or replacement of, components based on a multi-objective index. This index provides a means of relating competing maintenance objectives; that of controlling maintenance intervention costs and maintaining component condition ratings.

ACKNOWLEDGEMENTS

The authors acknowledge funding support from the Program of Energy Research and Development (PERD), the Publics Works and Government Service Canada, and the Institute for Research in Construction. As well, they would like to extend their gratitude for the support offered by the LGC, CUST, Clermont-Ferrand II, and University Blaise Pascal.

REFERENCES


