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A Multiobjective and Stochastic System for Building Maintenance Management

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Abstract: *Building maintenance management involves decision-making under multiple objectives and uncertainty, in addition to budgetary constraints. This paper presents the development of a multiobjective and stochastic optimization system for maintenance management of roofing systems that integrates stochastic condition assessment and performance prediction models with a multiobjective optimization approach. The maintenance optimization includes the determination of the optimal allocation of funds and prioritization of roofs for maintenance, repair and replacement that simultaneously satisfy the following conflicting objectives: (i) minimization of maintenance and repair costs; (ii) maximization of network performance; and (iii) minimization of risk of failure. A product model of the roof system is used to provide the data framework for collecting and processing data. Compromise programming is used to solve this multiobjective optimization problem and provides building managers an effective decision support system that identifies the optimal projects for repair and replacement while it achieves a satisfactory trade-off between the conflicting objectives.*

1 INTRODUCTION

The research presented in this paper is part of a more comprehensive research program related to *Building Envelope Life Cycle Asset Management* and referred to as *"BELCAM"*. The *"BELCAM"* project is attempting to address growing problems faced by building managers regarding when and how to repair or replace their building stock and components[18,12]. A review of recent Canadian construction statistics shows that $8.5 billion is spent annually for repairs and maintenance of buildings; this is well below the recommended maintenance expenditure levels. To make matters worse, some major property owners such *as Public Works and Government*

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Services Canada (a co-founder in the *"BELCAM"* project) have forecast reductions in operating and maintenance budgets. Effective decision support systems are required by asset and building managers to assist them in choosing whether a building or a building component, such as a roofing membrane, should be repaired or replaced, and when.

The main objective of the *"BELCAM"* project is the development of a life-cycle roofing maintenance management system at the network-level that will yield improved performance and reliability, reduced life-cycle costs, and extended service life of roofing elements. This system consists of many subsystems as illustrated in Figure 1. The main components of the system are:

- Condition assessment of roofing components using in-field visual inspection and non-destructive testing;
- Prediction of future performance and remaining service life of building elements using stochastic Markovian models ;
- Multi-objective maintenance optimization of roofing maintenance by considering multiple conflicting objectives, namely: (i) minimization of maintenance costs; (ii) maximization of network performance; and (iii) minimization of risk of failure.

The *"BELCAM"* project is using a *"Proof of Concept"* approach to reach its 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 a multi-objective optimization approach for maintenance management that seeks to find the satisficing solution that minimizes roofing network cost, risk and deterioration. The development of this optimization approach requires the prediction of the future roofing network performance using a discrete Markov chain, and the assessment of the risk of failure of the roofing system, including the membrane, insulation, flashing and deck.

2 ROOFING MANAGEMENT SYSTEM

The roofing management system proposed in the *"BELCAM"* project represents a systematic and cost-effective approach to the maintenance of a large stock or network of roofs of different buildings with different occupancies and operating conditions. This system combines a stochastic Markovian performance prediction model with a multi-objective optimization procedure to determine the optimal prioritization of roof sections for maintenance, repair and replacement, and the optimal allocation of funds. The proposed approach is shown schematically in Fig. 1, and is based on the following three key interrelated subsystems:

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.

The performance prediction is based on a probabilistic Markovian model[11,12,14,15] that captures the time-dependence, uncertainty and variability associated with the roofing system performance. This model is developed from in-field performance data collected (Fig. 1) 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 cost data on Maintenance, Repair and Replacement (MR&R), in addition to the cost of failure, which depend on the type of building and occupancy under the roof, and type of failure. Failure refers to the loss of water tightness, loss of energy control, structural collapse, and loss of structural serviceability. The risk of failure is obtained by multiplying the cost of failure by its associated probability of failure.

The multi-objective maintenance optimization is based upon compromise programming method[3,6,8,9], where the simultaneous satisfaction of conflicting objectives is considered: namely, minimization of maintenance and repair costs, maximization of network performance, and minimization of risk of failure. This optimization yields the optimal ranking of deteriorated roof sections, in terms of their priority for repair and replacement. One of the main advantages of multiobjective optimization is that it provides an organized approach to assist decision-making in the presence of conflicting and incommensurate objectives[16].

The approaches used in the development of this roofing management system, namely: the Markov chain model, the probabilistic risk assessment model and the multi-objective optimization method, have considerable data integration and communication demands that are readily met via a product model. 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 this paper requires the following three major components[19]:

1. An elemental aggregation model of typical roofing systems;
2. A classification model of in-field roof performance characteristics; and
3. An 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 roofing portfolio. It also identifies how the Markovian prediction models, multi-objective optimization approach and product models can be used to assist decision-makers maximize the return on investment of their maintenance expenditures.

3 PROBABILISTIC PERFORMANCE PREDICTION AND RISK ASSESSMENT 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 level of maintenance. 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 to assess the current condition and predict the future condition or performance.

3.1 Markov Chain Modeling of Roofing Performance

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 condition ratings and associated condition indices used by *"Roofer"*[2] for the condition assessment of roofing components is given in Table 1. These condition assessment techniques have been applied for various infrastructure systems including bridges, roofs, pavements, etc. [2,10] . 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 [14,15], i.e.:

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

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 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 modeled 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 [14,15]:

$$\mathbf{P}[S(t_n)] = \mathbf{P}[S(0)]\, \mathbf{P}^n \quad (2)$$

in which $\mathbf{P}[S(t_n)]$ is the state probability matrix at time t_n (or after n transitions); $\mathbf{P}[S(0)]$ is the initial state probability matrix; and $\mathbf{P}$ is the transition probability matrix.

The probabilistic performance prediction 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, however, as the roofing component ages and deteriorates, the probability mass shifts from states of high condition ratings to lower rating states. The mean performance curve and the corresponding mean service life (t_L) are also shown in Fig. 2(b).

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 ensure the validity of the Markov chain model, it may be necessary to develop transition probability matrices for roofing components and systems according to their classification with regard to these explanatory variables.

As mentioned earlier, the development of this probabilistic Markovian model is based on historical performance data of roofing components and systems that are being collected throughout Canada[12]. The selected data collection sites represent a wide range of buildings in geographically diverse and climatically challenging parts of the country. Each *"BELCAM"* project partner 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 the *"MicroROOFER"* system[2] as a data acquisition software[2].

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. Further data treatment, through the product modeling framework described in the next sections, will permit the grouping relative to the above explanatory variables. Moreover, this prediction model can be continuously improved using the Bayesian-updating technique as additional performance data become available.

3.2 Risk Assessment Model

A modern built-up roof system has in general five basic components: (i) waterproofing membrane; (ii) thermal insulation; (iii) flashings; (iv) structural deck; and (v) 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. 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.

A roof is a multi-component system with multiple failure modes that can be modeled as a hybrid system comprised of a combination of subsystems that are in series and parallel. 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:

- *Envelope failure*, defined by the loss of the envelope main functions (loss of water tightness and energy control); and
- *Structural failure*, defined by the deck failure that includes collapse and loss of serviceability.

In the *"BELCAM"* project, a greater emphasis is placed on the envelope failure, as a result of its higher frequency and excessive maintenance costs. The costs associated with envelope failure include the damage costs to the building contents under the roof, the costs of repair, energy costs and other incurred costs, such as costs of relocation and disruption.

4 MULTIOBJECTIVE MAINTENANCE OPTIMIZATION

At the network-level of maintenance management of a portfolio of roofs, the critical decision-making involves the 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) difference in risks of failure 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, roofing maintenance optimization includes the following three objectives: (i) minimization of MR&R costs (f_1); (ii) maximization of network performance (f_2); and (iii) minimization of risk of failure (f_3). In general, it is very difficult to estimate an overall utility function that includes all conflicting objectives[8,] and apply multiattribute utility theory to solve the optimization problem. To overcome this difficulty, multiobjective optimization methods, and more specifically the compromise programming approach[8] will be used in the *BELCAM* project to solve this maintenance management problem.

4.1 Multi-Objective Optimization and Pareto Optimality Concept

The methods of multiobjective optimization have been successfully applied to civil engineering optimization problems within the deterministic [3,4,6,7,8,13] and probabilistic frameworks[5,9,10]. 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, conflicting, and incommensurable 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"* is adopted in the *"BELCAM"* project as the solution to the multi-objective maintenance optimization problem. Assume that roofing sections with condition ratings less than or equal to some prescribed minimum value (S_{min}) may be scheduled for MR&R, and that the available budget for MR&R is B. Hence, the corresponding multi-objective maintenance management problem can be mathematically stated as follows[8]:

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

$$\Omega = \{x \in N\text{: } S_x(t) \le S_{min} \text{ ; and } \sum B_x(t) \le B\} \tag{3b}$$

in which **f** represents the vector of objective functions; Ω is the subset of the roofing network that at time t contains roof sections x with condition ratings less than or equal to the prescribed minimum value ; $\sum B_x(t)$ is the sum of MR&R costs for all roof sections; and 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[3,4,5,6,7,8], i.e.:

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

with

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

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[6,8,9]. The determination of this satisficing solution is discussed in the next section.

4.2 Decision-Making under Conflicting Objectives

In compromise programming, the "best" or "satisficing" solution is the one that minimizes the distance from the set of Pareto optima to a so-called "ideal solution" x^* which is defined as the solution that yields simultaneously extreme (minimum or maximum) values for all objectives. Such a solution does not exist (non-feasible), but is introduced in compromise programming as a target or a goal to get close to, although impossible to reach. Hence, the ideal solution is associated with the following "ideal vector objective $\mathbf{f}^*$":

$$\mathbf{f}^*(\mathbf{x}) = [\min f_1(x) \ \ \min f_2(x) \ \ldots\ldots \ \min f_m(x)]^T \qquad (5)$$

In our project, the ideal vector objective is the one that yields simultaneously minimum maintenance cost, maximum performance (or reliability), and minimum risk of failure. To achieve these objectives, the optimal sections for MR&R are those with minimum MR&R cost, minimum condition rating, and maximum risk of failure. Therefore, the satisficing solution is the one that minimizes the distance from the above "ideal" and non-feasible solution to the Pareto optima set. The distance measure used is the family of normalized and weighted L_p metrics, and the satisficing solution is the one that yields a minimum for the following L_p metric function:

$$\min\ L_p(x) = \min_{x \in \Omega} \left[\sum_{i=1}^{m} w_i{}^p \left| \frac{f_i(x) - \min\ f_i(x)}{\max\ f_i(x) - \min\ f_i(x)} \right|^p \right]^{1/p} \quad (1 \le p \le \infty)(6)$$

in which w_i are the weights associated with the corresponding objective functions f_i (i=1,2,…,m). The weighting of the maintenance objectives depends on the attitude of the decision-maker towards risk (risk averse or risk prone), economy, and network reliability. This L_p metric function indicates how close the satisficing solution is to the ideal solution, and the value of p indicates the type of distance. If p=1, all deviations from the ideal solution are considered in direct proportion to their magnitudes, which corresponds to a "group utility"[3]. However, for p≥2, a greater weight is given to larger deviations in the metric function, and L_2 represents the Euclidean metric. For p=∞, the largest deviation is the only one taken into consideration, and L_∞ is referred to as Chebyshev metric or "minimax criterion" and corresponds to a purely "individual utility"[3,6,8].

For the *"BELCAM"* project, the Euclidian metric function L_2 is adopted as a priority index for the establishment of the optimal ranking of roofing sections in terms of their need for maintenance, repair and replacement by considering simultaneously the MR&R cost, risk of failure and performance. 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. This task will be achieved through the combination of the dynamic programming method with the proposed multi-objective optimization approach.

5 PRODUCT MODELING

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[19]. *"BELCAM"* has adopted the *ISO STEP* representation for its research for a number of pragmatic reasons[19].

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 computer system, or application. 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.

Even though 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. Product modeling in the building and construction domains has primarily concentrated on design and construction; however, it should be further developed to encompass 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[18]. The product data model should permit the exchange of geometric data, as well as, the intercommunication of product data throughout a product life cycle.

In general, an *EXPRESS-G* model consists of Definitions and Relationships. The Definitions are concepts or things; these are the boxes shown in Fig. 3. 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.

6 INTEGRATION OF DECISION-MAKING TOOLS

As mentioned earlier, the *“BELCAM”* project has a number of requirements to meet its aforementioned goals, including: (i) collection of performance data from a number of roofing surveys taking place across North America; and (ii) assist decision-makers in predicting the remaining service life of roofing systems and optimizing their maintenance expenditures.

6.1 Proposed BELCAM Process

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:

- Obtain base building information, including drawings (.bmp, .dwg or .dxf), from the building owner to identify baseline information;
- Collect electronic information about the current roof condition using ‘*MicroROOFE*R” and pen-based systems, including digital images of distresses, to assess the baseline condition;
- Collect information for individual roofs regarding past maintenance activities and associated expenditures to document life cycle costs and level of MR&R investment;
- Upload new data to a central server to update the probabilistic model and the MR&R and failure costs;
- Query the central database on issues regarding specific roofing components to establish the remaining service life; and

- Use by asset managers of the performance and service life data calculated above in conjunction with risk data and MR&R costs to predict remaining service life and to optimize the maintenance expenditures using multi-objective and dynamic programming approaches.

6.2 Integration Requirements

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

- Condition assessment surveys using the *"MicroROOFER"* system[2] under MS Access™;
- Digital images of inspected roofs- Kodak™ DC 210 with JPEG interface under Win95™;
- Markov chain prediction of future performance and risk analysis[12]; and
- Multi-objective optimization of roofing maintenance[12].

  Future integration requirements include the following:
- 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).

6.3 Proposed User Interface

The maintenance decision-making system must have a graphical interactive interface such as the one proposed in Fig. 4. Such an interface would enable the decision-maker to quickly and efficiently view the predicted future "*Condition*", "*Risk Profile*", "*MR&R Costs*", and "*Priority Profile for MR&R*" of the building roofs at any time within the planning horizon, as shown in Fig. 4(a). The proposed interactive interface allows the building manager to study the impact of different objectives on the optimal maintenance plan and perform "what if" scenarios by toggling the *"Objective Weighting Factors"* sliders (w_1, w_2, w_3) shown in Fig. 4(b), depending on his risk aversion. Furthermore, this interface permits a quick assessment of the impact of varying the allocated budget on the network performance, risk of failure, and maintenance backlog. Fig. 4(a) shows graphically the priority profile for MR&R of a network of five buildings with 14 sections, where the black and white colors indicate high and low priority, respectively, while intermediate levels of priority are identified by intermediate grey colors.

7 ILLUSTRATIVE EXAMPLE

The multiobjective optimization approach presented in this paper is applied for the optimal maintenance management of five buildings with different occupancies under the roofs. The 5 roofs are divided into 14 sections as shown in Fig. 4(a). Assume that the maintenance is limited to the sections with condition ratings of 3 or less and that a $270,000 maintenance budget is allocated for the current year. The data on the condition rating, risk of envelope failure, and maintenance costs for the critical roof sections are summarized in Table 2. The total MR&R cost for the seven critical sections is $520, 000, which is about twice the allocated budget.

From Table 2, the "ideal" (non-feasible) roof section is associated with the following vector objective $\mathbf{f}^* = [f_{1min}\ \ f_{2min}\ \ f_{3max}]^T = [1\ \ 35{,}000\ \ 50{,}000]^T$. This means that the first section for MR&R is the one that has minimum condition rating, minimum MR&R cost, and maximum risk of failure. Obviously, such a section does not exist, however, the objective in compromise programming is to select those sections that are the closest to this so-called "ideal solution". Fig. 5(a) shows the variations of the normalized deviations from the ideal objective values for all sections, which are bounded by the values 0 and 1. A normalized deviation of 0 indicates that the section has the same objective value as the ideal value for the considered single objective, while a value of 1 indicates that the section is the farthest from the ideal solution. Using the Euclidian metric (Eq.6) 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.5(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, i.e. sections 1 and 3 have the highest and lowest priority respectively, as illustrated in Figs.4 (a) and 5(b). The other sections are not included because their condition ratings are higher than 3 and have low risk of failure. Hence, 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.

8 CONCLUSIONS

A multiobjective and stochastic system that integrates probabilistic performance prediction and risk assessment models with a multiobjective optimization approach is proposed for roofing maintenance management at the network level. The multiobjective maintenance optimization seeks to satisfy simultaneously three conflicting objectives: minimization of maintenance costs, minimization of risk of failure, and maximization of performance (or reliability). The compromise programming method is used to determine the optimal ranking of deteriorated roofs in terms of their 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 development of this management system is the main objective of the *"BELCAM"* project. This objective can not be addressed without the use of sophisticated computer tools, namely the use of product modeling that 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 support tools proposed in this paper will assist building managers in predicting the remaining service life of roofing systems and will allow them to optimize their maintenance expenditures. Moreover, the techniques developed in the *"BELCAM"* project will be applicable to other building systems, or for that matter other infrastructure systems.

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FIGURE CAPTIONS

Fig. 1. Decision support tools for roofing maintenance management.

Fig. 2. Probabilistic Markovian model for performance prediction.

Fig. 3. Roofing system product model.

Fig. 4. Proposed user interface for roofing maintenance management: (a) multiobjective-based priority profile for MR&R of a roofing network; (b) maintenance objectives and weights; (c) planning horizon and allocated budgets.

Fig. 5. Multiobjective optimization of roofing maintenance: (a) normalized deviations from ideal objective values for all sections; (b) Euclidian metric-based priority index for roofing maintenance.

TABLE TITLES

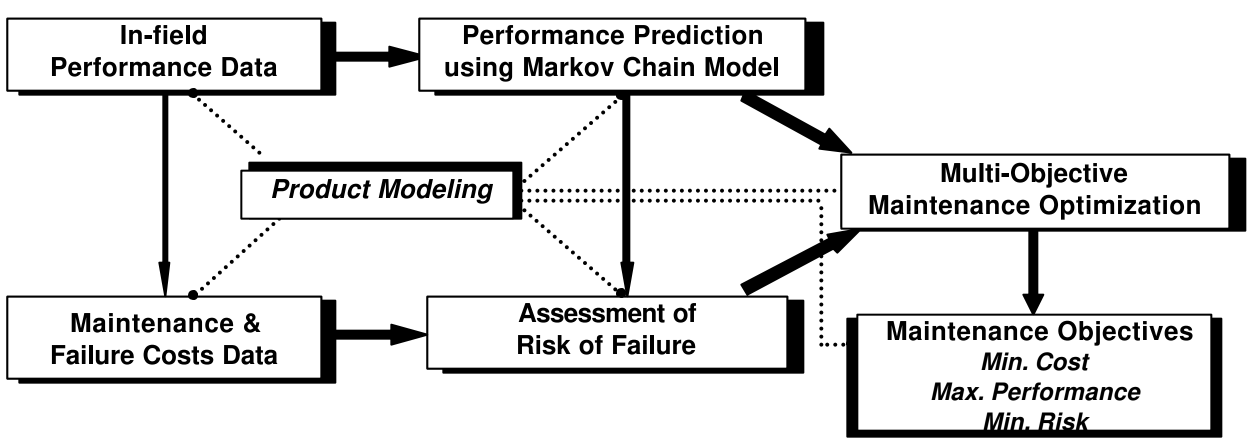
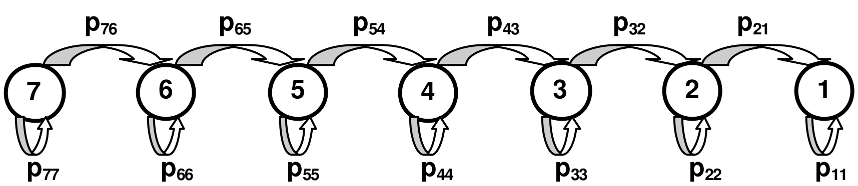
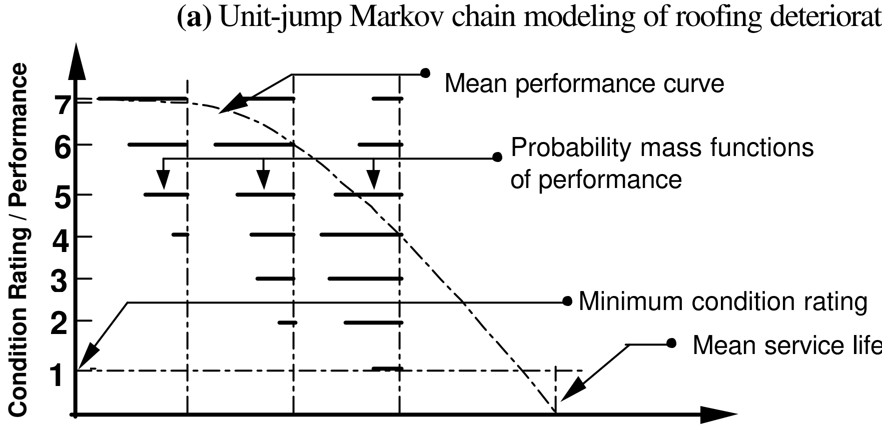

In-field
Performance Data
Performance Prediction
using Markov Chain Model
Product Modeling
Multi-Objective
Maintenance Optimization
Maintenance &
Failure Costs Data
Assessment of
Risk of Failure
Maintenance Objectives
Min. Cost
Max. Performance
Min. Risk

Fig. 1. Lounis & Vanier

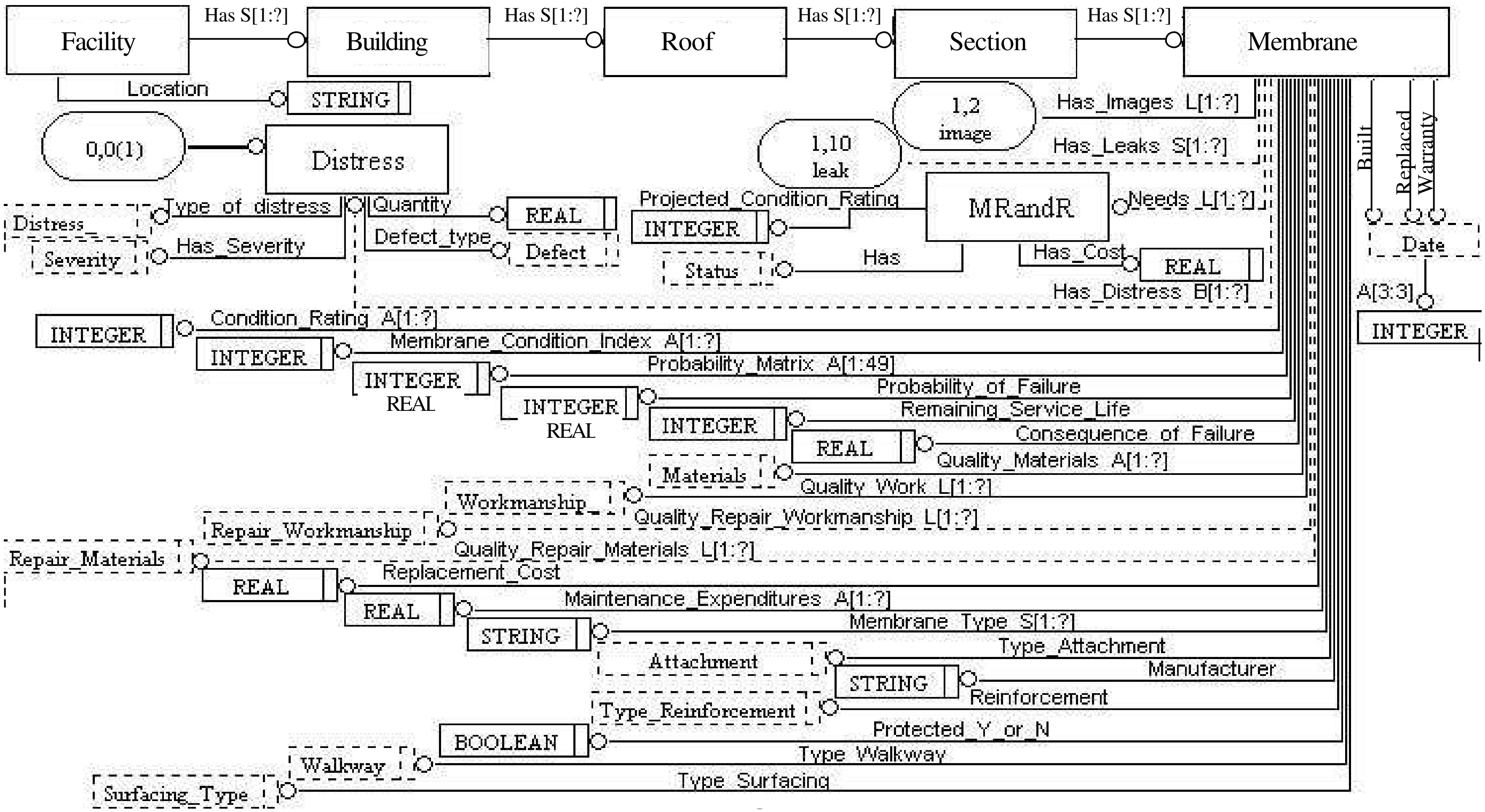


(a) Unit-jump Markov chain modeling of roofing deterioration



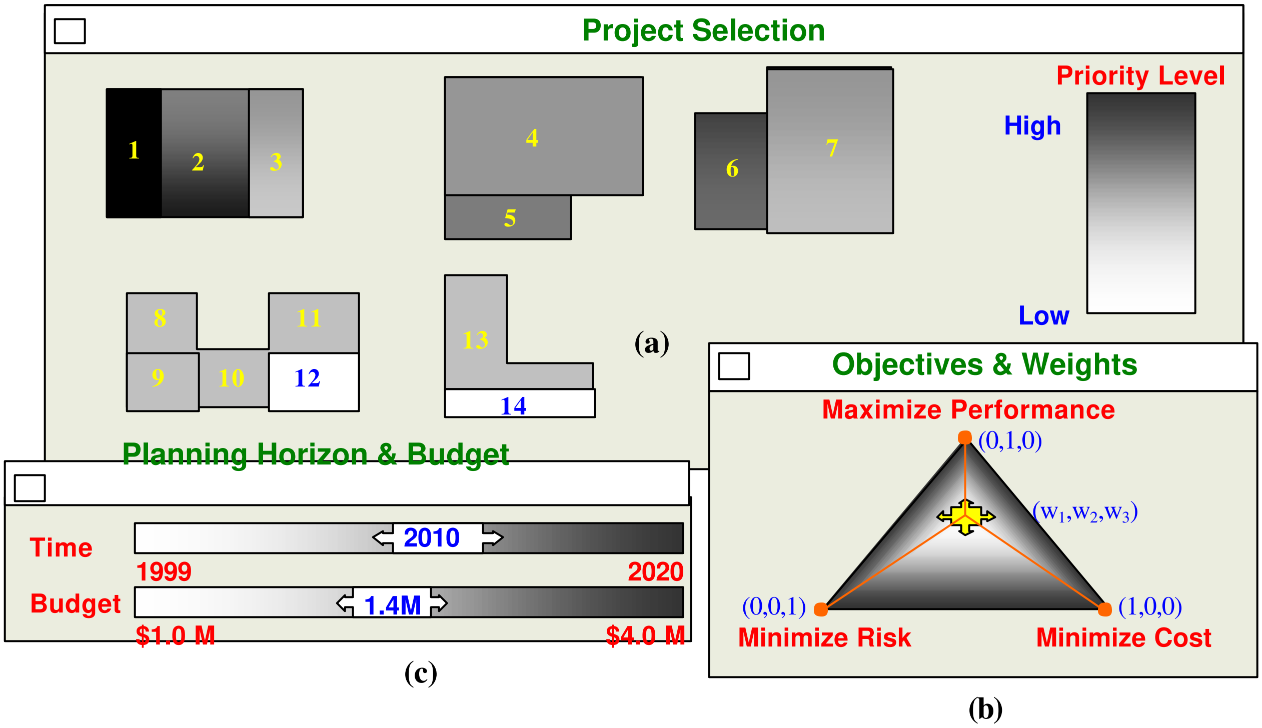
(b) Probabilistic performance prediction

Fig.2. Lounis & Vanier



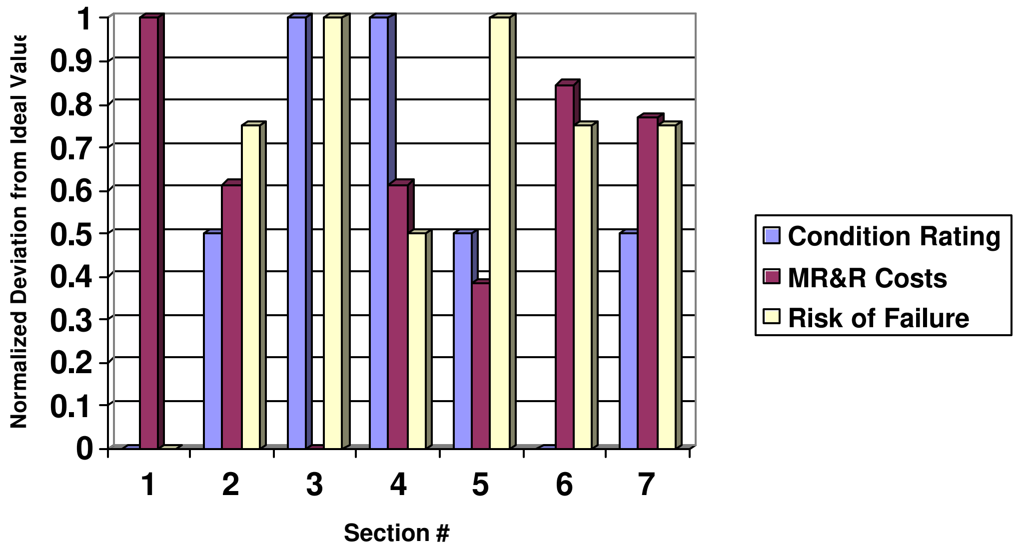
Facility
Has S[1:?]
Building
Has S[1:?]
Roof
Has S[1:?]
Section
Has S[1:?]
Membrane
Location
STRING
0,0(1)
Distress
1,2
image
1,10
leak
Has_Images L[1:?]
Has_Leaks S[1:?]
Built
Replaced
Warranty
Type_of_distress
Quantity
REAL
Projected_Condition_Rating
MRandR
Needs L[1:?]
Distress_
Defect_type
Defect
INTEGER
Date
Severity
Has_Severity
Status
Has
Has_Cost
REAL
Has_Distress B[1:?]
A[3:3]
INTEGER
Condition_Rating A[1:?]
INTEGER
Membrane_Condition_Index A[1:?]
INTEGER
Probability_Matrix A[1:49]
INTEGER
REAL
Probability_of_Failure
INTEGER
REAL
Remaining_Service_Life
INTEGER
Consequence_of_Failure
REAL
Quality_Materials A[1:?]
Materials
Quality_Work L[1:?]
Workmanship
Quality_Repair_Workmanship L[1:?]
Repair_Workmanship
Quality_Repair_Materials L[1:?]
Repair_Materials
Replacement_Cost
REAL
Maintenance_Expenditures A[1:?]
REAL
Membrane_Type S[1:?]
STRING
Type_Attachment
Attachment
Manufacturer
STRING
Reinforcement
Type_Reinforcement
Protected_Y_or_N
BOOLEAN
Type_Walkway
Walkway
Type_Surfacing
Surfacing_Type
INTEGER

Fig.3. Lounis & Vanier

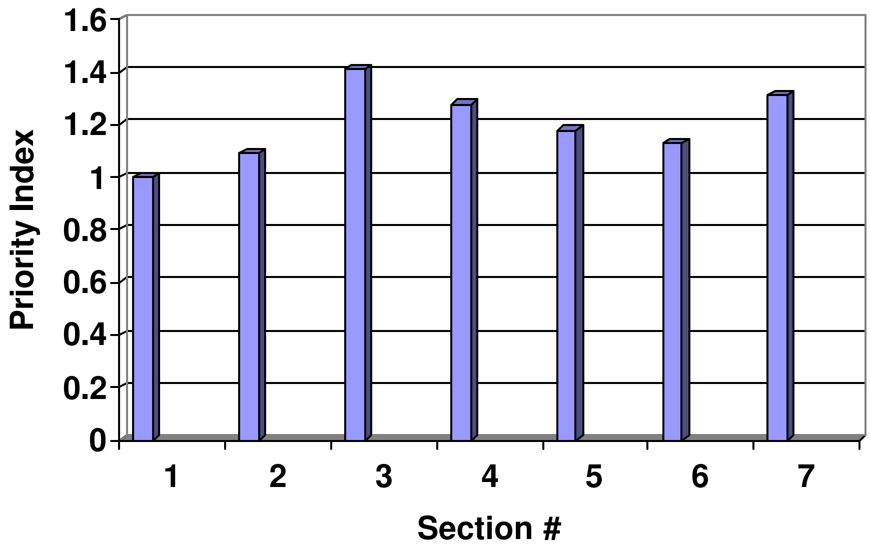


Project Selection
Priority Level
High
Low
1 2 3 4 5 6 7 8 9 10 11 12 13 14
(a)
Objectives & Weights
Maximize Performance
(0,1,0)
(w_1,w_2,w_3)
(0,0,1)
(1,0,0)
Minimize Risk
Minimize Cost
(b)
Planning Horizon & Budget
Time
2010
1999
2020
Budget
1.4M
$1.0 M
$4.0 M
(c)

Fig.4. Lounis & Vanier



(a)



(b)

Fig.5. Lounis & Vanier

BELCAM condition rating	*Description*	*"Roofer" condition index*
7	Excellent	86-100
6	Very Good	71-85
5	Good	56-70
4	Fair	41-55
3	Poor	26-40
2	Very Poor	11-25
1	Failed	0-10

Table 1 Lounis & Vanier

Section #	*Condition rating (f_1)*	*MR &R costs (f_2) ($1,000)*	*Risk of failure (f_3) ($1,000)*	*$L_2(x)$*
1	1	100	50	1.00
2	2	75	20	1.09
3	3	35	10	1.41
4	3	75	30	1.28
5	2	60	10	1.18
6	1	90	20	1.13
7	2	85	20	1.31

Table 2 Lounis & Vanier