DECISION SUPPORT TOOL FOR THE MAINTENANCE MANAGEMENT OF BUILDINGS

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ABSTRACT

Asset managers must be able to execute maintenance, rehabilitation and replacement (MR&R) strategies based on perceived economic advantage and prudence, while reflecting management's strategic plans for the facility. Given the complex nature of the building structure and makeup, with its intricate interconnection of building systems and components, it is imperative for asset managers to be able to closely monitor the performance of each building asset, and set priorities to the large number of projects and select the ones most feasible given the funds that are available and the maximization of benefits to the facility.

A Building Maintenance Decision Support System (BMDSS) has been developed to monitor and model the deterioration of building systems and components, to forecast the remaining service life of components, and to prioritize building systems and components. It utilizes the detailed inspections performed at the lowest level of the building hierarchy, and employs a roll-up procedure to determine the condition rating of the building. Further, the BDSS also provides the framework for prioritizing MR&R projects based on financial analysis and optimization tools that leads to maximum benefits within the framework of limited financial allocation.

KEY WORDS
decision support system, service life, deterioration, condition rating, optimization

INTRODUCTION

Many of our public facilities are over 40 year old, and are characterized by their seriously and continuously deteriorating condition as a result of aging, severe environmental conditions, and deferred maintenance decisions. In some instances, public agencies have been forced to extend the useful life of aging facilities; altering or retrofitting facilities to consolidate space or accommodate new functions and technologies; meeting evolving

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standards for safety, environmental quality and accessibility; and finding innovative ways and technologies to maximize limited resources. In today's dynamic policy and budget environment, asset managers are challenged to extend the useful life of aging facilities. Further, there is a continuous scarcity of resources available for the maintenance of buildings. This consequently results in only partial resources being made available for building maintenance, rehabilitation and replacement projects. Public agencies, which generally manage a large asset portfolio, find themselves in the predicament of having to allocate limited resources to deserving MR&R projects. Closely associated with this decision is the additional challenge of meeting the project requirements, a well as ensuring that the highest possible benefit accrues to the facility.

This paper presents a simple and effective decision making tool in the management of building maintenance. The Building Maintenance Decision Support System (BMDSS) was developed to provide a tangible and comprehensible methodology for modeling the deterioration of building components. It also presented a robust and flexible system of prioritizing building systems and components.

CONCEPTUAL FRAMEWORK

Figure 1 organizes the various procedures involved in the decision making process associated with a proactive approach in the maintenance management of a large portfolio of buildings. In the formulation of the BMDSS, the following were considered as key requirements:

1. Hierarchical decomposition of the building facilities and a methodological examination of the physical and functional state of existing building systems and components.
2. Prioritization of the various building systems, components, and elements that combine to make up a building facility. The system of prioritization must be able to represent the complex interaction that exists between building components.
3. Standardization and application of a building condition assessment program that provides baseline management information.
4. Application of a deterioration modeling mechanism that can utilize current condition assessment data to forecast the future condition of building components.
5. Rationalization of the various maintenance rehabilitation and replacement (MR&R) options available to building components.
6. Optimization of the MR&R budgets in instances where maintenance dollars are extremely scarce.

The BMDSS framework model brings together a collection of diverse tools that are capable of assisting asset managers to analyze their current maintenance management practices and make astute decisions regarding their building assets. Much of the cost information required for the analysis can be obtained from the Computerized Maintenance Management Systems (CMMS) that are currently utilized by public agencies.

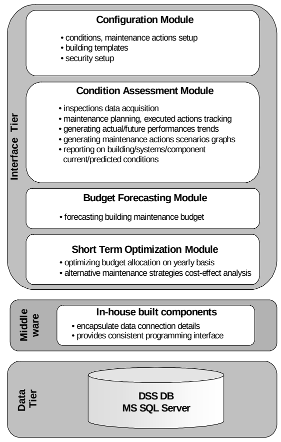
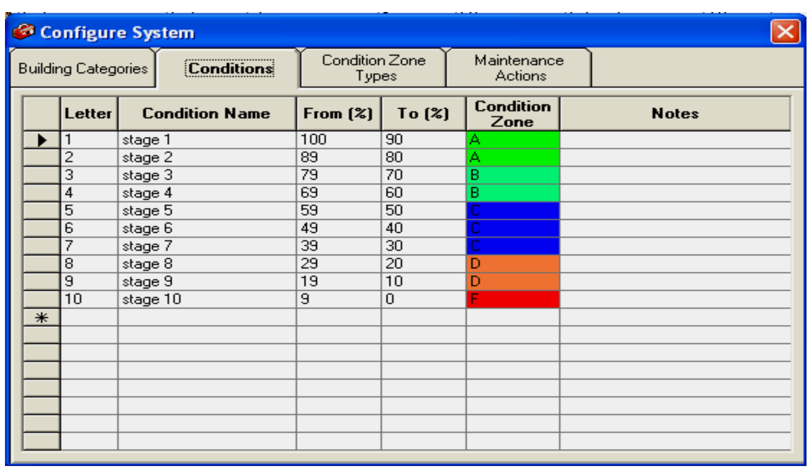


Figure 1: System Architecture of Building Maintenance Decision Support System

BUIDLING HIERCACHY

The building was decomposed into structural hierarchy of systems, components and elements, with the elements representing the lowest level at which maintenance activities are planned. The typical building element may represent a piece of equipment that may have an asset code or number associated with it; it is also the lowest management unit within the building schema. In order to fully scope the building's inventory, the UNIFORMAT II Elemental Classification system was used (Charatte and Marshall 1999). This system provided a trusted and tried process to map the inventory of basically any building type and an excellent framework for determining the overall condition index (CI) of a building. Building elements are inspected and assigned an inspection rating based on a specific performance scale (Uzarski and Burley 1997). The rating data are discrete ordinal measurements, which means that the numbers assigned do not indicate distances between ratings, but only a relative ordering. The condition performance rating scale is presented in Figure 2.



Letter	Condition Name	From (%)	To (%)	Condition Zone	Notes
1	stage 1	100	90	A	
2	stage 2	89	80	A	
3	stage 3	79	70	B	
4	stage 4	69	60	B	
5	stage 5	59	50	C	
6	stage 6	49	40	C	
7	stage 7	39	30	C	
8	stage 8	29	20	D	
9	stage 9	19	10	D	
10	stage 10	9	0	F	

Figure 2: Building component Condition Performance Rating Scale

USING AHP TO PRIORITIZE BUILDING COMPONENTS

Several authors have acknowledged the existence of a complex relationship among the functional building systems, and by extension their respective building components (Shohet and Perelstein 2004, Harris 1996, Hudson et al. 1997). The structuring of a building into a hierarchical framework of functional systems and components is fundamental to the application of the AHP methodology developed by Saaty (1996). This methodology facilitated the determination of the relative weights of each entity within the building structure. Researchers have applied the AHP methodology to solve problems in building maintenance (Shen et al. 1998, Spedding et al. 1995), and maintenance decision-making (Triantaphyllou et al. 1997). In each case, the AHP methodology was used to compensate for the lack of available data to help decision-makers to make proper evaluations and relatively accurate decisions. The developed model works in three stages. The first stage identifies the criteria upon which the evaluation and comparisons would be performed. The second stage prioritizes the different criteria by implementing a multi criteria evaluation method. And thirdly, based on the different criteria, the various building assets will be ranked. Figure 3 illustrates the building hierarchy.

PROBLEM STRUCTURING AND ALTERNATIVE DEVELOPMENT

The hierarchical features of the AHP present a convenient platform for conducting preliminary analysis in the domain of building facilities. Basically, the systems and components of a building structure can be decomposed into manageable elements with decreasing levels of uncertainty and ambiguity. Analyses can be performed at each level independently, but are linked and cumulated at higher levels in the hierarchy. Decisions and judgments can be made at each level (sub-hierarchy) of the structure, and finally aggregated to produce impacts higher in the hierarchy.

Furthermore, the interrelationships between systems and components can be quite multifaceted, resulting in complex interdependencies between components. As a consequence, the poor performance of one component can significantly affect the performance of another. The Analytical Hierarchy Process (AHP) methodology is capable of modeling this type of relationship. AHP uses established procedures to capture best rank from judgments, through the weighting and synthesizing of the decision process, into a hierarchy that is compatible with a network synthesized with various interdependencies. For this research, the AHP method was used to derive a single weighted score based on a specific set of criteria, for each component that is evaluated. Figure 4 shows an example of a typical input screen for the development of the priority weights.

DETERIORATION MODELING AND SERVICE PREDICTION

The deterioration of the physical and functional condition of a facility is a complex process, as shown by wear and aging due to usage, degradation of equipment and materials of construction as affected by the environment, and the interaction of these mechanisms. Deterioration modeling is therefore an integral and important part of infrastructure management. Maintenance and rehabilitation decision-making is based on current and future facility conditions. Current conditions are measured, and consequently their accuracy depends on the measurement technology. Future conditions, on the other hand, are predicted using a deterioration model. Hence reasonable predictions are essential for effective maintenance and rehabilitation decision-making.

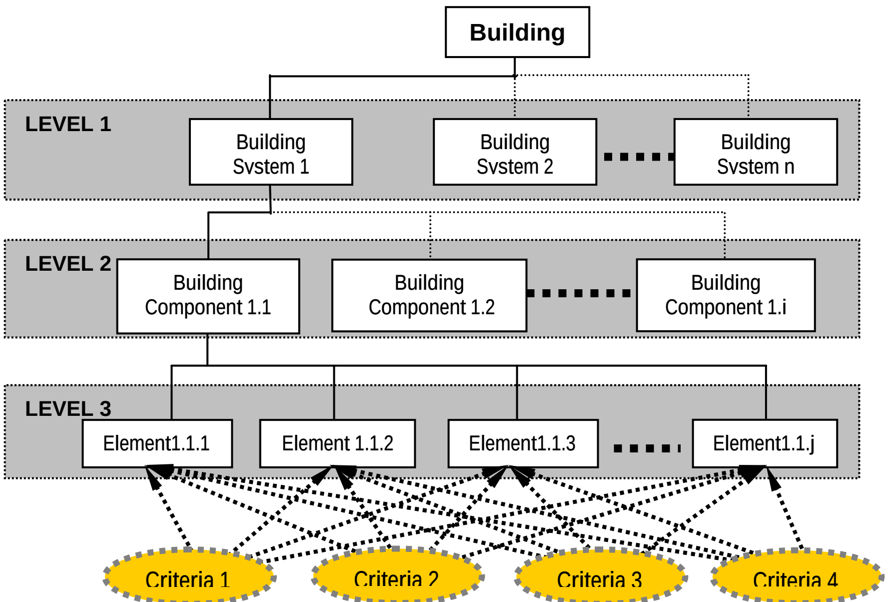


Figure 3: Hierarchical Framework for a Building

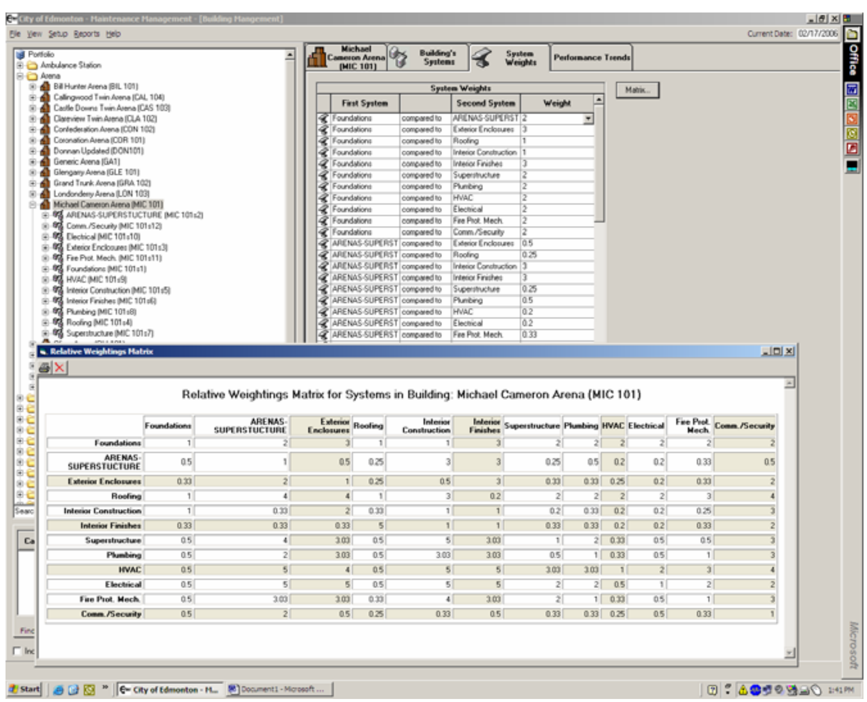


Figure 4: AHP application for the development of priority weights for components

STOCHASTIC MODELING APPROACH

The Markov chain model is a special type of stochastic process in which the conditional probability of any future event, given any past event and present state $\mathbf{S_t} = \boldsymbol{i}$, is independent of the past event and depends only on the present state. This property can be written as shown in equation (1) (Wirahadikusumah et al. 2001; Abraham et al. 1999).

$$P(S_{t+1} = i_{t+1} | S_t = i_t, S_{t-1} = i_{t-1}, \ldots\ldots\ldots\ldots, S_1 = i_1, S_0 = i_0) = P(S_{t+1} = i_{t+1} | S_t = i_t) \qquad (1)$$

The future condition of any component is assumed to depend only on the present state and is independent of $\boldsymbol{t}$. The probability $\boldsymbol{P_{ij}}$, that the component is in state $\boldsymbol{i}$ at time $\boldsymbol{t}$ and that it will be in state $\boldsymbol{j}$ at time $\boldsymbol{t + 1}$ does not change (remain stationary) over time. This stationary assumption is expressed by equation (2) (Zayed et al. 2002).

$$P(S_{t+1} = j | S_t = i) = P_{ij} \qquad (2)$$

Transition probabilities are commonly displayed as an $\boldsymbol{n \times n}$ matrix called a transition probability matrix $\boldsymbol{P}$. In this study, there are five states associated with the five possible conditions of building component ratings. State **A** corresponds to the best condition, and state **F** corresponds to the worst condition. The n-step transition probability matrix, $\boldsymbol{P^{(n)}}$, of the process that is in state $\boldsymbol{i}$ and will be in state $\boldsymbol{j}$ after $\boldsymbol{n}$ periods is computed by the Chapman-Kolmogrorov equation:

$$\boldsymbol{P^{(n)}} = \boldsymbol{P^n} \qquad (4)$$

To model the way in which any building component deteriorates over time, it is necessary to establish a Markov probability matrix. In this research, the assumption is made that a component's condition may not drop by more than one state in a single year. Thus the component will either stay in its current state or move to the next lower state in one year. Consequently, the transition probability matrix (TPM) will have the following general structure (Butt et al. 1994):

$$P = \begin{bmatrix} p(A) & q(A) & 0 & 0 & 0 \\ 0 & p(B) & q(B) & 0 & 0 \\ 0 & 0 & p(C) & q(C) & 0 \\ 0 & 0 & 0 & p(D) & q(D) \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} p(A) & 1-p(A) & 0 & 0 & 0 \\ 0 & p(B) & 1-p(B) & 0 & 0 \\ 0 & 0 & p(C) & 1-p(C) & 0 \\ 0 & 0 & 0 & p(D) & 1-p(D) \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5)$$

Where $\boldsymbol{p(i)}$ = probability of a element/component staying in state $\boldsymbol{i}$ during the duty cycle (of one year); and $\boldsymbol{q(i) = 1 - p(i)}$ is the probability of the component moving down to the next state $\boldsymbol{(i + 1)}$ during one duty cycle. In the absence of empirical data, expert judgments were used to determine the TPMs for various components.

As is evident from the zero entries in the transition matrix, it is assumed that a facility can either stay in its current state or deteriorate to some lower state. The entry of 1 in the last row of the transition matrix corresponding to state F indicates an "absorbing" state.

Building components cannot move from this state unless repair or rehabilitation action is performed. The state vector for any duty cycle or year ***n*** is obtained by multiplying the initial state vector ***S(0)*** by the transition probability matrix ***P*** raised to the power ***n***. Figures 5 and 6 highlight examples of generated deterioration curves.

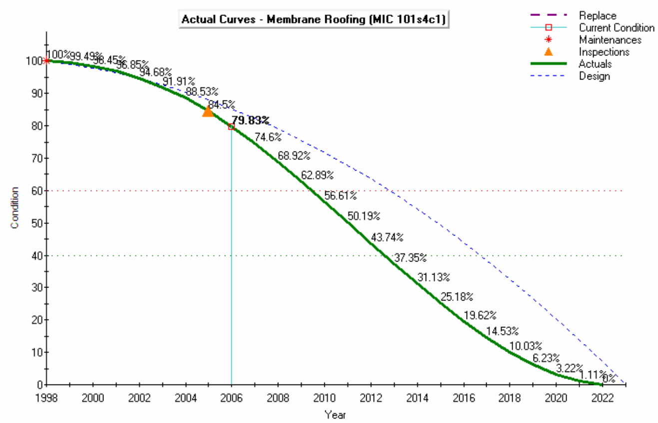


Figure 5: Generated deterioration curve for a building element/component

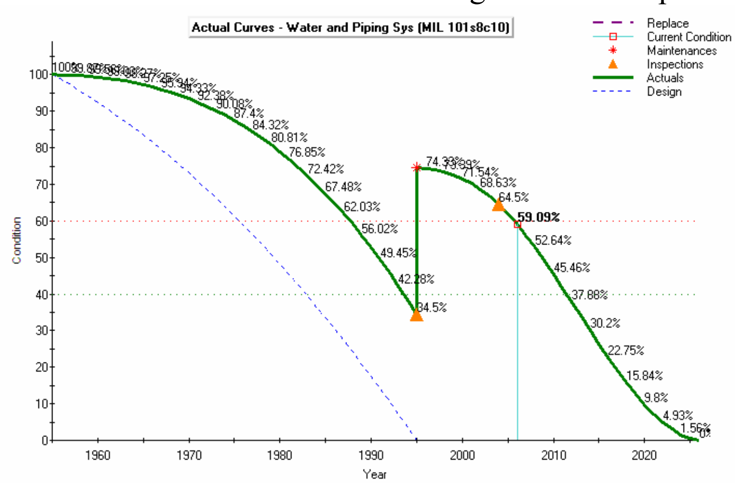


Figure 6: Deterioration curve for a rehabilitated building element/component

The Markovian model provides a reliable mechanism for developing prediction models. This process imposes a rational structure on the deterioration model because it explains the deterioration as an uncertain issue and it also ensures that the projections beyond the limits of the data will continue to have a worsening condition pattern with age. This model has been used in other types of infrastructure deterioration modeling, such as pavement and bridges (Wirahadikusumah 2001; Abraham et al. 1998; Butt et al. 1994).

OPTIMIZATION MODULE

For an Asset Manager tasked with the responsibility of managing a large building portfolio, the selection of candidate maintenance projects from a list of alternatives can be quite difficult. The multiplicity of possible alternatives for every candidate project makes it essential for the asset manager to devise methods for seeking and allocating resources by means of which the available resources can be divided among satisfactory solutions, while ensuring that the highest possible benefit is achieved. A quantitative model for selecting the most feasible MR&R alternative based on a combination of well-defined criteria would assist in this type of decision-making.

The aim of the optimization model, therefore, is to provide a methodology to assist the asset manager in determining the set of MR&R actions that will maximize the overall performance of the building under the current physical conditions of the systems of the building and under the current yearly budget constraints. The application of a hierarchical framework to the building lends itself to this approach.

REHABILITATION ALTERNATIVES

Four classes of maintenance, rehabilitation, and replacement (MR&R) strategies are available to the asset manager to respond to declining building systems and components.

- **Replacement of the component**: This option will ensure that the performance level and condition rating of the component will improve to **A.**
- **Major Rehabilitation:** This option will significantly improve the performance and condition of the component.
- **Minor Rehabilitation:** This is a partial rehabilitation that will marginally improve the condition of a component.
- **Marginal Repairs:** This option will not result in any noticeable improvement of the condition rating of the component, but it will serve to preserve its service life by preventing the asset from exceeding the level of intervention.

Cost estimates must be established for each maintenance and rehabilitation alternative strategy. This information will be a major input in the optimization module of the DSS. The budget allocation analysis is based on the current condition of building components (at time t) and their projected condition for following year (at time $t + 1$), as indicated by the deterioration curves. The requisite maintenance and rehabilitation alternatives will be selected for each component based on user requirements and needs. For some components, the only option may be to replace. For others, the full range of options may be applicable. For others still, only replacement and major rehabilitation may be the option of choice. The asset manager has the option of selecting any of the applicable strategies depending on the component type, condition of the component, and maintenance funds available. In the model development, a set of possible MR&R actions was selected for each component in each building system. The objective was to maximize the overall condition of the facility subject to the maintenance budget constraints, and any building component constraints. The Integer Programming formulation was utilized because of the simplicity of its application and its flexibility in use (Hudson et al. 1997).

OBJECTIVE FUNCTION

In attempting to formulate the model, the primary objective was to maximize the condition of the building, i.e., to ensure that the maximum condition rating accrues to the building irrespective of the maintenance budget available over the period of one year. For the time period ***(t + 1)***, therefore, the objective function can be represented as follows:

$$\text{Max B (t + 1)} = \sum_{i=1}^{n} w_i s_i (t+1) = \sum_{i=1}^{n} w_i \sum_{j=1}^{m} w_j^i c_j^i (t+1)$$

$$= \text{Max} \left[\sum_{i=1}^{n} \sum_{j=1}^{m} w_i s_i w_j^i c_j^1 (t+1) \right] \quad (6)$$

In a typical building system, the CI of components may vary widely depending on when they were installed and other relevant factors previously discussed in chapters 3 and 5. It is assumed that components are the lowest management unit to be considered in the building hierarchy. Therefore, in developing a maintenance strategy for time ***(t + 1),*** it is important to have cost estimates for all the maintenance options that are applicable to that component.

DEFINING THE CONSTRAINTS

The maintenance budget allocation to the building is the most important constraint, since it is usually predefined and cannot be altered or exceeded significantly (Shohet and Perelstein 2004, Hudson et al. 1997). Assuming that the annual maintenance budget is represented as **M**, this constraint is expressed as:

Building budget ≤ **M**

$$\therefore \sum_{i=1}^{n} \sum_{j=1}^{m} \$C_{jk}^i \leq M \quad (7)$$

Where, $\$C_{jk}^i$ is the cost for maintenance option ***k*** selected from A_{jk}^i for component ***j*** in building system ***i***.

CONCLUSION

The objective of the BMDSS was to facilitate the structuring of information for the purposes of making wise, cost-effective decisions regarding maintenance. It consisted of generic structures that facilitate the representation of complex infrastructure facilities in a hierarchically framework. This representation supports the replication of different building formats and allows the reuse of the structure at any decomposition level.

As asset managers continue to grapple with shrinking budgets and the need to maintain a high level of performance from a portfolio of increasingly aging building structures, there is a growing need for tools which enable planners to assess the overall condition of a system without substantially increasing costs. There is also a growing need for proactive maintenance and for a consistency in assigning conditions to inspected components. All of these objectives signify an overall need for the development of a thorough methodology and for a system based upon that methodology, which will enable users to respond to the needs they are facing. Our primary goal in this project was to fulfill this aim and to develop a system that is practical, versatile, and yet comprehensive in its scope.

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