EFFECTIVE DECISION-MAKING TOOLS FOR ROOFING MAINTENANCE MANAGEMENT

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Abstract

This paper presents a systematic decision-making approach for roofing maintenance management that combines a stochastic Markovian performance prediction model with a multi-objective optimization method to determine the optimal allocation of funds and prioritization of roofs for maintenance, repair and replacement. A product model of the roof system is used to provide the data framework for collecting and processing data. The prioritization of the roofs is based on the simultaneous satisfaction of several conflicting objectives, including minimization of maintenance and repair costs, maximization of the network condition rating, and minimization of risk of failure. The roofing maintenance management problem is formulated as a stochastic multi-objective optimization problem, where several conflicting objectives are simultaneously satisfied. Compromise programming is used to determine the optimal ranking of the deteriorated roofs in terms of their priority for repair and replacement, by achieving a satisfactory trade-off between the competing or conflicting objectives.

Résumé

Cet article présente une approche systématique de prise de décision pour la gestion d'entretien de toitures qui combine un modèle stochastique de type Markovien pour la prévision de la performance avec une méthode d'optimisation multi-objective pour déterminer l'attribution optimale de fonds et prioritisation des toits pour l'entretien, la réparation et le remplacement. Un modèle de produit du système de toit est employé pour fournir le cadre de données pour la collection et le traitement des données. Le prioritisation des toits est basée sur la satisfaction simultanée de plusieurs objectifs contradictoires, y compris la minimisation des coûts d'entretien et de réparation, la maximisation de la performance du réseau, et la minimisation du risque de rupture. Le problème de gestion d'entretien de toiture est formulé comme un problème d'optimisation multi-objectif et stochastique, où plusieurs objectifs contradictoires sont simultanément satisfaits. La méthode de programmation de compromis sera employée pour déterminer la classification optimale des toits détériorés en termes de leur priorité pour la réparation et le remplacement, en réalisant un compromis satisfaisant entre les objectifs contradictoires.

Keywords: maintenance management, Markovian model, multi-objective optimization, product model.

1. Introduction

1.1 BELCAM Project

The *Building Envelope Life Cycle Asset Management* (BELCAM) project is attempting to address growing problems faced by asset and building managers regarding when and how to repair or replace their building stock and components (Vanier and Lacasse, 1996). The dollar amounts involved for maintenance, repair and replacement (MR&R) are significant: A review of recent Canadian construction statistics shows that $8.5 billion is spent annually for repairs and maintenance to buildings; this is well below recommended maintenance expenditure levels. To make matters worse, some major property owners such as Public Works and Government Services Canada (PWGSC) - a co-founder in the BELCAM project - have forecast reductions in operating and maintenance budgets.

Effective decision-making tools are required by asset managers to assist them in choosing whether a building component, such as a roofing membrane, should be repaired or replaced, and when. The development of such tools is the main objective of the BELCAM project.

1.2 BELCAM Goals

The BELCAM project (Vanier and Lacasse, 1996) has identified two achievable goals that will assist asset managers in the course of their work:

(1) Develop tools, techniques and methodologies to predict the performance and service life of building components; and

(2) Establish protocols to optimize the maintenance management of facilities.

The BELCAM project is using a "*Proof of Concept*" approach to reach these goals. This project is concentrating on the service life of low-slope roofs in the initial three years of the project; however, the methodologies developed during the course of this research will be readily applicable to other building envelope systems. This paper describes two decision-making tools, namely a Probabilistic Markovian Modeling of Performance and Multi-Objective Optimization of Maintenance, that allow BELCAM to attain the aforementioned goals. Product Modeling, a data integration protocol, provides a third decision-making tool (Vanier, 1998).

1.3 Decision-Making Tools for Effective Roofing Management

One area of critical importance to meet the goals of the BELCAM project, amongst many, is the assessment of the probabilities of failure of roofing components and systems and associated risks of failure. Without such in-depth knowledge of the risk of roofing failure, it is impossible to prioritize repair or replacement projects. This paper proposes a systematic approach to roof management that combines a stochastic Markovian performance prediction model with a multi-objective optimization procedure to determine the prioritization of roof sections for maintenance, repair and replacement, and therefore the optimal allocation of funds. The proposed approach is shown schematically in Fig. 1, and is based on three key interrelated elements:

(1) Probabilistic models for performance prediction and risk assessment;

(2) Multi-objective optimization procedure for decision making under conflicting objectives;

(3) Product model of the roof system that provides the data framework for collecting and processing data.

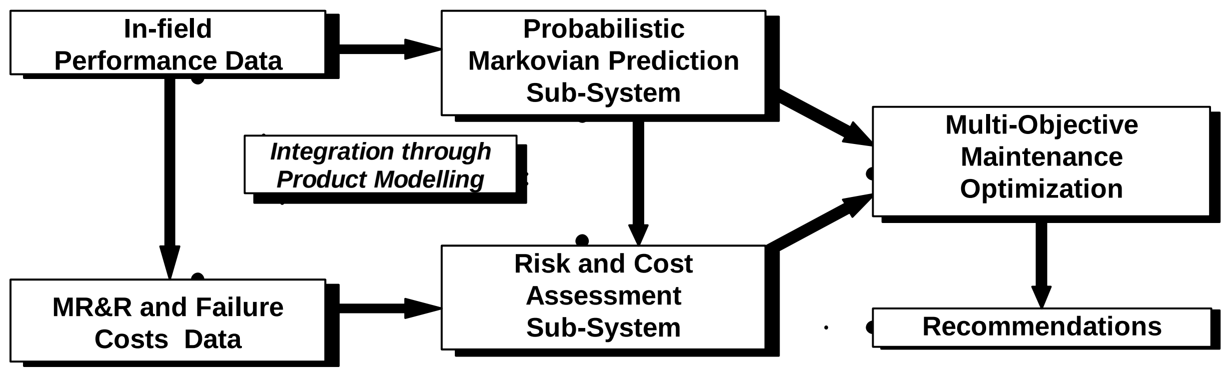


Fig. 1. *Decision-Making Tools for Roofing Management*

The performance prediction is based on a *probabilistic Markovian model* (Ross, 1996; Lounis et al., 1998) that captures the time-dependence, uncertainty and variability associated with the roof section performance (or condition rating). This model is developed from in-field performance data collected during roofing inspections, considering the system and material types, environmental conditions, age, workmanship quality and maintenance level. The performance predictions obtained from this probabilistic Markovian model are combined with a system risk assessment model to evaluate the probabilities of failure of the different roofing components and entire system taking into account the correlation between different components and failure modes. The consequences of failure can be evaluated from the available data on MR&R costs, and failure costs, which depend on the type of building, and type of failure (loss of water tightness, loss of energy control, structural collapse, and loss of structural serviceability). The risk of failure is obtained by weighting these costs of failure by their associated probabilities of failures.

The *multi-objective optimization* procedure is based upon compromise programming methods (Koski, 1984; Lounis and Cohn, 1995). The maintenance optimization problem is formulated as a stochastic multi-objective problem, where the simultaneous satisfaction of conflicting objectives is considered: namely, minimization of maintenance and repair costs, maximization of network condition rating, and minimization of risk of failure. Compromise programming is used to determine the optimal ranking of deteriorated roof sections, in terms of their priority for repair and replacement.

The Markov model and multi-objective optimization procedure have considerable data integration and communication demands. *A product model* is used to meet these data needs. Product modeling refers to the digital representation of elements that completely defines a product for all applications over its expected life. The product model proposed in the paper requires three major components (Vanier, 1998): (1) an elemental aggregation model of typical roofing systems, (2) a classification model of in-field roof performance characteristics, and (3) the instantiation of the subject roof portfolio.

This paper describes the framework needed to collect and analyze data required to prioritize repair and replacement projects in a given roof portfolio. It also identifies how the Markovian models, multi-objective optimization procedure and product models can be used to assist decision-makers maximize the return on investment of their maintenance expenditures.

2. Development of Performance Prediction and Risk Assessment Models

2.1 Performance Prediction using Probabilistic Markovian Models

The condition or performance of roofing components and systems deteriorate with time as a result of environmental degradation factors (temperature, solar radiation, water, wind), traffic loading, inadequate maintenance and poor workmanship. Moreover considerable uncertainty and variability are associated with the performance of roofing components resulting from the uncertainty and variability in the environmental factors, quality of workmanship and maintenance level. Hence, a probabilistic Markovian model, and more specifically a discrete Markov chain that captures both the time-dependence and randomness of the roofing performance is used in this project. The condition of roofing components and systems is represented by discrete condition ratings obtained by mapping the assessed damage levels to a 1-7 rating scale. As an example, a description of the seven ratings and associated damage levels used for the condition assessment of built-up roofing membranes is given in Table 1.

Table 1- *Condition Assessment of Built-up Roofing Membranes*

Condition Rating	Condition/State Description	Damage (%)
7	Excellent : No noticeable distresses/anomalies.	0-10
6	Very Good: Minor anomalies (e.g. small blisters).	11-25
5	Good: Presence of some distresses (ridges).	26-40
4	Fair: Moderate deterioration; Water tightness is still adequate.	41-55
3	Poor: Major deterioration; Potential loss of water tightness.	56-70
2	Very Poor: Extensive deterioration; Localized water leakage.	71-85
1	Failed: Extensive water leakage.	>85

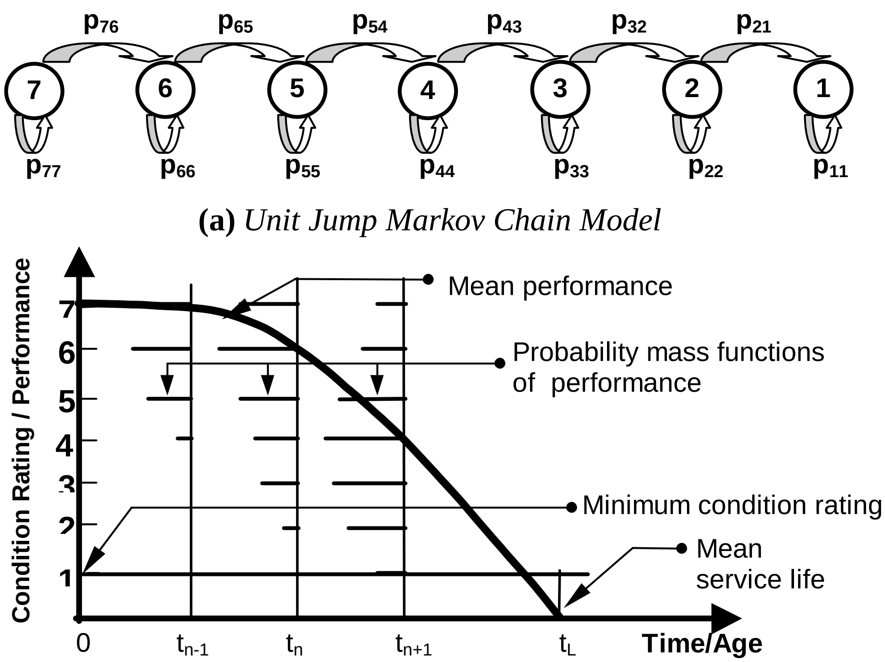
These condition assessment techniques have been applied for various infrastructure systems including bridges, pavements, dams, and roofs (Bailey et al., 1990; Lounis et al., 1998). A Markov chain is a stochastic process whose state space is finite, that may be described by the state space $\{\mathbf{S}(t_k) = 1, 2, \ldots, 7\}$, and time space $\{t_o, t_1, \ldots\ldots, t_n, \ldots\ldots, t_L\}$ such that the probability of a future state of the roofing component, $S(t_{n+1})$, at time t_{n+1} is governed solely by its present state $S(t_n)$ at time t_n and not its entire history (Ross, 1996), i.e.:

$$P[S(t_{n+1}) = s_j \mid S(0) = s_o, S(t_1) = s_1, \ldots, S(t_n) = s_i] = P[S(t_{n+1}) = s_j \mid S(t_n) = s_i] = p_{ij} \qquad (1)$$

The underlying assumption of the first-order Markov chain model is that the rate of deterioration is dependent upon the current stress and cumulative damage only, and not on the entire stress history. The transition probability, p_{ij}, represents the likelihood that the roofing condition will change from state i at time t_n to a lower state j at time t_{n+1}. The development of the Markovian model requires a relatively limited amount of historical performance data at two or more points in time. If the probability of a roofing component decaying by more than one state in one transition period is assumed negligible, the transition probability matrix is greatly simplified, and the deterioration process may be modelled by the unit-jump Markov chain shown in Fig. 2(a). Once the one-step transition probability matrix is generated, the future performance of the roofing component can be predicted using the n-step transition matrix as follows:

$$\mathbf{P}\{S(t_n)\} = \mathbf{P}\{S(0)\}\mathbf{P}^n \qquad (2)$$

in which $\mathbf{P}\{S(t_n)\}$ is the state probability matrix at time t_n after n transitions; $\mathbf{P}\{S(0)\}$ is the initial state probability matrix; and $\mathbf{P}$ is the transition probability matrix. The probabilistic prediction of the performance using Eq.(2) is illustrated in Fig. 2(b), which indicates the evolution with time of the probability mass function of roofing performance. Initially, the probability mass is close to condition rating 7. As the roofing component ages and deteriorates, this probability mass shifts from states of high condition ratings to those with lower ratings. The mean performance curve and the corresponding mean service life (t_L) are also shown in Fig. 2(b).



(b) *Probabilistic Performance Prediction*

FIG. 2. *Probabilistic Markovian Model for Performance Prediction*

The transition probability matrix is determined from the historical performance data collected during inspections. The proposed model enables the forecast of future performance of roofing systems throughout their entire service lives. Furthermore, the performance of roofing 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 validate the Markov chain model, it is necessary to develop transition probability matrices for roofing components and systems according to their classification with regard to these explanatory variables.

2.2 Data Collection

As mentioned earlier, the development of this probabilistic Markovian model is based on historical performance data of roofing components and systems collected throughout Canada. The locations of the participating Canadian agencies in the BELCAM consortium are identified by a large black dot in Fig. 3. These sites represent a wide range of buildings in geographically diverse and climatically challenging portions of the country. Each agency is to gather information on roofs under their mandate and forward the data for inclusion in a central database. The BELCAM standard data collection framework is the Fujitsu 1200 Stylistic™ pen-based computers running Microsoft Windows 95™ operating system and using *"MicroROOFER"* (Bailey et al., 1990) as a data acquisition software. In addition to the inventory, inspection and repair data, further information is required to adequately describe the explanatory variables listed above. Data relative to the design and as-built conditions, assessment of material and workmanship quality, as well as the condition of the structural elements is to be provided on all roofs surveyed for the BELCAM project. By gathering the data from these regional surveys over the next two years, the project will have generated the performance profile of a sample of roof sections that is representative of various climatic zones, construction techniques and maintenance practices and histories. Further data treatment, through the product modelling framework described in the next sections, will permit the grouping relative to the above explanatory variables. Further, this prediction model can be continuously improved using the Bayesian-updating method as additional performance data become available.

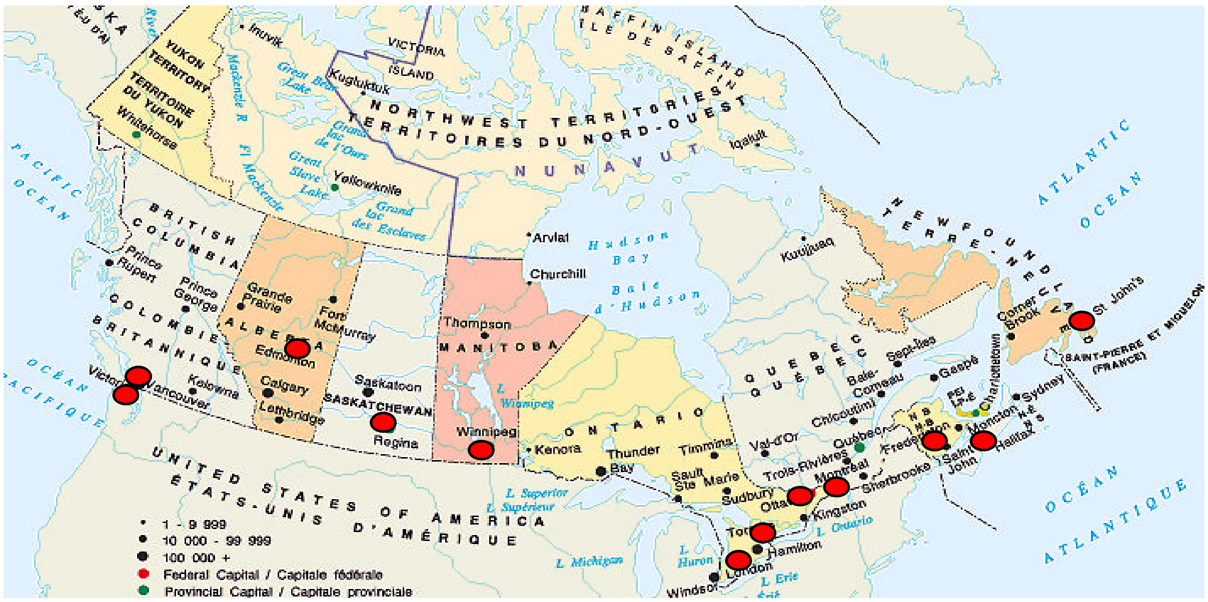


FIG. 3. *Historical Performance Data Collection Sites and Environmental Characterization*

2.3 Risk Assessment Model

A modern built-up roof system has in general five basic components: namely, a waterproofing membrane, thermal insulation, flashings, structural deck and possibly a vapor or air barrier. In general, there is some correlation between the performance of different components, which in turn has a direct impact on the performance of the entire roofing system, and its risk of failure.

2.3.1 Performance Requirements

The performance requirements of a roofing system can be summarized as follows:

- *Water Tightness*: prevention of water leakage into the building. This requirement is ensured by the waterproofing membrane and flashings;
- *Energy Control*: prevention or minimization of heat (or cooling) exchange between the interior and exterior. This requirement is ensured mainly by the thermal insulation;
- *Condensation Control*: prevention of water vapor condensation within the roof system using the vapor barrier;
- *Air Leakage Control*: minimize air leakage through the roof system by using the air barrier;
- *Load accommodation*: ability to sustain dead and live loads by the structural deck; and
- *Maintainability*: capability of economic repair.

2.3.2 Evaluation of Risk of System Failure

A roof is a multi-component system with multiple failure modes that can be modelled as a hybrid system comprised of a combination of series and parallel subsystems. The probability of failure of each roofing 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 roofing system may be evaluated once the consequences of failure are established. Two types of failures can be identified: (i) *Envelope failure*, defined by the loss of the envelope main functions (loss of water tightness and energy control), and (ii) *Structural failure*, defined by the deck failure that includes collapse and loss of serviceability. The envelope failure is the main concern of the BELCAM project. The cost of envelope failure depends on the value and vulnerability of the building contents under the roof, the costs of repair, energy costs and other incurred costs, such as costs of relocation and disruption.

3. Multi-Objective Optimization of Roofing Maintenance Management

At the network-level of maintenance management for a portfolio of roofs, the critical decision-making involves an optimal selection or prioritization of the projects that are in need of immediate MR&R. In general, this is not a straightforward task given: (i) large number of deteriorated roofs; (ii) limited funds available for MR&R; (iii) uncertainty and variability of the roofing performance; and (iv) different risks of failure are associated with different buildings, roof sections and components. Hence, it is clear that the actual 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. Specifically the optimization includes the following objectives: (1) minimization of MR&R costs; (2) maximization of network reliability; and (3) minimization of risk of failure. The solution of this maintenance management problem can be obtained using vector optimization techniques, and more specifically the compromise programming approach (Lounis and Cohn, 1993, 1995; Lounis and Vanier 1998), which is summarized in the following section.

3.1 Multi-Objective Optimization Methodology

For single-objective optimization problems, the notion of optimality is easily defined as the minimum or maximum value of some given objective function is sought. However, the notion of optimality in multi-objective optimization problems is not that obvious because of the presence of multiple, incommensurable and conflicting objectives. 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*" was adopted for the BELCAM project as the solution to its multi-objective optimization problem. Assuming that roofing sections with condition ratings less than or equal to 5 may be scheduled for MR&R, the corresponding multi-objective maintenance management problem can be mathematically stated as follows (Lounis and Cohn 1995):

$$\min\ \mathbf{f}(x)= [f_1(x)\ \ f_2(x)\ldots\ldots f_m(x)]^T \quad x \in \mathbf{W} \qquad [3a]$$

$$\mathbf{W} = \{x \in N\text{: } S_x(t)\ \leq 5\} \qquad [3b]$$

where $\mathbf{f}$ is the vector of objective functions; $\mathbf{W}$ is the subset of the roof network that at time t contains roofs with condition ratings $S_x \leq 5$; N is the entire roof network.

A solution x^* 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 (Koski 1984; Lounis and Cohn 1995). This Pareto optimality concept may be stated mathematically as follows (Koski 1984; Lounis and Cohn, 1993, 1995):

$$f_i(x) \le f_i(x^*) \text{ , for } i=1,2,\ldots,m \qquad [4a]$$

with

$$f_k(x) < f_k(x^*) \text{ , for at least one k.} \qquad [4b]$$

In general, for a multi-objective optimization problem, there are several Pareto optima, and the problem is to select the solution that achieves the best compromise between all competing objectives. Such a solution is referred to as "satisficing" solution in the multi-objective optimization literature (Koski 1984; Lounis and Cohn 1995, 1996). The determination of this satisficing solution is discussed in the next section.

3.2 Decision-Making under Conflicting Objectives

In compromise programming, the "best" or satisficing solution is defined as one that minimizes the distance from the set of Pareto optima to the so-called "ideal solution". This ideal solution is defined as the solution that yields the extreme (minimum or maximum) values for all objectives. Such a solution does not exist, but is introduced in compromise programming as a target or a goal to get close to, although impossible to reach. The adopted priority index is based on the minimization of the normalized deviation from the "ideal roof for repair" that is associated with the "ideal vector objective $\mathbf{f}^*$" measured by the family of L_p metrics defined as follows (Koski, 1984; Lounis and Cohn, 1995):

$$\min \ L_p(x) = \min_{x \in \Omega} \left[\sum_{i=1}^{m} \left| \frac{f_i(x) - \min \ f_i(x)}{\max \ f_i(x) - \min \ f_i(x)} \right|^p \right]^{1/p} \qquad [5]$$

These L_p ($1 \le p \le \infty$) metrics indicate how close the satisficing solution is to the ideal solution. For example, the minimum Euclidean distance (L_2) and minimax (L_∞) criteria are obtained for p=2, and p=∞, respectively. Another alternative to the above approach is possible through the introduction of weighting factors for the different objectives, depending on their relative importance with regard to the overall life-cycle management of roofs. The above criteria could be used to determine the satisficing solution and establish an optimal ranking of the roof sections in terms of their need for maintenance, repair and replacement. As an example, Fig.5 illustrates the priority indices (L_p) for a set of 12 sections of a given roofing network, where the priority is given for the sections with the lower priority indices L_p. A decision vector $\mathbf{d}=[d_1 \ d_2 \ d_3 \ d_4]^T$, which includes all MR&R strategies or decisions, is assumed: (i) d_1= do nothing (C_1=0); (ii) d_2=minor repair with a unit cost of C_2; (iii) d_3= rehabilitation (or major repair) with a unit cost C_3; and (iv) d_4= replacement with unit cost C_4. The cost-effectiveness of the different MR&R strategies may be evaluated in terms of their satisfaction of the selected objectives.

The proposed optimization approach represents the first step towards the development of a comprehensive roofing management system. The next step is the optimization of MR&R strategies within a finite or short term planning horizon, followed by an optimization within a longer planning horizon at both network- and project- levels of management. This task is achieved through the combination of the dynamic programming approach and the proposed multi-objective optimization procedure, in addition to the Markovian performance prediction model.

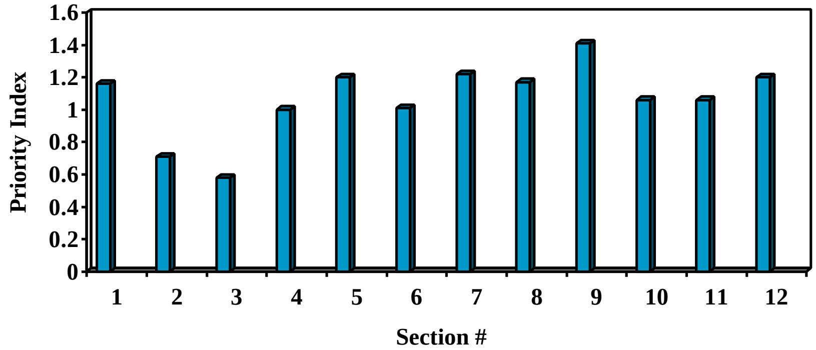


Fig. 4. *Multi-Objective Prioritization of Roofing Sections for MR&R*

4. Product Modelling

4.1 Overview

Product Modeling is a conceptual modeling field devoted to the digital representation of products. There are two major activities in this field that are related to the construction industry: ISO STEP (STandard for the Exchange of Product model data) and IAI (International Alliance for Interoperability). Both techniques support the "object-oriented" approach to data representation, with STEP being prevalent in the research community while the IAI predominates in construction practice. STEP has a longer history; whereas, the IAI appears to be gaining considerable grassroots' encouragement and support (Vanier, 1998). BELCAM has adopted the ISO STEP representation for its research for a number of pragmatic reasons (Vanier, 1998).

"ISO 10303 is an International Standard for the computer-interpretable representation and exchange of product data. The objective is to provide a neutral mechanism capable of describing product data throughout the life cycle of a product, independent from any particular system. The nature of this description makes it suitable not only for file exchange but also as a basis for implementing and sharing for product databases and archiving" (ISO 10303, 1998).

Although considerable work has been done in the STEP and IAI communities, very little can be used currently to address the needs of asset managers, and more specifically roofing management. Although product modeling in the building and construction domains has primarily concentrated on design and construction; product data models "should serve information handling throughout the design, manufacturing and usage phases of the life-cycle of the product with the purpose of computer-integrated design of the product and/or computer-integrated manufacturing and/or computer integrated information handling within the usage phase" (Svensson, 1998). The product data model should permit the exchange of geometric data, as well as, the intercommunication of product data throughout a product life-cycle.

4.2 Roofing System Product Model

In general, an EXPRESS-G model consists of Definitions and Relationships. The Definitions are concepts or things; these are the boxes shown in Fig. 5. The Relationships define the relations between Definitions; these are the lines joining the boxes. Heavy lines are used for "type_of" Relationships; whereas thin lines are for other relationships (e.g. a built-up roof is a "type_of" roof, whereas insulation is a "part of" a roof). Based on the general acceptance of EXPRESS-G tool by the construction product modeling community, it was selected to model the BELCAM requirements. Fig. 5 illustrates many of the data representation capabilities of the EXPRESS-G Language.

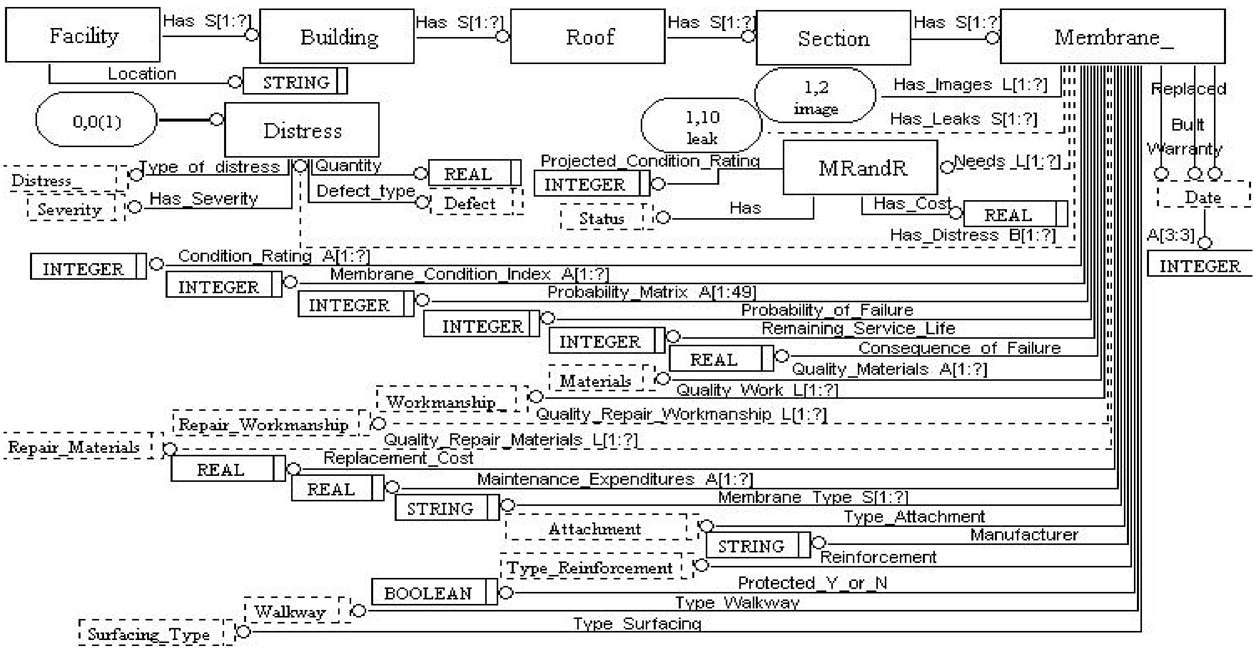


Fig. 5. *Roofing System Management Product Model*

5. Integration of Decision-Making Tools

5.1 Proposed BELCAM Process

BELCAM has two years remaining in the three years term of the project, and as such, should be viewed as *work in progress*. As mentioned earlier, the BELCAM project has a number of requirements to meet its aforementioned goals including : (1) collecting data for a number of roofing surveys to take place across North America in the upcoming two years; and (2) using this data to assist decision-makers to predict the remaining service life of roofing systems and to optimize the expenditure of their maintenance dollars.

It is anticipated that over 500 roofs will be surveyed in the course of the project by regional survey crews, with inspections recurring on an annual basis. This will be accomplished in the following steps: (1) obtain base building information, including drawings (.bmp, .dwg or .dxf), from the building owner to identify baseline information; (2) collect electronic information about the existing condition of the roof using MicroROOFER and pen-based systems, including digital images of distresses, to assess the baseline condition; (3) collect information for individual roofs regarding past maintenance activities and associated expenditures to document life cycle costs and level of MR&R investment; (4) upload new data to a central server to update the probabilistic model and the MR&R and failure costs; (5) query the central database on issues regarding specific roofing components to establish the remaining service life, and (6) use by asset managers of performance and service life data calculated in (5), in conjunction with risk data and MR&R costs to optimize the maintenance expenditures using multi-objective and dynamic programming approaches.

5.2 Integration Requirements

To support these processes, the roofing management product model has to communicate with the following applications:

- Condition assessment surveys (CAS) - MicroROOFER under MS Access;
- Digital Images - Kodak DC 210 with JPEG interface under Win95; and
- Risk Analysis-Markov chain prediction and multi-objective optimization (Lounis et al., 1998)

Future integration requirements include the following (these applications are not included in this discussion, but will be discussed in subsequent papers):

- CAD - AutoCAD DWG or DXF format for base building drawings or scanned images;
- Computerized maintenance management system (CMMS) - inventory system;
- Financial information management system (FIMS) -work order system;
- Energy analysis tools - calculation of heat loss of roofing insulation; and
- Geographical Information Systems (GIS).

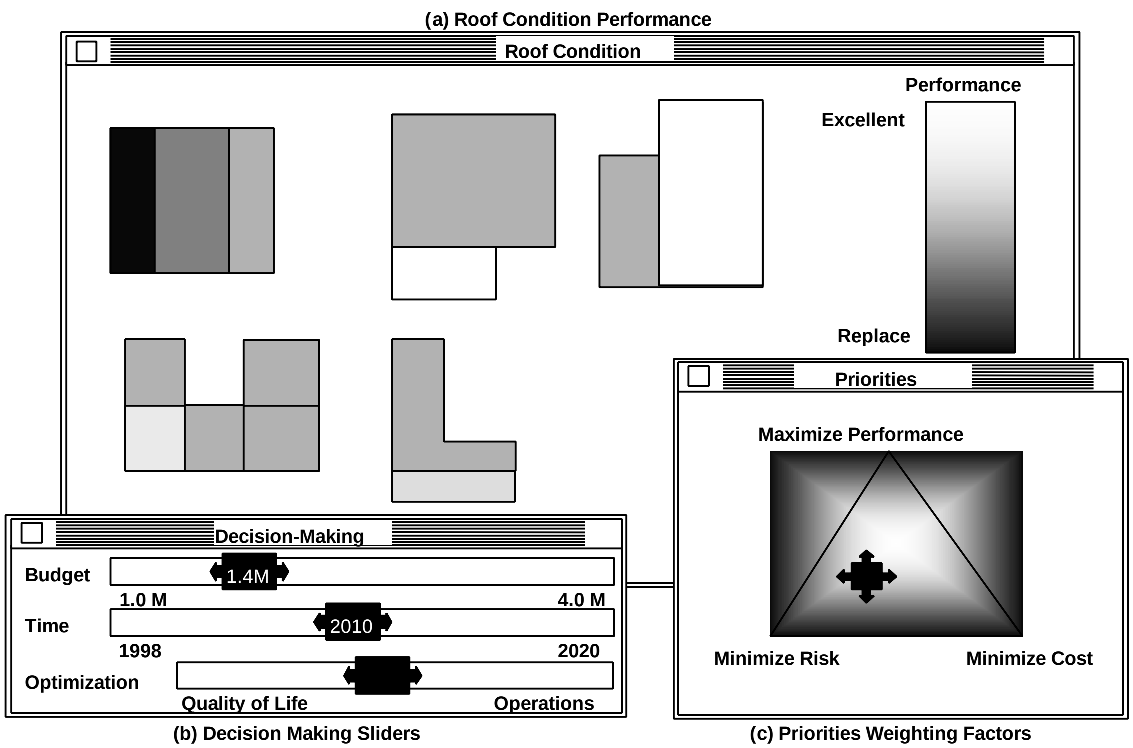


Fig. 6. *Proposed User Interface*

5.3 Proposed User Interface

The decision-making tool must have an intuitive interface such as the one proposed in Fig. 6. This interface should be able to permit the user to quickly and efficiently view the potential "*Roof Condition Performance*" of the assets as shown in Fig. 6(a), while being able to play "what if" scenarios by toggling the *"Decision-Making Sliders"* shown in Fig. 6(b), or the *"Priorities Weighting Factors"* shown in Fig. 6(c).

6. Summary and Conclusions

A multi-objective decision-making approach is proposed for the optimization of roofing maintenance management at both network and project levels. The problem has been formulated as a stochastic multi-objective optimization problem. A discrete Markov chain model is used to predict the performance of the roofing system during its service life. The maintenance optimization aims at satisfying simultaneously several conflicting objectives, including the minimization of the MR&R costs and risk of failure and maximization of the roofing network reliability or condition rating. Compromise programming is used to determine the optimal ranking of deteriorated roofs in terms of their priority for repair and replacement.

BELCAM's first goal of developing techniques for service life prediction is addressed by probabilistic Markovian modeling. The second goal of optimizing maintenance management is addressed by multi-objective optimization. These two goals could not be addressed without use of sophisticated computer applications; product modeling provides the data integration requirements for this project. The research plan is presented in this paper; however, considerable work is still required to collect the requisite data, to integrate the required applications, and to test and validate the techniques proposed in this paper. The decision-making tools proposed in this paper will assist asset managers to predict the remaining service life of roofing systems and will allow them to optimize the expenditures of their maintenance dollars. Hopefully, the techniques developed in the BELCAM project will be applicable to other building envelope domains.

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