University of Alberta

A Decision Support System for the Maintenance Management of Buildings

by

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ABSTRACT

Governing agencies across North America are currently facing extreme problems of deterioration, inadequacy, and insufficiency of their city's infrastructure facilities. The shortage of adequate funds has imposed serious constraints on how candidate maintenance, rehabilitation and replacement projects are planned, and executed. Asset managers are forced to compete with other cost centers to obtain the required funding for these renewal projects. Consequently, many urban infrastructure management agencies are falling behind in their efforts to improve and enhance the performance of their facilities.

To effectively operate and manage a portfolio of diverse facilities it is essential to have a firm grasp on the asset base, to monitor the in-situ performance over its service life, and to know the operational and functional requirements as well as the financial implications. Further, asset managers must be able to execute maintenance, rehabilitation and replacement strategies based on perceived economic advantage and prudence, while reflecting management's strategic plans for the facility. Given the complex nature of the building's structure and make-up, with its intricate interconnection of 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

that are 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 assist asset managers to monitor and model the deterioration of buildings (including their many 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 developed BMDSS combines available condition rating data, regression trend of the designed service life, expert knowledge, and Markov transition properties to predict the future of buildings performance. The BMDSS also provides the framework for prioritizing MR&R projects based on the financial allocation that leads to maximum benefits within the framework of a defined budget.

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Chapter 1 Introduction

1 Introduction

1.1 Overview

Much of the urban infrastructure in the United States and Canada requires remedial measures to continue functioning in a safe and efficient manner. This dilemma is not limited to just these two countries, but is found to differing degrees all around the world. This unsatisfactory situation is not due to a lack of technical competence but to institutional factors that range from a lack of money to indifference, poor management, and mismanagement (Hudson et al. 1997).

Civil infrastructure is, in many ways, a portfolio of systems that comprise the physical facilities of society's built or constructed environment. The concept of civil infrastructure systems arises from the support services provided by the constructed facilities. Building facilities are clearly a major part of any nation's infrastructure portfolio, since they provide physical support services, shelter, and accommodation for the performance of every conceivable human activity. Despite the historic, cultural, and architectural importance of, and economic investment in, buildings and other constructed facilities, there is mounting evidence that the physical condition, functionality, and quality of the facilities portfolio in many countries are deteriorating (ASCE 2001, Choate and Walter 1981, GAO 1990, 1991, 1993, 1995, 1997, CERF 1996). Because of aging, overuse, exposure, misuse, mismanagement and neglect, many of these facilities are becoming more vulnerable to catastrophic failure (GAO 1998). It would be prohibitively costly and disruptive to replace these facilities. They must instead be renewed in an intelligent manner, which includes the prudent and effective use of economic, material, and human resources, and which focuses on optimizing the performance of both the individual building level and the system level of the facility portfolio.

1.2 Background of the Study

At the turn of the century, it was estimated that Canada now had a "built environment" of buildings and infrastructure with a value in excess of US$5 Trillion (CND$ = US$ 0.67). The value of the "built environment" of the USA at the same time was estimated to be US$30 Trillion (Statistics Canada 1994, 1996, 1999, Vanier 2000). As the economies of these two countries continue to grow at rates comparable to the highest levels of the past four decades (approximately 3%), the amount of assets could double in 20 years. The key question is who is going to pay for the maintenance management of this "built environment"? The recent announcements of infrastructure renewal programs in both the USA and Canada are an indication that there is growing concern about the rapidly deteriorating infrastructure. The amount of deferred maintenance in some industry sectors is staggering. The results of a survey conducted by the Association of Higher Education Facilities Officers estimates that there is a backlog of $26 Billion in deferred maintenance on U.S. higher education facilities. The equivalent number for Canada has been reported at CDN$3.6 Billion (Vanier 2000). In the hospital sector in the USA, there is a deferred maintenance of approximately 20% of the Current Replacement Value (CRV), of which 6.7% is deemed urgent (Sawers 1997).

The estimated maintenance and repair expenditure requirements in Canada are nearly CDN$110.0 Billion per year, whereas capital renewal figures are close to CDN$86.5 Billion per year (Vanier 2000). The sum of these two figures is close to double the value of new construction in Canada currently valued at CDN$100 Billion (Vanier 2000). Similar maintenance and renewal figures in the USA are approximately US$800 Billion per year. These figures are significant and highlight the enormous challenge facing asset managers. Further, much emphasis has been placed on new construction over the past three decades, to the detriment of maintaining the existing facilities (Johnson and Clayton 1998). Given the current situation, managers of municipal infrastructure assets are realizing the need for effective tools to manage this vast asset base (Lacasse and Vanier 1996). The operation, maintenance, repair, rehabilitation, and eventual renewal of this "built environment" represent, therefore, a major and rapidly growing cost to Canada and the USA.

1.3 Problem Statement

There is increasing political and economic pressure for existing facilities to be kept in service for a longer period of time. One of the major reasons is the realization that investment in existing facilities and their replacement costs are extremely high (Melchers 2001). Increasing consideration must be given to either the replacement or life-extension of facilities that were designed and constructed to last for what was then a reasonable life expectancy of 40, 50, or even 75 years (NRC 1998).

The quandary asset managers face is when to repair, rehabilitate, renovate, or replace an asset. Invariably, the primary reasons for much of the asset manager's predicament relate directly to the lack of usable data and knowledge related to service life prediction, and to the lack of tools to assist the asset manager in making proper maintenance, repair, or replacement choices. The situation becomes more complex when severe budgetary constraints are implemented by agencies, essentially limiting the asset manager's ability to implement much-needed planned maintenance programs.

The prevalent problem of major funding constraints for this multi-billion dollar effort tends to mask the important need for developing rational methods for making these decisions. Of primary importance to the asset manager is whether the deficiency, damage, or deterioration observed is serious enough to warrant entering the planning-programming-budgeting cycle, leading to a capital budget request, or is it minor enough to address with the field-maintenance budget?

Against this background, it would be appropriate to consider the issue of budgeting techniques and activities for facility maintenance and repair. Within Public Agencies, facilities maintenance and repair is often deemed to be a low priority issue because asset managers invariably do not have the information they need to present their case for funding to senior managers and public officials (Hudson et al. 1997, Urban Institute 1994). Estimates of the implications of deferred maintenance on cost and quality are lacking. Hence there is a need for all "players" (the asset manger as well as public officials) to fully understand the magnitude of the associated risks involved in continuously deferring needed maintenance and repair – major damage to facilities, disruptions in service and business, and costly and serious health and safety consequences.

Further, in the context of asset management, there is considerable depth and breadth to studies on service life prediction, as is evident from the research literature (Madanat et al. 1997, 1995, Madanat and Ben-Akiva 1994, Gopal and Majidzadeh 1991, Harper et al. 1990, Carnahan 1988, Carnahan et al. 1987, Feighan et al. 1988, Jiang et al. 1988, Golabi et al. 1982). What is missing is the technical information and research that is readily useable by building/facility managers. How can the asset manager utilize the enabling technologies available to forecast future conditions of building components, or the building itself?

The purpose of this research is to provide decision support tools specific to the domain of Building Maintenance Management that can assist asset and facility managers in making better decisions on their building inventory.

1.4 Research Hypotheses and Objectives

Systematic asset management is the best approach for balancing the growing demands of aging infrastructure and constrained resources. Inadequate funding for the maintenance and repair of public buildings at all levels of government is a long-standing and well-documented problem (NRC1998, GOA 1997, CERF 1996, GOA 1991, NRC 1990). The primary objective of this research, therefore, is to develop a decision support system, which will assist asset managers within the public sector to monitor and forecast the deterioration of buildings, as well as to determine maintenance standards and strategies, appropriate funding levels, and to allocate funds for competing building maintenance needs.

In keeping with the main objective, the following sub-objectives were formulated to investigate and prove the hypothesis:

(1) To develop a conceptual, integrated framework for the Decision Support System for the maintenance management of buildings.

(2) To develop a uniform condition assessment procedure that can provide quantification of engineering judgments when inspecting building assets.

(3) To review the building hierarchal structure in order to facilitate proper delineation of the building inventory. Furthermore, to propose a flexible methodology and rationale that will be able to replicate the complex relationship between building components within a building system, with a view to developing relative weights for the said components.

(4) To develop a system for monitoring the performance of building assets, and to identify a mathematical model to evaluate and forecast the deterioration process of major building components. Furthermore, to identify a mechanism for budgeting and

programming optimal building maintenance works that will maximize public economic benefits.

(5) To develop a prototype of the Decision Support System for Building Maintenance Management and to conduct validation trials on the procedures and systems developed during the research, ultimately presenting the findings.

1.5 Research Methodology

To achieve the above stated objectives the following steps will taken in the project methodology:

(1) A comprehensive literature review was conducted to determine the current status in building and infrastructure management. A review was made of the various enabling technologies such as service life prediction, deterioration modeling, and life cycle analysis. Interviews and discussions with facility and asset management professionals (a total of 10 individuals) from the City of Edmonton were also conducted to solicit knowledge from their experience and feedback. A conceptual schematic design of the proposed Decision Support System for building maintenance management was developed. Its analytical functions were based on the application of available engineering and mathematical modeling tools.

(2) Develop a hierarchical structure for buildings, with the intent of identifying all the building systems and associated building assets. It is imperative that this structure be strictly and consistently adhered to in the planning and execution of maintenance activities. The UNIFORMAT II Classification for Building Elements is best suited for this process because it provides a consistent standardized framework for decomposing a building. Review the current condition assessment practices of the City of Edmonton and other agencies and develop a simple index-based condition assessment procedure that will provide quantification of engineering judgment. This procedure will be applied to all building components in the building structure. The Analytical Hierarchy Process (AHP) methodology will be used to evaluate the relative weights of each building component within the building inventory framework.

(3) Review current deterioration modeling techniques, with a view to proposing a robust yet flexible and dynamic methodology to predict future performance of building assets. Flexible and dynamic in the sense that it must be able to capture and reflect the conditions specific to a building and explicit enough to recognize and portray any improvement made to an asset's condition through the implementation of a maintenance action. In the absence of historical building component performance

information, experts from the City of Edmonton familiar with the particular equipment, materials, climatic factors, and conditions, were relied upon to provide service life estimates of building components. These estimates were used to formulate deterioration curves.

(4) System development and implementation involves defining the architectures and user interface for the integration system. An application of a building in accordance with the aforementioned objectives will be demonstrated. The Decision Support System for Building Maintenance Management was developed in SQL server.

1.6 Scope and Limitations

The main focus of this research is public buildings and facilities. Hence the maintenance management framework that will be developed will be generic, limited neither by the complexity, scale, size, or type of building. Most of the data and information gleaned from interviews that will be used in the development of the decision support system will be obtained from the Lands and Buildings Branch, Department of Asset Management and Public Works, City of Edmonton. The scope of application development will also be tailored to accommodate data exchanges from a Computerized Maintenance Management System.

1.7 Expected Results

The objective of implementing a Decision Support System within an asset management agency, public or private, is to provide decision makers with processed quantitative data that can be used to examine the impact of various maintenance strategies. It represents an organized approach to helping asset managers manage their building inventory more efficiently and effectively. It is expected that the models developed will provide a rational framework for evaluating maintenance strategies, determining budget levels, and allocating funds between competing asset maintenance needs.

1.8 Benefits and Contributions to the Domain of Buildings Maintenance Management

Asset managers are faced with many difficult decisions regarding when to effect repair, rehabilitation, or replacement on their building inventory. The models, methodologies, and procedures for the integrated building maintenance management decision support system are aimed at providing the essential service of transforming raw data into information and intelligence. The aim is to reduce the risk in policy and budgeting decisions with regards to major maintenance and rehabilitation projects. A summary of the anticipated key benefits to be derived from the integrated building maintenance management system is presented below:

a. Better definition of project maintenance and rehabilitation needs and related budgets;
b. Control user cost by providing a known level of funding;
c. More effective spending on buildings;
d. Knowledge of portfolio-wide conditions and maintenance and rehabilitation needs;
e. Improved serviceability level of building portfolio; and
f. Improved methods for planning maintenance and rehabilitation projects.

This strategic decision-support tool will allow for setting the overall goals of system performance and policies of an agency by analyzing tradeoffs among competing modes and programs. Network or program level tools predict asset performance over time and assist in identifying appropriate maintenance, rehabilitation, or replacement strategies for each asset. They also provide the capability of optimizing scarce budget resource allocations to maximize the benefits of the overall system. "Intelligent" alternatives for knowledge-demanding tasks such as condition assessment, performance prediction, and project selection have great potential to enhance the asset management process.

1.9 Dissertation Organization

This dissertation is organized as follows:

Chapter 2: Literature Review

This chapter presents a background to the research work by providing a description of the relevant knowledge areas in building maintenance management. The chapter then presents a conceptual design for the Decision Support System in Building Maintenance Management. A review of some of the Computerized Maintenance Management Systems is also presented, as well as some foundations for the research work provided in the later chapters.

Chapter 3: Condition Assessment.

This chapter identifies a simple framework that can be used by municipalities in developing uniform condition assessment procedures for many of their buildings. The condition assessment is based on objective and repeatable measurements and assessments that are assigned to specific condition attributes. The results are then processed by an algorithm, which produces a numeric indicator, the condition index (CI). As an indicator, the developed CI is useful to asset managers and engineers at all hierarchical levels of management, since it serves as the key statistic for the planning and development of maintenance strategies.

condition throughout their service life is currently unavailable, transition probabilities were estimated. The defined deterioration boundaries, in conjunction with the actual performance curve of the asset provides a good planning tool for asset managers, since it provides them with a opportunity to effectively utilize scarce maintenance dollars.

Chapter 6: Optimization Model Development

Because financial resources for the maintenance of building structures are always limited, there is a need for ways to allocate them among the various projects suggested for maintenance, rehabilitation, and replacement. In this chapter, an integer-programming model was used to solve the problem of resource allocation. The implemented model endeavored to maximize the benefits to the facility within the framework of a constrained or limited budget.

Chapter 7: System Development

The most important step required to acquire the real benefits of a decision support system is to apply the developed concepts and integrate the components into an active working system. This chapter therefore provides some background to the development of the Decision Support System for Buildings Maintenance Management. The general description, main structure, and major operational functions, along with some data-flow diagrams and computer screen examples are the primary focus of this chapter. This can be viewed as an essential starting point from which further refinements and improvements can be made.

Chapter 8: Conclusions and Recommendations

This chapter presents the general findings of the study. It also outlines the benefits of the DSS, highlighting its potential at a time when many public agencies are grappling with infrastructure management issues with very few decision support tools. Determining the most critical issues facing asset managers in the areas of consistent condition assessment, transforming this data into meaningful decisions, and more astute planning of MR&R projects have been have been cited as major contributions of this research.

Chapter 2 Literature Review

2. Literature Review

2.1 Introduction

Public attention was drawn to the infrastructure crisis in the 1980s by such headlines as “America in Ruins” and “Crumbling Infrastructure”. Increasing needs and lack of funds to maintain and improve the infrastructure are often cited as the cause of the problem. While cost is a factor, a major problem has been the lack of comprehensive approach to managing infrastructure. Hudson et al. (1997) posited that there are four major issues responsible for the decline:

- **Infrastructure decaying/aging.** This is due primarily to the fact that the condition and level of service of infrastructure has deteriorated through aging and usage. Some infrastructure has failed due to natural disasters and, historically, design processes have not given adequate consideration to environmental effects and their interaction with loads and material variability.
- **Lack of rational maintenance, preservation, and renovation programs.** Here, past design practices were geared toward producing physical systems that would last a given design life with no maintenance or future preservation treatments; changes in use and the inability to predict future loads and service requirements accurately have caused problems; “ad hoc” maintenance practices

in response to public complaints, emergency situations, and catastrophic failures are not adequate to sustain a healthy infrastructure.

- **Scarcity of financing resources.** Traditionally, the federal government has financed most of the national public works infrastructure, while states and provinces, and local agencies have financed infrastructure related to their jurisdiction. However, the accumulated federal budget deficit has been steadily rising, and there is strong pressure to cut federal spending and bring the deficit under control. At the same time, competing demands make the federal budget a combination of solemn and deeply felt commitments to people, high-priority emergencies, and absolutely essential expenditures.
- **Inadequate financial reporting.** Infrastructure inventory and monitoring of costs are important issues that have not been fully recognized in government accounting and financial reporting procedures. As a consequence, the necessary infrastructure information is not always available to decision makers. The US Governmental Accounting Standards Board (GSAB), established in 1984, initiated a first comprehensive look at accounting and reporting of infrastructure/fixed assets. The intent is to ensure that governmental agencies account for their assets (Lemer 2000, McElroy 2000).

2.1.1 The State of Canada's Existing Municipal Infrastructure Assets

A recent Municipal Infrastructure Investment Planning (MIIP) Report (Vanier and Rahman, 2004) provided the following information on the condition and age of Canada's civil infrastructure:

- The estimated public infrastructure debt for all governments in Canada is $125 billion (CAD).
- The 1994 the Office of the Auditor General of Canada reported that the Department of National Defense aging infrastructure has approximately $1.7 billion (CAD) in maintenance expenditures that have been deferred on an asset base of $17 billion (CAD).
- The Canadian Society of Civil Engineers (CSCE) has estimated the current municipal infrastructure maintenance debt at $57 billion (CAD) in 2003 and potentially $110 billion (CAD) in 25 years.
- A study of the Federation of Canadian Municipalities noted that more than $44 billion is required to bring the municipal infrastructure systems to an acceptable level (FCM 1996).
- The Canadian Association of University Business Officers (CAUBO 2000) indicated that there is $3.6 billion (CAD) in deferred maintenance on an asset portfolio of $37 billion (CAD).

The City of Edmonton (2002) published a report showing the overall status of its infrastructure using a ranking system that provided a strategic perspective of the state and distribution of its infrastructure:

- 13% ($2.3 billion) was in poor and critical condition.
- 17% ($3.1 billion) was in poor and critical condition with respect to meeting demand/capacity.
- 8% ($1.4 billion) was in poor and critical condition with respect to functionality.

The report further indicated that the infrastructure gap was widening and that there was insufficient funding for rehabilitating the existing infrastructure and for building new infrastructure to support growth. The City's 10-year infrastructure gap totaled approximately $3.2 billion (CAD). Roughly 40% ($1.3 billion) of this gap comprises projects required to rehabilitate existing infrastructure.

Vanier (2000) estimated the value of Canada's building infrastructure portfolio to be approximately $0.7 trillion (CAD). Although there are no data available on the actual replacement costs of government and other public facilities, most of these facilities are approximately 40 to 50 years old (BOMA 2004). The situation is no different in the United States of America where the public assets are just as substantial. State and local government buildings in the United States of America replacement value is estimated at US $400 billion, while the replacement value of public schools and institutions of higher learning (public and private) is tabled at US $722 billion (Vanier 2001, AWPA 1090). Public officials are therefore faced with the constant challenge of balancing competing public priorities and limited fiscal resources in the area of maintenance management

2.2 Status of Research in Building Maintenance Management

Service life and durability research has been part of the construction vernacular for the past 40 years. It was first identified as a research field as early as the 1950s and has spawned numerous research projects since then (Legget and Hutcheon 1958, Sjostrom 1985, Lacasse 1996). Research efforts undertaken in the late 1960s at the National Bureau of Standards (now the NIST), brought about the development of a systematic approach to assess the service life and durability of building materials and construction. These efforts were fostered by several projects and research initiatives undertaken by various agencies (Masters et al. 1975; Frohnsdorff et al. 1980; ASTM 1982).

These research efforts were also the precursor to increased international cooperation for assessing the long-term performance on building materials. Accordingly, these activities exposed building researchers to the performance concept in building (Lacasse and Vanier 1996). A joint symposium sponsored by the International Union of Testing and Research Laboratories for materials and Structures (RILEM), the American Society for Testing and Materials (ASTM), and the International Council for Building Research Studies and Documentation (CIB) highlighted the many efforts being made at the time in advancing the state of the art in durability and service life prediction (Foster 1972).

Efforts in other countries are also noteworthy. Work in this area has been underway since 1953 in Japan where researchers have already developed the essential elements of a method for testing, evaluating, and selecting building materials and elements (Shirayama 1972). Furthermore, Japanese researchers proposed an empirical "factorial" approach to monitor the durability of structural and building envelope elements (Lounis et al. 1998, AIJ 1993). This approach presumed that the service life of building components can be estimated based on the assumption that a standard life of a component can be adjusted through the use of factors that account for use, location, and workmanship. Lounis et al. (1998) identified three key limitations to this approach: (i) it was not performance based and therefore has no adopted minimum performance requirement; (ii) it was arbitrary in its choice of standard service life and adjusting factors; and (iii) it was a deterministic approach.

Numerous other laboratories have also engaged in the service life prediction of building components including Australia, Britain, Finland, France, Germany, Israel, Italy, The Netherlands, New Zealand, Norway, and Sweden (Lacasse 1996). Mayer et al. (1995) presented deterioration curves of 10 building envelope elements based on studies that were conducted on 120 buildings. Three deterioration curves were used to distinguish the performance of elements in favorable conditions (indicative of elements of good quality, protective positions, and good maintenance), normal conditions, and unfavorable conditions (representing elements of inferior quality, exposed to harsh weather, and bad maintenance).

Flourentzou et al. (1999) proposed the MEDIC approach to determine the residual service life of building materials and components. MEDIC refers to *Mèthode d'Ȅvaluation de scènarios de Dègradation probables dĺnvestissements Correspondants*. MEDIC was developed on the theories of conditional probabilities, in which four codes (a, b, c, and d) are used to represent the deterioration state of building elements. Code "a" represents an element in good condition; code "b", an element with minor deterioration; code "c", an element with more serious deterioration; and code "d", an element with that needed replacement. The knowledge base of the method is summarized in four probability curves for each building element. For a certain element, these curves show at any time in the element's lifetime the probability for deterioration code to be in a, b, c, or d, respectively. Since this is a probabilistic approach, the probable residual service life is not a single figure but corresponds to an interval.

Lounis et al. (1998) used a discrete Markov chain to model the performance of roofing membranes. This approach was chosen primarily because the actual performance of roofing membranes is time-dependent and presents considerable uncertainty and variability due to the time dependence and randomness of degradation factors, material properties, workmanship, and maintenance. The development of this model was based on the availability of in-service performance data collected during successive inspections of the roof.

2.3 Integrated Facilities Management (FM) Models

Several attempts have been made to develop explicit and integrated models for facilities management (Yu et al. 1999, Svensson 1998). This section reviews some of the developed models.

1. The RATAS Maintenance Model: This model was developed within the RATAS project, for which product models were developed to represent the requirements of facilities maintenance and operations. The model focused on facilities maintenance and operations (Möttönen 1995; Möttönen, Matilainen, and Parjanen 1994; Bjork 1989).

2. Object-oriented Model for a Facility Information System (FMIS): The FMIS project identified some of the fundamental requirements of an information system for FM. It stressed the need for

comprehensive FM models, data repositories, and usage requirements in an integrated FM system that must be flexible to changes and must provide a uniform language and intuitive user interfaces. The FMIS model identified some of FM entities such as space, furniture, and apparatuses (Bos 1995).

3. Information System for Facility Management (ISFM): The models for this project were conceptual models that included both products and FM processes at high levels. This project set an example of applying identifiable facilities management processes into product model requirements. The ISFM project also attempted to formalize the FM data transformation methodology through the models for a documentation system (Majahalme 1995).

4. Integration Facilities Management Information System based on STEP: This project integrated a CAD system with an asset and maintenance management system and a building energy management system. The project suggested a STEP-conforming system architecture for integrated FM systems and specified a generic product data model to support the data shared by the three integrated systems (Cheng, Patel, and Bancroft 1997).

5. The KBS Model: The KBS model was aimed at supporting the integration of FM functions. The model was developed based on a set of standard national building product classification tables. The scope of the KBS model covers building products in different model views and as such spatial systems, building technical systems, construction sections, and construction parts. Several implementation prototypes based on the KBS model demonstrated that the model was able to support FN functions such as operation and maintenance management, tenancy agreement management, and indoor-climate calculation processes (Svensson 1998).

6. Integrated Systems of Maintenance Management Model: This model focused on integrating data and knowledge through the development of shared product models that maintain a combination of product and process views of the project. Development of these models followed a methodology similar to that of the International Alliance for Interoperability (IAI) to develop data standards in the form of Industry Foundation Classes (IFCs). The maintenance project models developed provided a direction for implementing IFCs in a distributed model-based application. This application was able to implement the developed process and data models, and provide the capability to import and export IFC information from and

to other legacy applications, thus facilitating data exchange and achieving software interoperability (Hassanain 2002).

2.4 Computerized Maintenance Management Systems (CMMS)

The objective of this software review is to determine the capability and to study the operational characteristics and functionalities of the several commercially available asset management tools on the market. Computerized Maintenance Management Systems (CMMS) have been developed to provide asset owners with a systematic and rational approach to carrying out all the activities related to maintaining their assets (Hudson et al. 1997; Morcous and Rivard 2003). Asset managers have utilized various CMMS for different types of infrastructure facilities, such as bridges, roads, airports, parking lots, and sewers. Table 2.1 provides a summary of the capabilities of some of the most popular CMMS used in asset management as well as the specific target areas of the decision support system (DSS). Hassanain et al. (2003) provided an objective review of some of these applications, namely BUILDER, MAXIMO, and RECAPP. Most of these software programs provide the capabilities for inventory collection, maintenance work order reporting, maintenance planning and scheduling, and for some form of condition monitoring.

RECAPP facilitates the prioritizing of maintenance projects based on condition and budgetary constraints. BUILDER is able to provide a rigid methodology for determining the building condition index. The inspection procedures are conducted at the component (or even the sub-component) level and components are evaluated against a set of predefined rating criteria. The determination of the final condition assessment, however, is based on the application of complex deduct curves developed to represent each distress (and distress severity) that occurs on the component. This arrangement is much too cumbersome and has not found favor with building inspectors. This program also provides for the ranking of maintenance and repair actions according to condition indexes, available funding, and the remaining service life of the component.

Other application programs (namely SPAN FM, Facility Center, and a SAP) are very similar in their operational characteristics, each possessing capabilities in the day-to-day management of maintenance tasks. SPAN FM, Facility Center, and SAP encourage priority ranking to be assigned to maintenance projects. There is, however, a limited capacity in these programs for condition monitoring relative to the existing performance requirements and deterioration modeling of building assets.

Table 2.1 Asset Management Software Review

CATEGORY	NAME	CAPABILITIES & FEATURES							ADDITIONAL FEATURES				
		INVENTORY IDENTIFIC.	MAINT. PLANNING	MAINT. SCHEDULES	MANAGING WORK ORDERS	ACTIVITY BASED BUDGET	CONDITION ASSESSMENT	GIS & CAD INTEGRATION	DETERIOR. MODELING	SERVICE LIFE PREDICTION	MAINT. PRIORITIZATION	BUDGET PLANNING & OPTIMIZATION	RISK ANALYSIS
CMMS	MAXIMO	X	X		X	X							
	RECAPP	X	X		X	X							
	FACILITY CENTER	X	X	X	X	X							
	SAP	X	X	X	X	X							
EMS	BUILDER	X	X			X	X	X	X				
	ROOFER	X	X			X	X	X	X				
OTHERS	ARCHIBUS	X				X	X	X					
	VISUALIZER	X				X	X	X	X	X			
	Building Maint. DSS								X	X	X	X	

2.5 Infrastructure Service Life

Infrastructure service life depends on design and construction methods, usage and environment, and in-service maintenance and operation practices. This service life is not the same as design life or economic life. The following terminology is based on the Building Research Board publication "*Pay Now or Pay Later*" (BRB 1991).

Service Life: "The period in years over which a building, component, or subsystem provides adequate performance; a technical parameter that depends on design, construction quality, operations and maintenance practices, use, and environmental factors."

Performance: "The degree to which a building or other facility serves its users and fulfills the purpose for which it was built or acquired."

Physical infrastructure facilities are generally fixed assets. From the design and analysis point of view, a finite number of years of design life/analysis period is associated with each component of the infrastructure. In reality, the public and users expect the infrastructure to provide a particular service forever, unless a catastrophic failure occurs. However, the responsible agency managers and decision makers know that there comes a time when the infrastructure facility cannot provide adequate service because of one or more reasons:

1. Structurally unsafe
2. Functionally obsolete

3. Causes delay and inconvenience to users due to overuse and over demand
4. Costly to maintain and preserve
5. Neglect due to poor maintenance practices.

This leads to the concept of the service life (based on the physical service life as contrasted to a social/economic service life) of an infrastructure within a life cycle. Unlike the design and analysis period, service life is typically not a single number. The same type of facility may have a wide variation in its initial and total service life because of the varying influence of use and traffic by users/patrons, environmental inputs, and maintenance practices. Maintenance history has a significant influence on total service life. An adequately maintained facility will have a better probability of extended service life, as compared to a poorly maintained facility. It is therefore critical to recognize the importance of service life analysis, including agency costs (for construction, maintenance, rehabilitation and renovation/replacement) as well as user costs and benefits.

The prediction of effective service life is more complex for buildings. This is primarily because the structural integrity of a building depends upon many factors aside from the materials of construction and the performance of the various functional subsystems (NRC 1998, Hudson et al. 1997). These complexities generally have discouraged the use of routine life cycle cost analysis for design and maintenance, repair, and rehabilitation programming in the past.

2.6 BELCAM Project

The Building Envelope Life Cycle Asset Management (BELCAM) project at the Institute for Research in Construction (IRC) has identified "enabling" technologies critical to attaining the project objectives of optimizing the service life of building envelope components and systems (Vanier and Lacasse 1996). Six enabling technologies were identified: life-cycle economics, service life prediction, user requirement models, risk analysis, product modeling, and maintenance management. The main focus of this project was low-slope conventional roofing systems. A framework for the integration of the process of managing maintenance of roofing systems entailed a five-step approach (Hassanain et al. 1999): 1) identification of the roofing system components; 2) identification of the roofing system performance requirements; 3) identification of the performance assessment methods; 4) roofing system maintenance planning; and 5) roofing system maintenance management.

2.7 Modeling Infrastructure Performance

Information on current and future infrastructure conditions is essential for maintenance and rehabilitation decision making. Data on current condition is obtained from facility inspection. These data can be used to develop facility deterioration models, which in turn can be used to predict future facility condition. Both the current condition and the predicted future condition are used to select maintenance and rehabilitation activity. The success of infrastructure management system is dependent, to a large extent, on its ability to predict future conditions accurately (Madanat 1993).

The literature reflects various efforts to provide quantitative based decisions to infrastructure or other components of the built environment. The Factor Method was developed by the International Organization for Standardization (ISO) to establish the service life of building components (ISO 1997). The method simply multiplies the reference service life of the component by the factors affecting it. For example, the factor of a high level of maintenance may be >1, acting to extend the life of the component, whereas a harsh outdoor environment may add a factor <1, acting to shorten its life. The values of the factors can be determined by a Delphi process (Moser 1999).

Flourentzou et al. (1999) developed an approach in which the life of a building element is divided into four conditions states; good, fair, poor, and needs replacement. With sufficient field data, the age distribution of a component in any condition state can be estimated. Using conditional probabilities, the time to replace and the expected cost can be estimated.

2.8 Deterioration Best Characterized by Probabilistic Models

It is generally accepted that the deterioration of an infrastructure is a stochastic process that varies widely with based on several factors, many of which are generally not captured by available data. Hence probabilistic models are often used to characterize deterioration. Two types of discrete-state probabilistic models have been used for infrastructure facility deterioration prediction: discrete-time state-based models and time-based models. Mauch and Madanat (2001) described both types of models and discussed several from the infrastructure literature. Discrete-time state-based models such as Markov chains, characterize the probability that a facility undergoes a change in condition state at a given discrete time, given a set of explanatory variables such as design attributes, traffic loading, environmental factors, age, and maintenance history. Time-based models, on the other hand, characterize the probability density function of the time it takes an infrastructure facility to leave a particular condition state once entered (this time is referred to as state duration), given the same set of explanatory variables (Mishalani and Madanat 2002).

2.8.1 Applications of Markov Chains

Many state-of-the-art infrastructure management systems utilize the Markov Decision Process (MDP) for maintenance and rehabilitation decision-making (Abraham and Wirahadikusumah 1999, Madanat and

Ben-Akiva 1994, Gopal and Majidzadeh 1991, Harper et al. 1990, Carnahan 1988, Feighan et al. 1988, Carnahan et al. 1987, Golabi et al. 1982). In this methodology, facility condition is represented by a discrete state, and a discrete Markov chain is used to model the deterioration process.

The underlying assumption of the Markov process is that at any time t, the distribution of condition states at $t + 1$ depends on the history of the facility only through the present state. Another assumption is that the transition probabilities do not depend on age, that is, that the transition probabilities are age-homogeneous (Guignier and Madanat 1999). While the second assumption is not necessary to optimize transient maintenance policies in finite horizon problems, it has been imposed to permit the solution for steady-state maintenance policies in infinite horizon problems (Golabi et al. 1982). Unfortunately, this assumption is supported neither by mechanistic knowledge of material behavior nor by empirical observations of facility deterioration. In fact, empirical research has shown that age is a significant determinant of a facility's deterioration rate (Madanat et al. 1997, 1995, Jiang et al. 1988).

2.8.2 Estimation of the Transition Probability Matrix

Researchers have addressed the problem of estimating transition probabilities of discrete-time state-based deterioration models. Madanat et al. (1995) summarized and critiqued a common method for estimating Markov transition probabilities. This approach, referred to as the expected value method, minimizes a measure of distance between the theoretical expected value of the state, and the state as predicted by a linear regression model (Jiang et al. 1988, Carnahan et al. 1987). The theoretical expected value of the state is derived from the structure of the Markov chain, and the linear regression model is estimated using observations of state as the dependent variable and age as the explanatory variable. Madanat et al. (1995) argued that this approach has limitations, especially since it does not explicitly capture the various explanatory variables. Also, the authors argued that the possible non-homogeneity (i.e., time dependence) in the deterioration process could only be captured indirectly through ad hoc time segmentation.

2.9 Case Base Reasoning

Although there has been some success in the application of the Markov Decision Process in bridges, pavement, sewers, and other infrastructure applications, Morocus et al. (2001) pointed out that there are some limitations in their applications. These authors opined that MDP models are not able to recognize the effect of previous conditions and maintenance treatments on the deterioration process, to account for the interactive effects among different deterioration mechanisms of facility components, or to consider some explanatory variables that significantly affect facility deterioration. Furthermore, these models are difficult to update whenever new data are obtained or a different rating system is used.

Case-based Reasoning (CBR), an artificial intelligence technique, was proposed by Morocus et al. (2001) for modeling deterioration based on the premise that the performance of an infrastructure asset (i.e., a query case) can be predicted using recorded performance of other facilities (i.e., stored cases) that are similar to the query case in their physical features (such as material, geometry, and structural system) operational and environmental conditions (such as location, condition of neighboring components, and service load) and inspection and maintenance history. The CBR approach to modeling infrastructure deterioration was used to provide government agencies with realistic, accurate, and versatile deterioration models that overcome the shortcomings of current models and benefit from the large amount of facility data stored in Infrastructure Management Systems (IMS) databases and updated on a continuous basis.

2.10 Limitations within the Building Asset Domain

In reviewing available literature on the management of building assets, there is a dire need for specific tools to address the obvious challenges that exist in the industry. The current gaps within the building maintenance industry are a consistent condition assessment strategy for building assets; a methodology for determining the weights of building assets within the building hierarchy taking into consideration the deterioration mechanisms that can affect the assets and the interdependency between building assets; a methodology for monitoring the deterioration of the building asset and forecasting its future conditions and remaining service life; and a decision support tool that can use the aforementioned data to assist the asset manager to make meaningful maintenance management decisions on the continued usage of the asset.

2.10.1 Condition Assessment Framework and Criteria

A lack of knowledge of the condition of the building asset can result in an inefficient usage of the scarce resources available for maintenance and repair. Consistent condition monitoring at the asset level can provide much needed information to the asset manager on building components. Without a consistent and reliable structure and strategy, the condition assessment process becomes cumbersome and ineffective. The intent is to provide a rigid framework to facilitate this condition assessment and monitoring of building assets by types.

2.10.2 Assessing the Priority Weights of Building Asset

The use of priority or relative weights in conjunction with the condition assessment framework is critical to the development and application of condition indexes of building assets. It provides the basis of determining the condition of building systems and the building itself. It is just as important to have a robust yet flexible framework for the formulation of these weights. It is also important to have these weights reflect the complex interdependency that exists between building systems and components. Such a framework is sorely lacking within the industry.

2.10.3 Deterioration Modeling of Building Components

There is an increasing demand by asset managers for tools to monitor and forecast the deterioration of building assets. While there has been ongoing research in the other domains of infrastructure management, there have been comparatively fewer applications for building assets. To meet the challenge of adequately financing the maintenance needs of a large building portfolio; asset managers will need to know the immediate and long-term conditions of the building assets. In view of the paucity of data and research in the area of building components, asset managers will be better served by an interactive tool that monitors their own unique circumstances, environment, and practices and provides forecasts of future conditions based on those unique circumstances.

2.11 Need for a Decision Support Tool

For many municipal agencies, the major issues of service delivery are "repair and renew" rather than "design and build" (Vanier 2001).

Consequently, asset managers, administrators and politicians will all benefit if decisions about maintenance, repair, and renewal are based on reliable data, solid engineering principles, and accepted economic values. When reliable data and effective decision support tools are in place, the costs for maintenance, repair and renewal will be reduced and services will be timely, with fewer disruptions. These improvements will all reduce the costs of managing municipal building facilities.

2.12 Conceptual Design of the Decision Support System (DSS)

The DSS was designed to interface with the CMMS; in that way it will facilitate an easy transfer of information. The CMMS database is a repository of information on the entire asset portfolio. It contains basic information such as the specifications of the asset, installation (and construction) date, and expected service life, as well as the schedule of preventative maintenance tasks. Additionally, it is expected to contain historical costs associated with the asset, emergency maintenance and planned maintenance activities, as well as deferred maintenance projects. The performance of the analytical tasks of the DSS is contingent upon it being able to access this information.

The proposed DSS consists of four modules. They are as follows:

1. Condition Assessment module.
2. Computing Priority Weights module

3. The Deterioration Modeling module.
4. Budget Optimization Module

The conceptual design of the DSS is presented in Figure 2.1. Its primary objective is to facilitate proper decision-making within the building maintenance environment. The following key tasks of the DSS are: to monitor the performance of building assets and forecast its future performance; to develop priority weights for building components, and systems so as to facilitate the condition index of a building asset based on the roll up approach; and to assist in the prioritizing and optimizing of the maintenance budget.

2.13 Conclusions

This literature survey has attempted to outline the current status of research in the area of infrastructure facilities. Given the vastness of the infrastructure facilities portfolio, its deteriorating physical condition, and the inadequate funding available for its maintenance, there is an increasing need for decision support tools to aid asset managers in managing and maintaining their portfolio.

Properly maintained facilities are critical to the effective performance of a government agency's missions and the provision of government services.

Inadequate maintenance in public buildings can have serious and costly consequences, such as:

- Can cause disruption of work;

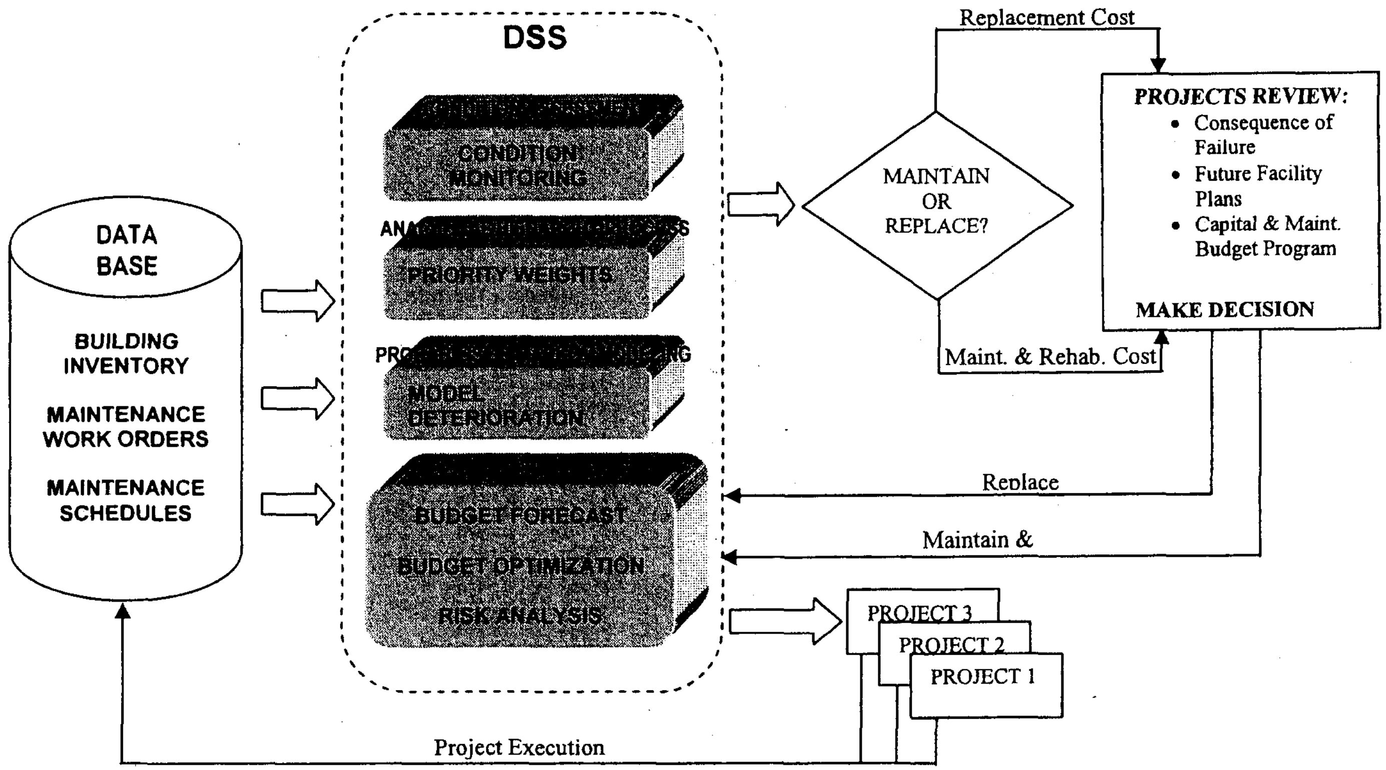


Figure 2.1 Conceptual design of the Decision Support System

- Can cause computer and other technological breakdowns;
- Can create risks to occupants' health and safety;
- Can reduce productivity;
- Can cost millions of dollars in emergency repairs.

The deferral of maintenance and repairs because of under-funding is a widespread, persistent, and long-standing problem, and pressures to defer maintenance are increasing. In today's dynamic policy and budget environment, public facilities and asset managers are facing the following challenges:

- To extend the useful life of aging facilities;
- To alter or retrofit facilities to consolidate space or accommodate new functions and technologies;
- To meet evolving standards for safety, environmental quality, and accessibility; and,
- To find innovative ways and technologies to maximize limited resources.

The proposed decision support system will add to the current knowledge and practice in the specific domain of buildings maintenance management by providing asset managers with the necessary tools to meet their needs.

Chapter 3 Development of a Condition Assessment Strategy

3 Development of a Condition Assessment Strategy

3.1 Introduction

The primary motivation for assessing infrastructure performance and condition lies within the context of a larger system of decision making aimed at allocating resources and taking action to pursue the public purpose of infrastructure – that is, to produce the desired outcomes. With more and more emphasis being placed on extending the service life of facilities, justifying budgets with data driven decisions, prioritizing, and more effectively focusing on Maintenance, Rehabilitation, and Repair (MR&R) dollars, there is an urgent need for a standard for condition assessment. Information on a current building condition can assist asset managers to forecast future conditions, which in turn is essential for planning MR&R decision-making.

A National Research Council study defined performance as the degree to which infrastructure provides the services the community expects of it, measured in terms of effectiveness, reliability, and costs (NRC 1995). Regardless of the particular motivation, the performance assessment process is a primary mechanism for the expression of community values and subsequent decision-making about infrastructure development and management. It is through this process that objectives for infrastructure are defined, specific measures of performance selected, and judgments made about performance.

Good evaluation information is required to model maintenance and rehabilitation requirements adequately and to measure the effectiveness of various maintenance and rehabilitation methods. This evaluation involves monitoring the usage and physical condition of the asset. Monitoring involves the collection of field inspection data. Evaluation involves the analysis, interpretation, and/or judgment of the meaning of the information collected. The purpose of in-service evaluation is to assess conditions periodically to provide data (Hudson et al. 1997):

- To update facility inventory programs
- To assess the operational integrity (current condition) and possible failure of facilities
- To schedule rehabilitation and maintenance as indicated by these inspections and evaluations, and updated predictions
- To check and update performance predictions

These are all tasks undertaken by the Decision Support System (DSS).

3.2 Evaluation of Buildings

Proper functioning of buildings requires inspections and maintenance of structural systems, as well as electrical, heating, ventilation, and air conditioning (HVAC), water and drainage, conveying, emergency and security systems, parking and other non-structural components. In order to effectively implement an in-service condition assessment of a building facility, three major steps are involved:

1. Make a detailed inventory of all components within the facility.
2. Monitor condition via measurements or observations recorded in a useful format.
3. Processing and evaluation via manipulation and interpretation of the data collected to provide an overall condition rating and to make a judgment based on the results.

A review of the evaluation and inspection process by the City of Edmonton revealed that the process was somewhat unsystematic and lacked consistency. While a very detailed inspection was being conducted on some components, e.g., roofs and some of the mechanical and electrical components, other components, such as the walls, floor finishes, and wall finishes, are not given the same detailed attention. For the latter components, detailed distress evaluation procedures are lacking. Furthermore, in conducting the overall evaluation exercise, the attribute factors are not all well defined or apportioned. The inspector subjectively resolves all the scores and weights associated with the requisite attribute factors (e.g. severity, distress, age, safety, obsolescence) into one overall condition rating. The fact that inspectors are well trained and experienced does not preclude the need for a more structured and systematic approach to the process of formulating the final condition rating for any component. A key advantage to this is that subsequent inspections will be conducted in the same format and will thus facilitate better monitoring of any change in magnitude of distresses, and their severity. Also, more precise MR&R plans can be developed.

3.3 Building Audit

The building audit can be considered as an inspection program conducted by technically qualified and trained personnel who are familiar with the facilities and equipment to be maintained. The audit entails planned and organized visual inspections as well as non-destructive tests where necessary. It will produce complete and quantitative reports of deficiencies, recommended maintenance priorities, and provide creditable work planning and budget support data.

An accurate, current, and complete inventory for each facility is the first step in setting up such an audit. The inventory data will include the following information at both the building and component level:

- Facility name and type
- Asset No. / Code
- Size and/or capacity
- Manufacturer
- Acquisition and Commissioning Date

- Installation Date
- Acquisition Cost
- Design service life
- Serial No.
- Material
- Maintenance Type
- Maintenance Interval

The UNIFORMAT II elemental classification discussed in Chapter 2 provided the basis for developing the detailed inventory of the facility. This hierarchical structure, which provides for building systems, building components as well as subcomponents/elements, is a tested and tried arrangement for building design, planning, and construction.

3.4 Use of the Condition Index

The Condition Index (CI) can be described as a condition-based measurement of performance based on observations and/or measurements at a specific point in time. It provides a basis for determining through a formal standardized process a “best judgment” approach on the condition of building components. The CI communicates the experience of knowledgeable engineers who have evaluated important parameters and quantified the process to provide a consistent measuring scale that can be utilized across an organization. The periodic inspection process (usually carried out on an annual basis for major building components) will provide a "snap shot" in time of the condition of the component.

The determination of the CI is based on observable deviations from a desired condition or performance, and observable safety infringement. Several factors are considered in the evaluations, including but not limited to observed distresses, severity of distress, functional performance, safety, appearance, and obsolescence.

Although some subjectivity is involved in determining the weight and importance of the stated factors contributing to the overall CI of a component, the resulting subjectivity should not be considered a hindrance. See Appendix A for the inspection sheets to be used by inspectors.

The assessed CI of a component may be based on evaluations of individual subcomponents (elements) that make up the component. To facilitate the determination of the overall CI of the component, weights will have to be formulated for each of the subcomponents/elements. The weights will be based on the functional importance of each of the subcomponents. Take the boiler as an example. As a component it comprises several key functional subcomponents (or elements):

- Combustion chamber and Drum
- Water Column

- Boiler trim
- Pressure gauges
- Boiler tubes
- Piping
- Circulation pump
- Safety valves
- Gas valves
- Electrical controls
- Boiler Vent
- Surface Blow down Line

The relative weights of each of the above sub-components can be determined using APH (to be discussed in chapter 4). Once the CI of each sub-component has been evaluated, the CI of the boiler is determined by rolling up the CIs of its sub-components.

3.4.1 Condition Index Scale

The suggested condition assessment scale presented in Table 4 extends from 0 to 100, with 0 indicating complete failure and 100 indicating perfect condition and function. This scale was finalized after several discussions with engineers from the Lands and Buildings Branch. The scale is divided into three "action" zones. In Zone 1 (CI ranging from 100 – 60, with a condition rating of either A or B), condition and function are generally at a level at which only routine preventative maintenance is required. In Zone 3

(CI ranging fro 29 – 0, with condition rating of either D or F) the condition or function is usually poor enough to warrant immediate attention. Facilities or components falling in Zone 2 (CI ranging from 59 – 30, condition rating of C) show moderate deterioration condition and/or experience partial functional deficiency. It is within this transition zone that the greatest potential for maintenance and rehabilitation planning typically exists.

Table 3.1 Suggested Condition Index Scale (adapted from McKay 1999)

Zone	Condition Rating	Condition Index	Condition Description	Recommended Action
1	A	100 – 90	Excellent: No noticeable defects.	Immediate action is not required.
		89 - 80	Some aging or wear may be visible.	
	B	79 - 70	Good: Only minor deterioration or defects are visible.	
		69 - 60		
2	C	59 – 50	Fair: Some deterioration or defects are evident, but function is not significantly affected.	Candidate for maintenance action. Economic analysis of repair alternatives is recommended to determine appropriate action.
		49 – 40		
		39 – 30	Marginal: Moderate deterioration. Function is still adequate.	
3	D	29 – 20	Poor: Serious deterioration in at least some portions of the structure. Function is inadequate.	Detailed evaluation is required to determine the need for repair, rehabilitation, or reconstruction. Safety evaluation is recommended.
		19 – 10	Very Poor: Extensive deterioration. Barely functional.	
	F	9 - 0	Failed: No longer functions. General failure of a major structural component.	

Each zone is subdivided into three or four condition levels. A brief description of the general condition and function for these levels is included. The use of the numerical condition indicator allows for convenient data storage and handling by computer. It also allows the condition indicators to be included in mathematical expressions.

3.4.2 Development of the Condition Index Structure

Asset managers, engineers, and building inspectors of the Lands and Buildings Branch of the City of Edmonton (hereafter referred to as "experts") with extensive experience in the various functional systems of a building as well as in engineering, construction, and maintenance provided both expertise and knowledge in developing the structure for the CI. The primary evaluation criterion of a building component is the extent to which it satisfies its functional requirements. Age and appearance quality, obsolescence, environment, and applicable distresses are factors that are given consideration in the assessment process. A review was conducted on each building component and the key questions raised relative to each component were similar to those used by McKay et al (1999), viz.:

1. How does the component deteriorate?
2. What are the distresses associated with the component?
3. What are the first indicators that something is going wrong?
4. How bad must the distresses become before the experts become concerned?

5. How bad must the distresses become before the situation becomes critical?
6. What tests can be conducted to assess the severity of distresses?
7. Are these tests affordable and cost effective?

The consensus was that this information could be incorporated into a CI system. The experts had reservations as to whether inspectors would be consistent in their assessment of the conditions detected in the field. Such reservations did not affect the development of a tangible strategy for determining the CI.

3.5 Inspection Process

The CI of the component is related to a formula that provides for a condition index of 100 (excellent condition or new construction). In such a condition there are no distresses, no safety concerns, and no impaired functionality. It is possible to develop a composite condition index that combines two or more condition attributes and therefore represents an aggregation of different measures of condition (Hudson et al. 1997). Weighting factors are used for those condition attributes that are applicable to the specific component. Table 3.2 provides a list of the condition attributes that apply to various building systems and their respective components. The inspection data on a component will invariably include the following:

- Age

- End of service life date
- Functionality level
- Observed distresses
- Conditions contributing to distresses
- Distress severity
- Infringement on functional performance
- Safety and code concerns
- Defective parts
- Details of repairs
- Estimated repair/replacement costs
- Projected estimate of next years condition
- Projected estimate of service life if different from design service life
- Failure Mode
- Cause of Failure

For each building component, inspectors would use their engineering judgment to evaluate the observed distresses and assess the severity. Where applicable, and if financially feasible, nondestructive tests such as ultrasonic testing, infrared thermography, laser testing, can be conducted to determine the severity of the defects and the integrity of components.

TABLE 3. 2 Condition Attributes of Various Building Systems

BUILDING SYSTEM	CONDITION ATTRIBUTES							
	FUNCTIONAL PERFORMANCE	DISTRESS	DISTRESS SEVERITY	SAFETY	OBSOLESCENCE	APPEARANCE	OPERATING CONDITIONS	AGE
Foundations	x	x	x	x				x
Super Structure	x	x	x	x				x
Exterior Envelope	x	x	x			x		x
Roofing	x	x	x					
Interior Construction	x	x	x				x	x
Finishes	x	x	x	x		x	x	x
Conveying	x	x	x	x	x		x	x
Plumbing	x	x	x					
HVAC	x	x	x	x	x		x	x
Electrical	x	x	x	x	x		x	x
Fire Protection	x	x	x	x	x		x	x
Site Services	x	x	x			x		

The combined condition index of the component will be based on the field rating given for each of the condition attributes associated with the component (see Table 3.3). It can be computed using the following formula.

$$CI_{Combined} = \sum_{i=1}^{n} (W_i)(C_i), \; i = 1, \ldots\ldots, n \qquad (3.1)$$

Where W_i represents the weight factors (to be provided by experts) for the condition attributes and C_i represents the value for condition measures. It is generally expected that the asset manager in conjunction with the inspection engineer will select the applicable condition attributes and decide upon their respective weight factors.

Table 3.3 Condition attributes associated with the Development of the Combined Index

CONDITION ATTRIBUTE	CONDITION MEASURE	WEIGHT	CI
FUNCTIONAL PERFORMANCE	C_{FC}	W_{fc}	C_{FC}* W_{fc}
DISTRESS	C_D	W_d	C_D* W_d
DISTRESS SEVERITY	C_{DS}	W_{ds}	C_{DS}* W_{ds}
SAFETY	C_S	W_s	C_S* W_s
APPEARANCE	C_{AP}	W_{ap}	C_{AP}* W_{ap}
AGE	C_{AG}	W_{ag}	C_{AG}* W_{ag}
	$CI_{COMBINED}$		$\sum_{i=1}^{n} (W_i)(C_i)$

3.5.1 Functional Performance

Measurements related to functional performance can be determined by specific tests where applicable or by the subjective assessment of the inspector. The inspector usually relies on his experience and his preexisting knowledge of the component. For electrical and mechanical components, simple load tests can be carried out to assess the performance of some equipment. Other components such as external walls, roofs, and boilers may require more substantial tests that may be expensive to administer. As a consequence, the general practice is for inspectors to make a judgment that is consistent with the applicable design code requirements, and to make estimates for their future performance based on the same philosophy.

3.5.2 Distress

The Building Condition Assessment Protocols developed by the NRC (1999) can be very instructive in developing a list of the distresses associated with specific building components. The different mode of behavior and distresses that is representative of the wear and deterioration of components can be depicted and measured. In the latter case, this may entail physically measuring the affected area or other forms of quantitative measurements for some components, but for others a subjective judgment based on experience will suffice.

3.5.3 Distress Severity

The severity associated with certain distresses will vary depending on the type and magnitude of the distress. The severity can be estimated realistically by employing a series of linguistic choices that can translate into numeric values. Inspectors can make their evaluation based on the outline provided in Table 3.4.

Table 3.4 Severity Measurement

Distress Type	Cause of Distress	Distress Severity	Severity Measurement
	Weather Settlement Vandalism	None	100
		Very Minimal	90
		Minimal	80
		Medium	60
		High	40
		Very High	20

3.5.4 Safety

One of the key issues warranting attention relates to safety. Traditionally, this has been interpreted to refer to structural safety and its related consequences and the sequences of structural system failure. There are, however, other safety-related issues that inspectors may have to take into consideration when conducting inspections on building, especially facilities that are frequently used by the public. There are safety issues with regards to the operation of the boiler, elevator, and escalators. There are also other safety issues governing the work environment and public spaces (e.g., those that may be equipment and may pose a threat to fire safety). These are all issues that the inspectors will evaluate to overall condition index for the safety condition attribute.

3.5.5 Appearance

Physical appearance may not be an engineering issue or a performance issue, but it is a public-perception issue. Some distress may not be hazardous in scale or severity, but general appearance may be quite unsightly, necessitating some form of maintenance action. Invariably, these types of problems are more evident on exterior and interior walls, windows, doors, ceilings, floors, and other finishes.

3.5.6 Age

The age factor relates specifically to components that may not be significant, or components whose condition cannot be monitored, or for which the application of condition monitoring techniques may not be cost effective. Invariably, the service life of these components may be comparatively short (1 – 5 years). Under those circumstances it is more expedient to make an assessment based on age.

3.6 Roll-Up Algorithm

Each of the building components contributes to the overall performance of the building system. The same relationship exists between the building systems and each building. The magnitude of the contribution is determined by the relative importance or weight of each component to the overall system performance.

Figure 3.1 demonstrates this general process and illustrates how the CI of a building is determined. The overall facility CI is computed using the bottom-up or roll-up process (Uzarski and Burley 1997). First, the CIs are determined for the element or component level (i.e., the lowest level that building maintenance is administered within the agency). The AHP methodology is then used to determine relative weights (w_i) of building systems and components as (see chapter 4). The derived weights and the assigned CI will combine to determine the CI for each building component, system, and, subsequently, for the entire building. The relative weights would vary according to facility type. Similarly, the level of detail involved in the assessment process and the number of items to be evaluated are dictated by the requirements for managing each building type.

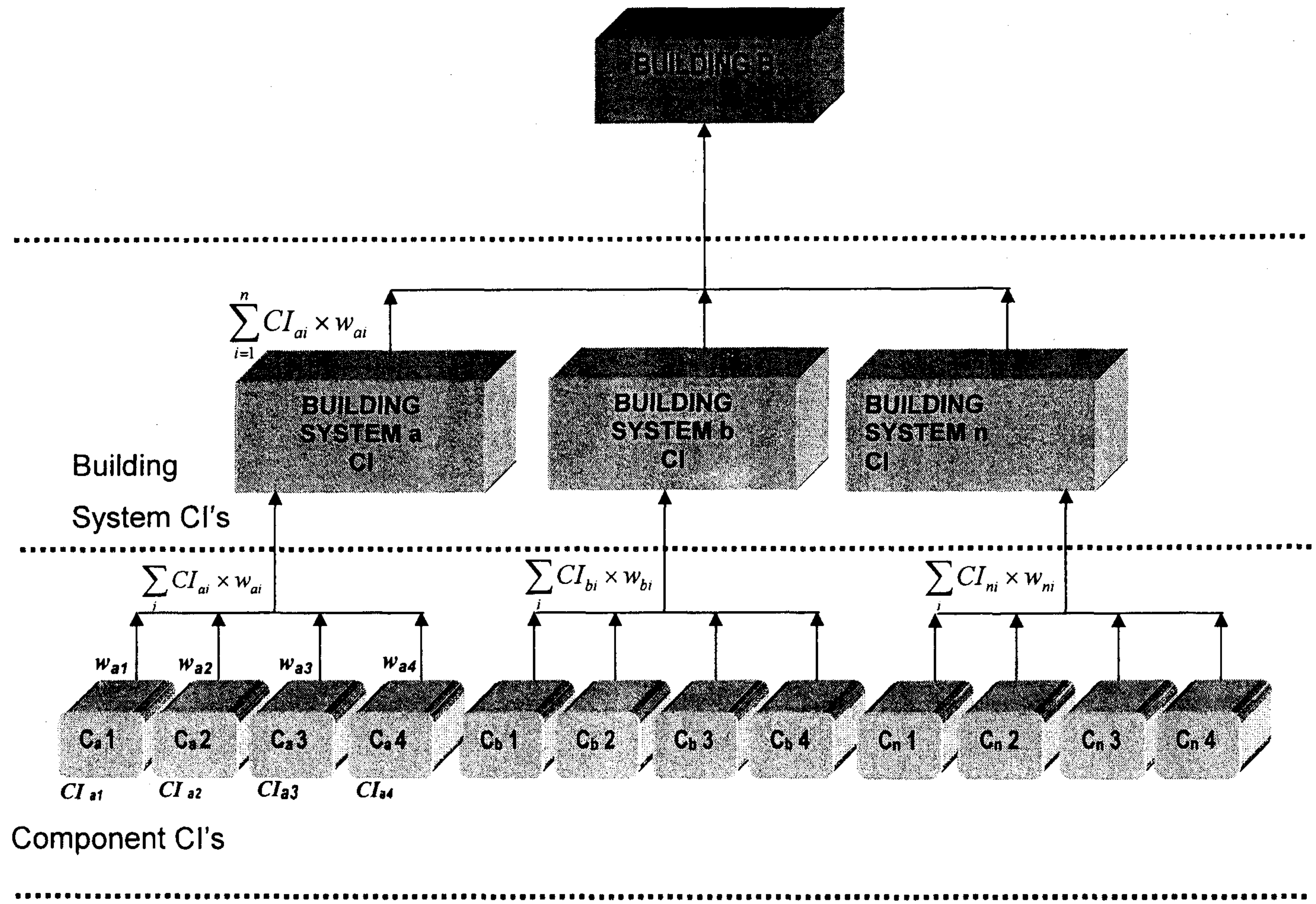


Figure 3.1 General Structure of the CI Process

For example, the condition rating of building system S_a depends mainly on the condition of its n components C_a1, C_a2, ..., C_an which have weights w_a1, w_a2, ..., w_an respectively. At any time, when information on the condition of the components is available, the condition of the system can be calculated using the following formula:

$$CI\ S_a = \sum_{i=1}^{n} C_i w_{ai} \tag{3.2}$$

Where:

CI S_a denotes the condition index of the system S.

Finally, the overall condition rating of a building B in terms of the condition of its m systems S_1, S_2, ..., S_m with weights w_s1, w_s2, ..., w_sm, is obtained in the same manner:

$$CI\,B = \sum_{j=1}^{m} s_j w_{sj} = \sum_{k=1}^{k=m} \sum_{j=1}^{j=p} \sum_{i=1}^{i=n} C_i w_{cj} w_{sk} \tag{3.3}$$

3.7 Conclusions

There is no single best engineering or analytical formula for establishing a CI. The key to developing a combined or composite index for the condition of a building system or component is to recognize the subjective nature of both the assessed CI as well as the relative weights assigned to components. Once the process is consistent, it provides asset managers with a tool to gauge or measure the condition of building assets. It also conveys much needed information to facilitate timely decisions on required maintenance actions. The developed indexes and underlying data serve to establish an engineering baseline to quantify condition and track trends in condition. They also provide the asset manager with a mechanism for ensuring consistency in the definition of conditions being applied across the building asset portfolio.

The importance of condition indices as a major input in the development of the decision support schemes that measure the impact of performing specific MR&R operations cannot be overstated. It is on the basis of this type of feedback that future MR&R strategies will be planned and implemented. This approach will allow asset managers to make decisions in advance about:

- Selecting the most cost effective maintenance strategy for each building component; and
- The optimal allocation of logistics resources such as spares, tools, and personnel, which are needed for the execution of maintenance tasks.

Chapter 4 An Analytical Approach to Prioritize Building Components: A Framework of the Evaluation Method

4 An Analytical Approach to Prioritize Building Components: A Framework of the Evaluation Method

4.1 Introduction

Buildings can be viewed as a collection of interconnected building systems, with each system consisting of a multifarious grouping of 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, NRC 1998, Hudson et al. 1997, Uzarski and Burley, 1997). The structuring of a building into a hierarchical framework of functional systems and components is fundamental to the application of the AHP methodology, which facilitates the determination of the relative weights of each entity within the building structure.

Researchers have applied the AHP methodology to solve problems in the disciplines of computer-integrated manufacturing (Triantaphyllou and Mann 1995), layout design (Cambron and Evans 1991), building maintenance (Shen et al. 1998, Spedding et al. 1995), industrial engineering (Putrus 1990) 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.

Current literature provides very little information on a methodology for determining the relative weights of building assets, i.e., with specific reference to defined building systems and components. Shohet and Perelstein (2004) used life cycle cost (LCC) analysis as a means to determine the weighting of each building system, with the weighting of a system being equal to its proportion in the LCC of the building. However, obtaining the data, scoping the study, and assessing the impacts may turn out to be a long and complex process, especially if the analysis is being carried out on a building that has been operational for quite sometime. Furthermore, this approach does not take into account cognizance of key factors such as safety and functional performance of components in the determination of these relative weights. Uzarski and Burly (1997) referred to the application of a weight or value factor (0 – 1) for building components in the computation of the condition indexes, but does not present a methodology for developing or estimating this factor.

The present research was therefore motivated by the need for a robust approach that can be used to assess and compare building systems, components and elements (if needed) on a common basis. The approach is formulated to determine a single weighted score for building assets. 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.

4.2 Problem Structuring and Alternative Development

Buildings, like other infrastructure facilities, are complex structures. And, although it is rare to find two facilities that are physically identical, it is common to have facilities with similar systems and components. 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.

Before performing any analysis, problem conceptualization and formulation need to be performed to gain a better understanding into the nature of the problem. 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.

4.2.1 Group Facilitation

The data presented in this thesis forms part of a research project that was carried out by the Lands and Buildings Branch of the City of Edmonton, Alberta, Canada. This agency manages an inventory of over 1100 facilities of varying building types. A total of eight experienced asset managers, engineers, and building inspectors considered experts in the domain of building and facilities maintenance and management were interviewed to gather the required data for the computation of the priority weights for building systems and components.

Obtaining the opinion of the experts on the comparative analysis of building systems and components was essentially an exercise highly dependent on the ability to manage group interactions and to accommodate multiple inputs efficiently. The underlying goal was to manage or facilitate group interactions so that in the end some level of acceptable compromise was achieved, unless consensus can be reached. In instances where there was no consensus, the geometric mean of the responses was taken (Saaty 1996).

The AHP, with its consistency measures, offered a pragmatic way to facilitate group decisions so that choices can be progressively and systematically steered toward an acceptable compromise. Consistency indices and consistency ratios can serve as guides to help direct the decision process towards better collective choices. The opportunity provided by the AHP for each participant to provide their input, and because these inputs are treated by the AHP in a manner transparent to participants, it increases the likelihood that results of the analysis will be acceptable to all.

4.3 An AHP Model for Building Hierarchy Evaluation

4.3.1 An Overview of the AHP Model

In this research, an AHP model is formulated for a comparative analysis of building components and systems within the building structure. This comparative analysis is a multiple criteria evaluation, in which the components and systems are ranked or prioritized at the end of the evaluation. The AHP hierarchical model is illustrated in Figure 4.1, which presents the hierarchical framework of a building. This hierarchy was based on the UNIFORMAT II Elemental Classification (Charette and Marshall 1999). Level 1 represents the building systems, Level 2 represents the building components, and Level 3 represents the building elements. Subjective judgments on the relative importance of the requisite building systems and components were elicited from the Asset Managers from the City of Edmonton based on a set of well-defined criteria, namely, functional performance, cost, and reliability.

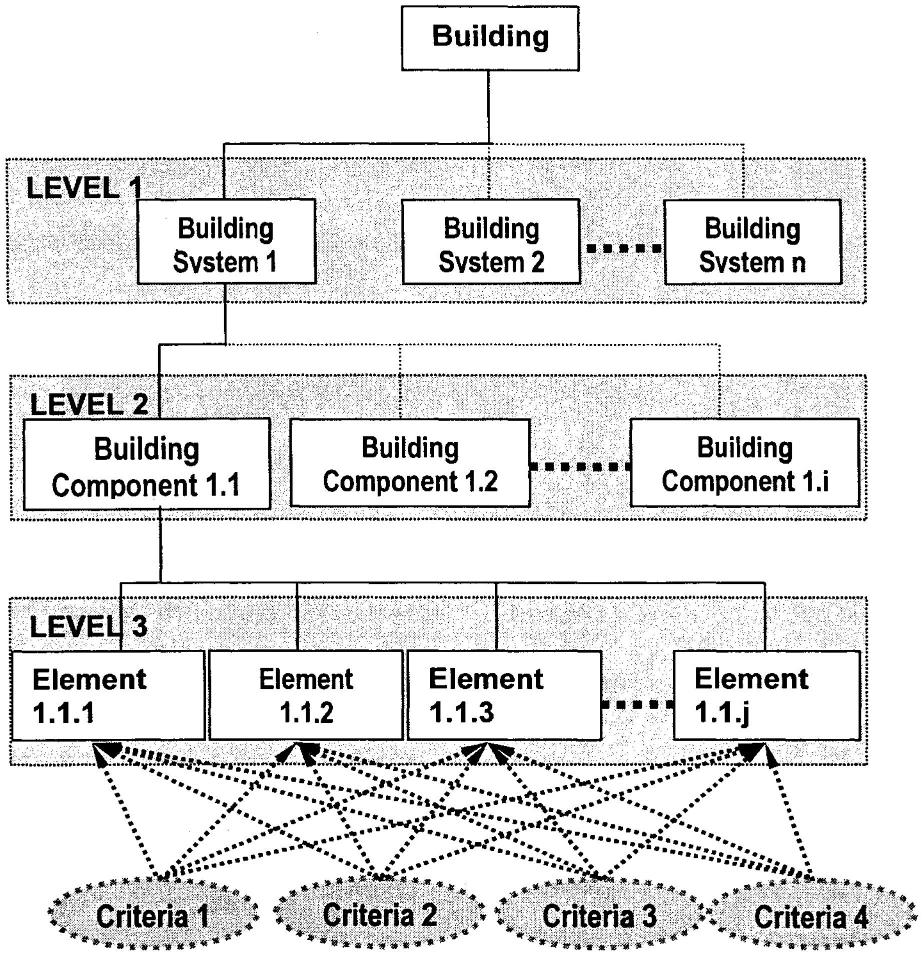


Figure 4.1 Hierarchical Framework for a Building

The model was based on the theory of AHP (Saaty 1996). The AHP method derives ratios from reciprocal comparisons of the criteria and variables by assigning numerical values to subjective judgments on the relative importance of these variables and criteria. The decision maker has to select an answer from the 10 – 17 discrete choices shown in Table 4.1 (Saaty 1996). Each choice is a linguistic phrase. The judgments are then synthesized to determine the overall priorities of the variables and the criteria. Pair wise comparisons are used to determine the relative importance of each component and system in terms of each criterion.

Table 4.1 Fundamental Ratio Scale in Pair Wise Comparison (Saaty 1990)

Intensity of Importance	Description	Explanation
1	Equal Importance	Two activities contribute to the objective.
3	Weak importance of one over the other	Experience and judgment slightly favor one over another.
5	Essential or strong importance	Experience and judgment strongly favor one over another.
7	Very strong or demonstrated importance	The activity favors very strongly one over another; its dominance demonstrated in practice.
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between adjacent scale value	When a compromise in judgment is needed.

A consistency index (CI) can be determined at the end of the synthesis to reflect the consistency of the judgment the smaller the value of the CI, the smaller the deviation from consistency. A CI of 0.10 or less reflects an informed judgment, which could be attributed to the knowledge of the analyst or experts about the problem under study, the homogeneity of the variables in the comparison, or the number of variables in the comparison. In the formulated AHP model, both the relative and absolute modes of comparison can be performed. The relative mode can be used when users have prior good knowledge of the criteria to be used, or when quantitative data of the criteria to be evaluated is unavailable. The absolute mode is used when data of the criteria to be evaluated are readily available. In the absolute mode, CI is always equal to 0, i.e., complete consistency, since the exact values are used in the comparison matrices.

4.4 The Structure of the AHP Model

In the formulated AHP model, the building systems or components under evaluation are denoted as $\mathbf{S}_i$ (i = 1, 2, ..., n). The criteria used for comparative analysis are denoted as $\mathbf{C}_j$ (j = 1, 2, ..., m). The number of criteria used in this evaluation is m. The criteria are denoted as $\mathbf{C}_1$, $\mathbf{C}_2$, ... $\mathbf{C}_m$(see Figure 4.2)

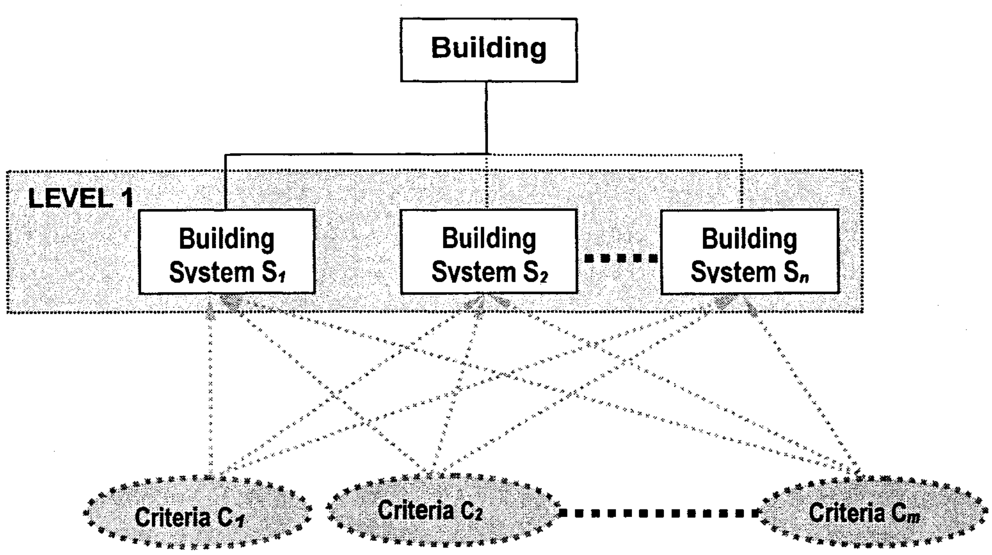


Figure 4.2 Simple breakdown of a Building

4.4.1 Evaluation of Building Systems/Components

4.4.1.1 Determination of the Matrix of Comparison

For n number of systems/components considered, there are n number of matrices, with $\mathbf{MS}_k$ (k = 1, 2, ...n), each being a comparison matrix of the n systems or components with respect to each other for one criterion. The matrix is determined as follows:

$$\mathbf{MS}_k = (\mathbf{s}_{ij}) \qquad (i, j = 1, 2, \ldots\ldots, n) \tag{4.1}$$

For the relative mode of comparison, entries are defined by two entry rules:

Rule 1. If $\mathbf{s}_{ij} = \alpha$, $\mathbf{s}_{ji} = \frac{1}{\alpha}$, $\alpha \neq 0$.

Rule 2. If $\mathbf{A}_i$ is judged to be of equal relative importance as $\mathbf{A}_j$, $\mathbf{s}_{ij} = 1$, $\mathbf{s}_{ji} = 1$; in particular $\mathbf{s}_{ii} = 1$ for all i.

Thus the matrix $\mathbf{MS}_k$ is as follows:

$$\mathbf{MS}_k = \begin{bmatrix} s_{11} & s_{12} & s_{13} & \cdots & s_{1l} & \cdots & s_{1n} \\ s_{21} & s_{22} & s_{23} & \cdots & s_{2l} & \cdots & s_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ s_{l1} & s_{l2} & s_{l3} & \vdots & s_{ll} & \vdots & s_{ln} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ s_{n1} & s_{n2} & s_{n3} & \cdots & s_{nl} & \cdots & s_{nn} \end{bmatrix}$$

$$
= \begin{bmatrix} 1 & s_{12} & s_{13} & \cdots & s_{1l} & \cdots & s_{1n} \\ \frac{1}{s_{12}} & 1 & s_{23} & \cdots & s_{2l} & \cdots & s_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{1}{s_{1l}} & \frac{1}{s_{2l}} & \frac{1}{s_{3l}} & \cdots & 1 & \cdots & s_{\ln} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{1}{s_{1n}} & \frac{1}{s_{2n}} & \frac{1}{s_{2n}} & \cdots & \frac{1}{s_{\ln}} & \cdots & 1 \end{bmatrix} \qquad (4.2)
$$

4.4.1.2 Determination of the Vector of Priorities ($\mathbf{VPS}_k$)

After $\mathbf{MS}_k$ has been determined, the vector of priorities $\mathbf{VPS}_k$ for $\mathbf{MS}_k$ is computed. The initial step in obtaining $\mathbf{VPS}_k$ is to multiply the n elements in each row in $\mathbf{MS}_k$ and take the n^{th} root, resulting in a column vector. The column vector is normalized to obtain the vector of priorities, $\mathbf{VPS}_k$, as in the equation

$$
\mathbf{VPS}_k = \begin{bmatrix} vnorm_{k,1} \\ vnorm_{k,2} \\ \vdots \\ vnorm_{k,l} \\ \vdots \\ vnorm_{k,n} \end{bmatrix} \qquad (4.3)
$$

4.4.1.3 Determination of the Eigenvalue, $\lambda_{\max}$

$\lambda_{\max}$ is used to estimate the consistency as reflected in the proportionality of preferences (Saaty 1996, 1990). In this example, for $\mathbf{MS}_k$ the closer

λ_{max} is to n, i.e., the number of criteria, the more consistent is the result. The initial step in obtaining the λ_{max} for $\mathbf{MS}_k$ is to multiply each matrix of comparison by its vector of priorities ($\mathbf{VPS}_k$). The first component of the resulting vector is divided by the first component of the $\mathbf{VPS}_k$, the second component by the second component of the $\mathbf{VPS}_k$, and so forth. λ_{max} for the $\mathbf{MS}_k$ is finally determined by first summing the components in the final resulting vector by n, the number of systems or components being compared.

4.4.1.4 Determination of the Consistency Index (CI)

The consistency index (CI) indicates the deviation from consistency. The smaller the value of the CI, the smaller is the deviation from the consistency. The CI for $\mathbf{MS}_k$ is determined using the following equation:

$$\text{CI } (\mathbf{MS}_k) = \frac{\lambda_{max} - n}{n-1} \quad (4.4)$$

4.4.2 Evaluation of the Criteria

4.4.2.1 Determination of $\mathbf{MC}_i$:

For m number of criteria being considered in the comparison matrix, there are m number of matrices, $\mathbf{MC}_i$ (i = 1, 2, ..., m), each being a comparison matrix of m criteria with respect to one another. The procedure to determine the vector of priorities, $\mathbf{VPC}_k$, is similar to the procedure used to determine $\mathbf{VPS}_k$ discussed above **(Section 4.4.1)**.

4.4.3 Determination of the Single Score or Weight for each System or Component

The third stage of the AHP process involves determining a final score for each of the building systems (or components) that were evaluated based on the weights that were computed.

4.4.3.1 Formation of Matrix MS

The vector of priorities $\mathbf{VPS}_k$ are weights generated for systems $\mathbf{S}_k$. In order to obtain an overall score for each of the systems based on the criteria, the $\mathbf{VPS}_k$ are arranged into matrix **MS**. Matrix **MS** is determined by the equation:

$$\mathbf{MS} = \left[[VPS_1] \ [VPS_2] \ \cdots \ [VPS_m] \right] \qquad (4.5)$$

4.4.3.2 Final Priority Score

After matrix MS has been generated, the next step is to compute the final priority scores for the building systems, $\mathbf{WS}_l$. To obtain $\mathbf{WS}_l$, matrix **MS** is multiplied by $\mathbf{VPC}_l$. This procedure is equivalent to weighting each of the judgments ($\mathbf{MS}_l$) by the priority of the corresponding criteria ($\mathbf{MC}_k$). The final priority score $\mathbf{WS}_l$ is determined using the following equation:

$\mathbf{WS}_l = [\mathbf{MS}]\ [\mathbf{VPC}_l]$

$$= \begin{bmatrix} vnorm_{1,1} & vnorm_{2,1} & \cdots & vnorm_{m,1} \\ vnorm_{1,2} & vnorm_{2,2} & \cdots & vnorm_{m,2} \\ \vdots & \vdots & \vdots & \vdots \\ vnorm_{1,l} & vnorm_{2,l} & \cdots & vnorm_{m,l} \end{bmatrix} \times \begin{bmatrix} ynorm_{1,l} \\ ynorm_{2,l} \\ \vdots \\ ynorm_{m,l} \end{bmatrix} = \begin{bmatrix} ws_{1,l} \\ ws_{2,l} \\ \vdots \\ ws_{n,l} \end{bmatrix}$$

(4.6)

The computed values for $\mathbf{WS}_{1l}$ ....$\mathbf{WS}_{nl}$ represents the final priority weights assigned to the systems (or components) that were being compared.

4.5 Dealing with Interdependency

In conducting the pair wise comparisons between building systems (and components) the decision makers sequentially compares two systems at a time with respect to an upper level control criterion. The evaluations therefore are done in a manner that implies that building systems exists as independent entities. Within a building however, the interdependency between building systems is critical to its functional performance. It is important to model this interaction between systems (and components). AHP facilitates the evaluation and estimation of this interdependency between systems (and components).

4.5.1 Accounting for Interdependency between Building Systems

Within the complex building environment of interconnected building systems, the impaired functionality of a specific system may have an impact on itself as well as inhibiting other systems from carrying out their quintessential functions. It is important to account for these interactive effects between building systems wherever such interaction exists. To attempt to estimate the magnitude of this dynamic relationship would require obtaining further judgments from experts on interdependency between the building systems. Interdependency here implies contribution, influence, or impact from other systems. Judgments of the interdependency between building systems and components will serve the purpose of clearly defining what entities have a greater weight within the building, and consequently what entity should be given priority in the planning and execution of maintenance projects and in the disbursement of the limited maintenance funds.

AHP has the capability of addressing this important issue of interdependency. Saaty (1990) suggested that when assessing the interdependence between factors, the assumption should be made that each factor does not contribute to itself. This assumption does not necessarily hold true for building facilities or any physical assets for that matter. Most physical assets are designed to function independently as well as in conjunction with others. The failure of an asset may not necessarily mean that all components contributing to the functioning of that asset have failed. Conversely, the failure of a component can seriously impact the performance of other components within an asset, perhaps even contributing to the failure of the asset itself. In reality, most components contribute to their own performance while at the same time supporting others. This is illustrated in Figures 4.3 and 4.4. In Figure 4.3, the condition rating of all components are assessed to be in either condition A or B; hence, the overall condition rating of the asset or system is determined by computation (of weights and condition) to be B. In Figure 4.4, considering the very same asset, the condition ratings of two of the components are assessed to be in either D or F (poor or failed) condition, which results in the rapid deterioration of the asset resulting in functional failure despite the fact that the remaining components have a condition rating of B. A good example of this is the Building System – Superstructure, where the failure of one or two building columns (a critical component) is serious enough to contribute to the failure of the entire system as well as the building asset, despite the fact that the structural floors, the roof construction, the structural interior walls, and expansion controls, are all in good condition.

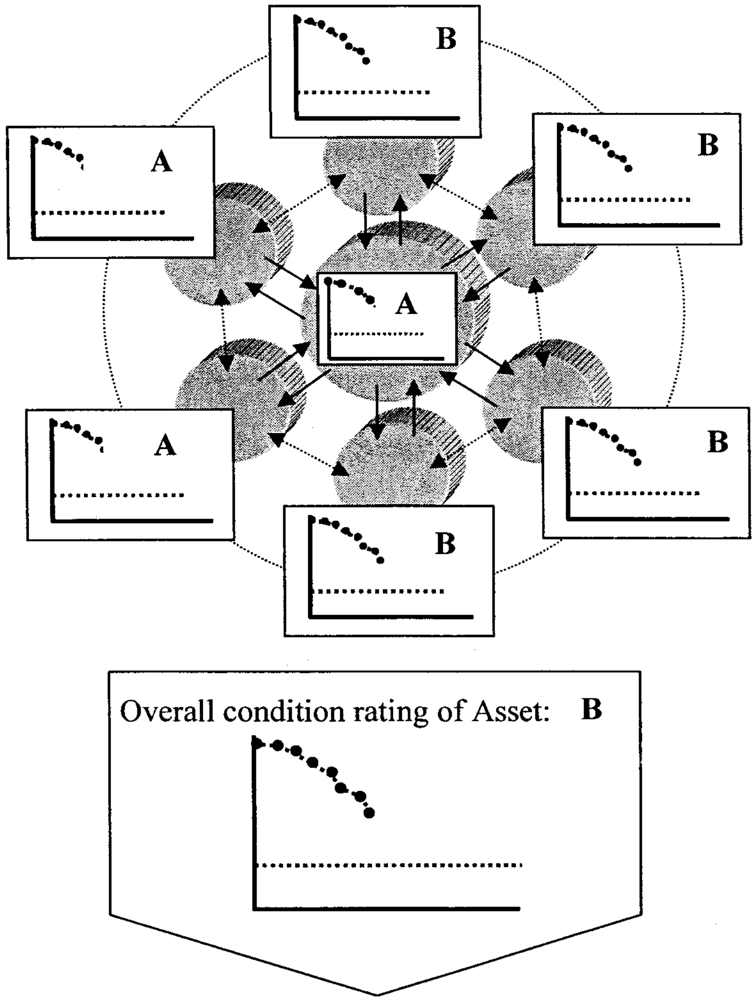


Figure 4.3 Interdependency of Building Components Contribute to Overall Condition of Asset

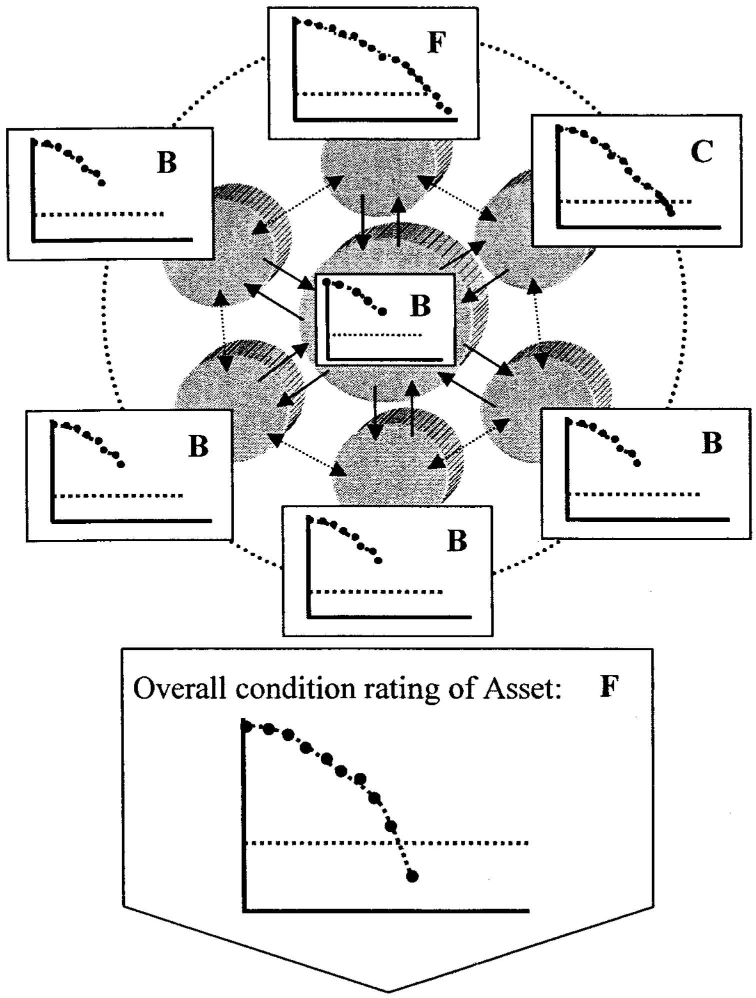


Figure 4.4 Interdependency of Building Components Contribute to Overall Failure of Asset

4.5.2 The Concept of Self Contribution in Interdependency Between Building Systems

Since there exists an undisputed interdependency between building systems, it would be extremely important to assess and quantify the weight of that interdependency and have that factored into the priority weights of building systems. The level of interdependency of the different systems could be rated between the two extremes of no dependency and total dependency. This infers that the functional performance of a given system may or may not be affected by the failure of another system. The strength or level of this interdependency can be evaluated using the concept of self-contribution in interdependencies between components developed by Allouche et al. (2004).

4.5.3 Evaluating the Self-Contribution of a System

Assuming that an building is comprised of n systems $S_1, \ldots, S_i, \ldots, S_n$ of absolute weights $w_1, \ldots, w_i, \ldots, w_n$, respectively. The condition rating of the asset or building is a function of the conditions of its systems. Most public agencies would stipulate a minimum performance measure or minimum level of service (los_{min}) for most of their assets (Hudson et al. 1997, Uzarski and Burley 1997). This minimum performance measure ensures provisions of an adequate level of service to the general public. The minimum level of service will vary depending on the how critical that system or component is. In the example illustrated in Figure 4.5, that minimum level of service is represented by a condition index (CI) of 40. For other components that minimum level of service can be represented by a CI of 50. Should deterioration be allowed to continue unchecked past that minimum acceptable level without maintenance intervention, rapid failure can result, affecting the performance of other systems and jeopardizing the integrity and functionality of the building.

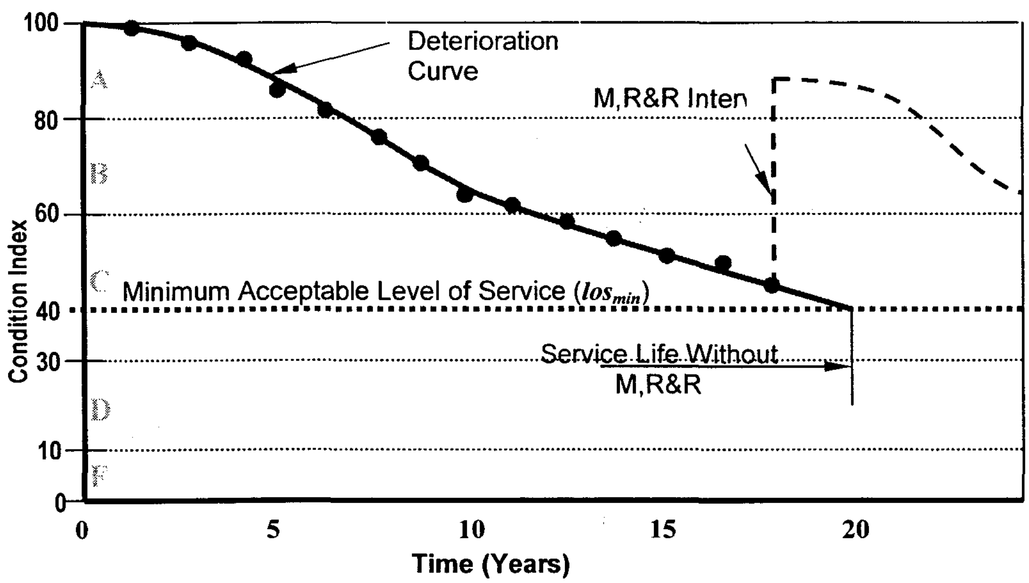


Figure 4.5 Deterioration of Building System (or Component)

To calculate the magnitude of the self-contribution, we use the following equation, which reflects to a certain degree the overall condition of the asset.

Condition of building $\boldsymbol{B} = \sum_{i=1}^{n} w_i * Condition(S_i)$ (4.7)

Since the minimum level of service S_1los_{min} ... S_ilos_i, ..., S_nlos_n refers to the CI that relates the minimum level of service of building systems S_1, ..., S_i, ..., S_n, respectively, then from the above equation $Blos_{min}$ can be obtained as shown below:

$$Blos_{min} = \sum_{i=1}^{n} w_i * S_i los_{min} \tag{4.8}$$

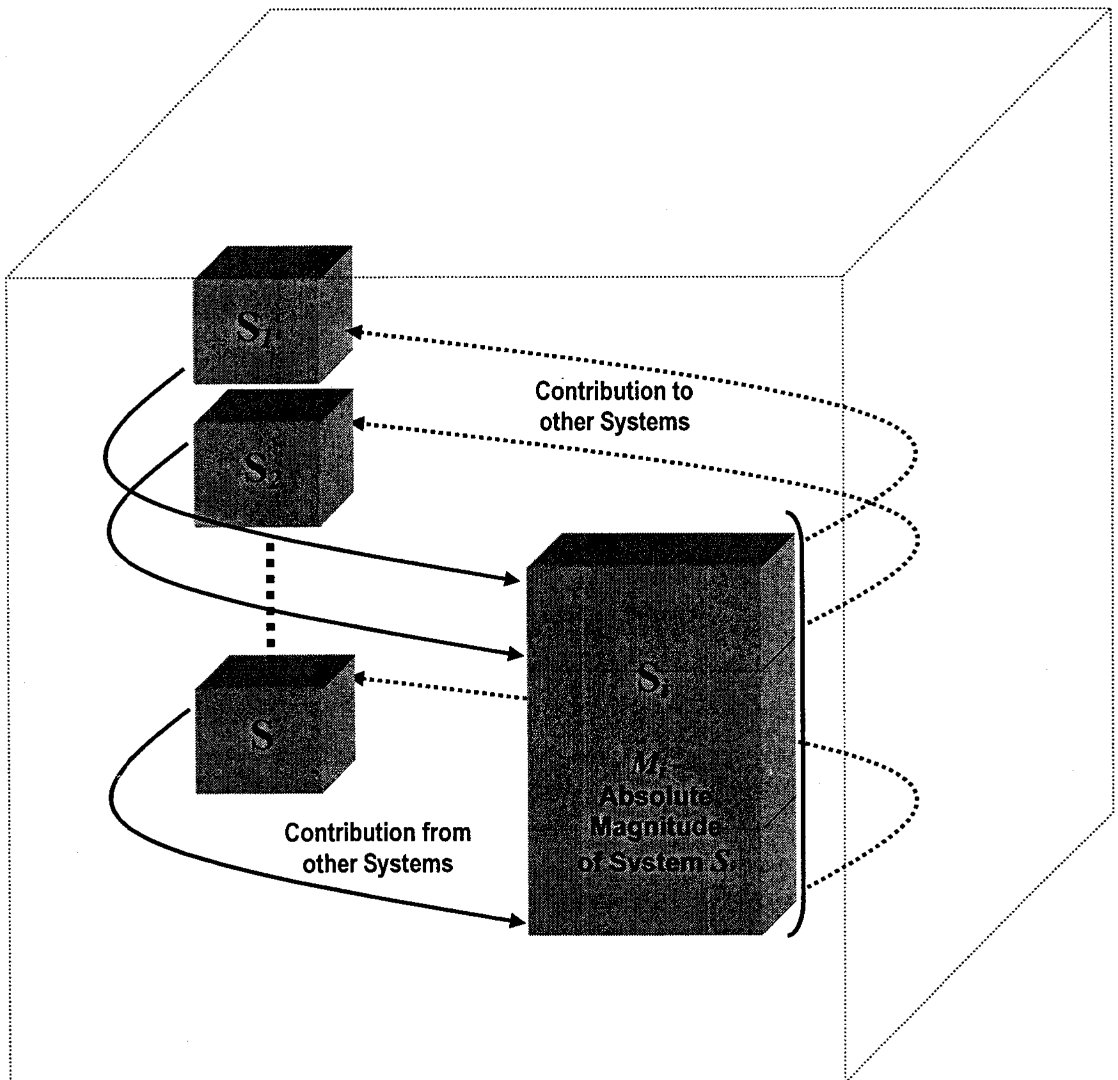


Figure 4.6 Flow Chart Showing the Concept of Interdependency Between Building Systems

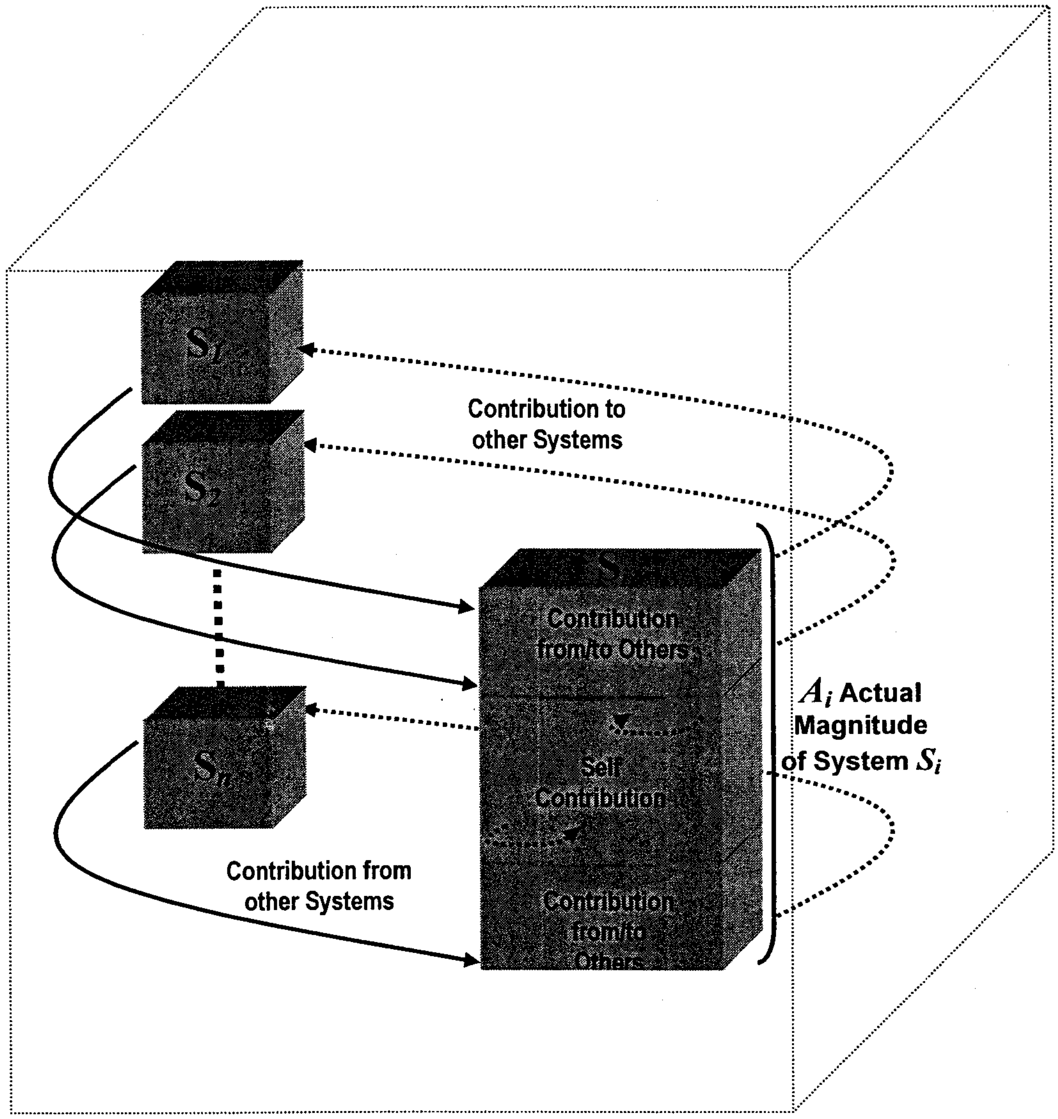


Figure 4.7 Flow Chart Showing the Concept of Self-Contribution

As mentioned earlier, the self-contribution of a system S_j to the overall performance of B represents the level of independency of this system relative to the other related systems of B (please refer to Figures 4. 6 and 4.7). Experts should be able to determine the impact on S_j when all other systems are at their minimum ***los*** levels. The strength of this impact can range from "Total" to "None" and is based on the scale provided in Table 4.2. Within this general framework, the scope of the performance of S_j can be evaluated. The magnitude or the weight of the self-contribution of such system is a measure of that level of independency. For instance, if we denote "condition (B_j)" the condition of the asset B when all systems S_i (i not equal to j) are at their minimum ***los*** level of performance, then the magnitude of the self-contribution of S_j is seen as a percentage of w_j defined by the difference between condition (B_j) and minimum $Blos_{min}$. This weight is represented in equation (4.9):

$$W(Self\ S_j) = \text{condition } B_j - Blos_{min} = (\text{condition } S_j - S_j\,los_{min})^* \, w_j \quad (4.9)$$

It should be noted here that the "*Self S*" is a characteristic of the system and not that of the asset. However, the change in the scores of performance asset has been used to measure the weight of "*Self S*".

Table 4.2. Scale of Self-Contribution

Degree of Impact	Measure of Dependency (r_i)	Self-Contribution % ($s_i = 1 - r_i$)
Nil	0	100
Minimal	20	80
Moderate	40	60
Strong	60	40
Very Strong	80	20
Complete	100	0

In order to develop a matrix of interdependency, respondents were asked to provide their expert judgments to the following question: "**How does system S_i compare to system S_j with respect to its contribution to system S_k?**" It should be noted here that $k \neq i$ and j. The responses are presented in Tables 4.4 – 4.11. The priority vectors and consistency ratio (CR) were derived from each judgment matrix.

Respondents were next required to provide self-contribution data for each building system. The question asked of respondents was "**If other systems (S_i ....S_n) have poor performances (e.g., CI 40), what is the impact of this poor performance on system S_k?** The responses were based on the scale provided in Table 4.2. The following case study will contribute to a better understanding of these terms.

4.6 Case Study

This case study demonstrates the application of determining the relative weights of building systems of an Arena Building Type. Only one criterion will be used to assess the weights of the building systems, i.e., functional performance (see Figure 4.8). A similar approach can be used to determine the relative weights of the building systems. The results of the pair wise comparison made with the building systems are highlighted in the following tables. Table 4.3 illustrates the results of the pair wise comparison when the systems were considered as independent entities.

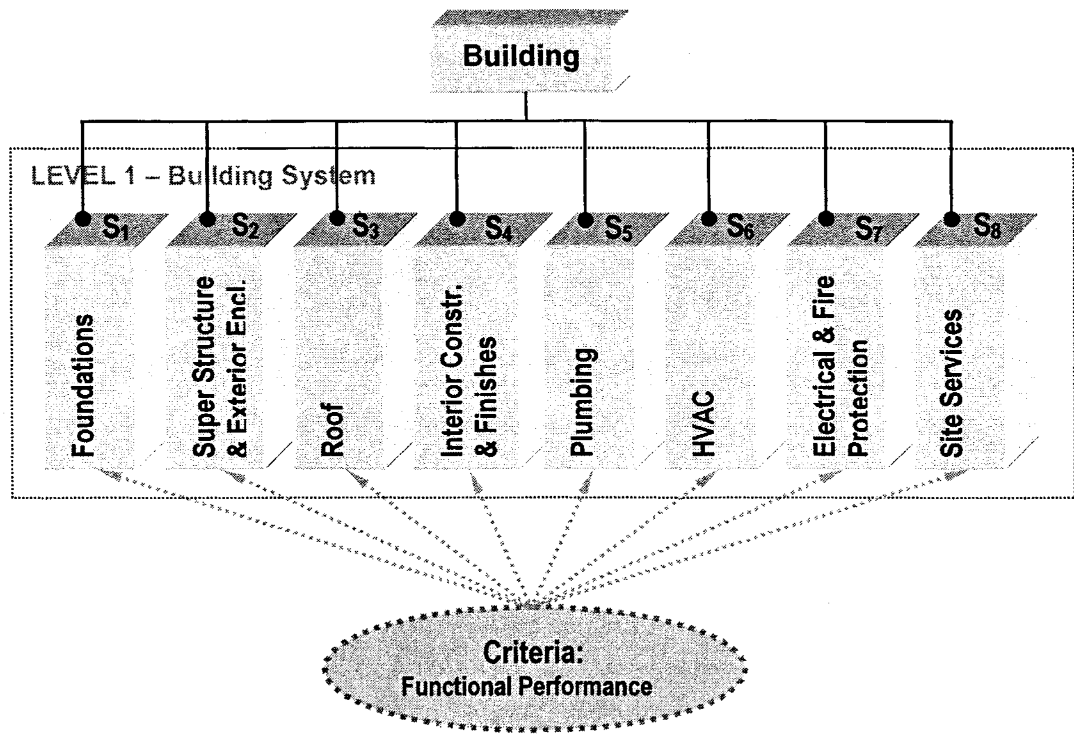


Figure 4.8 Applicable Building Systems for Ambulance Station

To assess the level or interdependency between the building systems, respondents were asked to provide their expert judgments to the following question: "How does system S_i compare to system S_j with respect to its contribution to system S_k?" Their responses were captured in Tables 4.4 – 4.11. The vector of priorities from Tables 4.4 – 4.11 were next weighted by the priority vector obtained previously as if they were independent (Table 4.3) and the rows added. Table 4.13 provides the resultant vector of priorities for the interdependency between building systems. The self contribution weights were assessed (see Table 4.12) and these were used to compute the interdependency weights of the building systems. The results are presented in Table 4.14.

Table 4.3 Judgment Matrix for Building Systems

CRITERIA: FUNC. PER.	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	PRIORITY VECTOR
S_1	1	1/3	1/7	1/2	1/7	1/7	1/8	4	0.04
S_2	3	1	1	6	3	1/2	1/2	8	0.15
S_3	7	1	1	7	3	1/2	1/2	7	0.17
S_4	2	1/6	1/7	1	1/8	1/8	1/8	7	0.04
S_5	7	1/3	1/3	8	1	1/4	1/4	8	0.10
S_6	7	2	2	8	4	1	1	8	0.24
S_7	8	2	2	8	4	1	1	8	0.24
S_8	1/4	1/8	1/7	1/7	1/8	1/8	1/8	1	0.02
	λ_{max}: 9.050096			CI: 0.150014			CR: 0.106393		

Table 4.4 Judgment Matrix for Building Systems with Respect to Foundations

FNDS (S_1)	S_2	S_3	S_4	S_5	S_6	S_7	S_8	PRIORITY VECTOR
S_2	1	4	5	5	4	4	4	0.37
S_3	1/4	1	4	4	4	4	4	0.24
S_4	1/5	1/4	0	1	1/4	1/4	1/4	0.03
S_5	1/5	1/4	0	1	1/4	1/4	0	0.03
S_6	1/4	1/4	4	4	1	2	4	0.16
S_7	1/4	1/4	3	4	1/2	1	4	0.13
S_8	1/4	1/4	0	0	1/4	1/4	1	0.04
		λ_{max}: 7.12498913			CI: 0.02083152		CR: 0.01578146	

Table 4.5 **Judgment Matrix for Building Systems with Respect to Super Structure & Exterior Enclosures**

SS&EE S_2	S_1	S_3	S_4	S_5	S_6	S_7	S_8	PRIORITY VECTOR
S_1	1	3	5	3	4	4	8	0.35
S_3	1/3	1	4	4	3	3	8	0.23
S_4	1/5	1/4	1	1/3	1/3	1/3	3	0.05
S_5	1/3	1/4	3	1	1/3	1/3	4	0.08
S_6	1/4	1/3	3	3	1	3	6	0.15
S_7	1/4	1/3	3	3	1/3	1	6	0.12
S_8	1/8	1/8	1/3	1/6	1/6	1/6	1	0.02
	λ_{max}: 7.61038509			CI: 0.10173085			CR: 0.07706882	

Table 4.6 **Judgment Matrix for Building Systems with Respect to Roofing**

ROOF S_3	S_1	S_2	S_4	S_5	S_6	S_7	S_8	PRIORITY VECTOR
S_1	1	1/3	5	2	5	5	8	0.24
S_2	3	1	5	5	7	7	8	0.41
S_4	1/5	1/5	1	2	3	3	6	0.13
S_5	1/2	1/5	1/2	1	2	2	6	0.10
S_6	1/5	1/7	1/3	1/2	1	2	3	0.06
S_7	1/5	1/7	1/3	1/2	1/2	1	0	0.04
S_8	1/8	1/8	1/6	1/6	1/3	0	1	0.02
	λ_{max}: 7.20388561			CI: 0.03398093			CR: 0.02574313	

Table 4.7 **Judgment Matrix for Building Systems with Respect to Interior Construction & Finishes**

IC&F S_4	S_1	S_2	S_3	S_5	S_6	S_7	S_8	PRIORITY VECTOR
S_1	1	1	1/2	3	3	3	9	0.20
S_2	1	1	1/2	3	3	3	8	0.20
S_3	2	2	1	4	4	4	9	0.31
S_5	1/3	1/3	1/4	1	1/3	1	6	0.07
S_6	1/3	1/3	1/4	3	1	3	6	0.12
S_7	1/3	1/3	1/4	1	1/3	1	6	0.07
S_8	1/9	1/8	1/9	1/6	1/6	1/6	1	0.02
	λ_{max}: 7.3832163			CI: 0.06386938			CR: 0.0483859	

Table 4.8 Judgment Matrix for Building Systems with Respect to Plumbing

PLUMB S_5	S_1	S_2	S_3	S_4	S_6	S_7	S_8	PRIORITY VECTOR
S_1	1	1	1/4	1/4	1/4	1/3	4	0.07
S_2	1	1	1/4	1/4	1/4	1/3	1/2	0.05
S_3	4	4	1	1/3	1/2	3	6	0.18
S_4	4	4	3	1	3	3	5	0.32
S_6	4	4	2	1/3	1	3	6	0.22
S_7	3	3	1/3	1/3	1/3	1	6	0.12
S_8	1/4	2	1/6	1/5	1/6	1/6	1	0.04
		λ_{max}: 7.09688144		CI: 0.01614691			CR: 0.0122325	

Table 4.9 Judgment Matrix for Building Systems with Respect to HVAC

HVAC S_6	S_1	S_2	S_3	S_4	S_5	S_7	S_8	PRIORITY VECTOR
S_1	1	1/3	1/4	1/2	1/4	1/4	6	0.06
S_2	3	1	1/3	3	2	2	8	0.20
S_3	4	3	1	3	3	3	8	0.32
S_4	2	1/3	1/3	1	1/3	1/3	6	0.08
S_5	4	1/2	1/3	3	1	2	8	0.17
S_7	4	1/2	1/3	3	1/2	1	8	0.14
S_8	1/6	1/8	1/8	1/6	1/8	1/8	1	0.02
		λ_{max}: 7.55104517		CI: 0.09184086			CR: 0.06957641	

Table 4.10 Judgment Matrix for Building Systems with Respect to Electrical & Fire Protection

E&FP S_7	S_1	S_2	S_3	S_4	S_5	S_6	S_8	PRIORITY VECTOR
S_1	1	1/3	1/3	1/4	0	2	1/2	0.06
S_2	3	1	3	1/3	4	3	3	0.20
S_3	3	1/3	1	1/3	4	4	6	0.19
S_4	4	3	3	1	6	5	5	0.35
S_5	0	1/4	1/4	1/6	1	1/2	1/5	0.03
S_6	1/2	1/3	1/4	1/5	2	1	1/5	0.05
S_8	2	1/3	1/6	1/5	5	5	1	0.12
		λ_{max}: 7.65895358			CI: 0.1098256		CR: 0.08320121	

Table 4.11 Judgment Matrix for Building Systems with Respect to Site Improvements

SITE S_8	S_1	S_2	S_3	S_4	S_5	S_6	S_7	PRIORITY VECTOR
S_1	1	1/3	1/4	1	1/8	0	1/8	0.03
S_2	3	1	4	4	1/8	5	1/9	0.11
S_3	4	1/4	1	2	1/8	6	1/9	0.09
S_4	1	1/4	1/2	1	1/8	1/3	1/9	0.03
S_5	8	8	8	8	1	4	3	0.39
S_6	0	1/5	1/6	0	1/4	1	1/9	0.03
S_7	8	9	9	9	1/3	9	1	0.33
	λ_{max}: 7.76362194				CI: 0.12727032		CR: 0.09641691	

Table 4.12 Self Contribution of Building Systems

BUILDING SYSTEMS	RESPONSE	SELF-CONTRIB. *S*	MAGNITUDE OF DEPEN. *R = 100-S*	ABSOLUTE WEIGHT (*wi*)	SELF CONTR. Wt.	OTHER FACTORS Wt.
S_1	Minimal	0.80	0.20	0.029	0.0232	0.0058
S_2	Moderate	0.60	0.40	0.150	0.09	0.06
S_3	Strong	0.40	0.60	0.167	0.0668	0.1002
S_4	Very Strong	0.20	0.80	0.033	0.0066	0.0264
S_5	Moderate	0.60	0.40	0.096	0.0576	0.0384
S_6	Moderate	0.60	0.40	0.253	0.1518	0.1012
S_7	Moderate	0.60	0.40	0.257	0.1542	0.1028
S_8	Minimal	0.80	0.20	0.015	0.012	0.003

Table 4.13 Judgment Matrix for Dependency for Building Systems

COMBINED	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	PRIORITY VECTOR
S_1	0.00	0.33	0.26	0.20	0.07	0.07	0.00	0.00	0.029
S_2	0.41	0.00	0.41	0.20	0.05	0.20	0.23	0.12	0.150
S_3	0.27	0.23	0.00	0.29	0.19	0.30	0.20	0.08	0.167
S_4	0.00	0.06	0.14	0.00	0.30	0.09	0.38	0.04	0.033
S_5	0.00	0.08	0.12	0.08	0.00	0.17	0.00	0.40	0.096
S_6	0.18	0.15	0.07	0.12	0.22	0.00	0.06	0.00	0.253
S_7	0.14	0.12	0.00	0.08	0.12	0.15	0.00	0.35	0.257
S_8	0.00	0.03	0.00	0.03	0.04	0.03	0.12	0.00	0.015

Table 4.14 Judgment Matrix for Dependency Factoring Self Contribution and Contribution from other Building Systems

COMBINED	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	PRIORITY VECTOR
S_1	0.023	0.03	0.03	0.01	0.00	0.01	0.00	0.00	**0.090**
S_2	0.00	0.09	0.05	0.01	0.00	0.03	0.01	0.00	**0.179**
S_3	0.00	0.02	0.067	0.01	0.01	0.04	0.01	0.00	**0.149**
S_4	0.00	0.00	0.01	0.007	0.02	0.01	0.01	0.00	**0.080**
S_5	0.00	0.01	0.01	0.00	0.058	0.02	0.00	0.00	**0.097**
S_6	0.00	0.01	0.01	0.00	0.01	0.152	0.00	0.00	**0.185**
S_7	0.00	0.01	0.00	0.00	0.01	0.02	0.154	0.00	**0.189**
S_8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.012	**0.031**

Table 4.15 Comparison of Results

BUILDING SYSTEM	INDEPENDENT PRIORITY VECTORS	DEPENDENCY PRIORITY VECTORS	VARIANCE
S_1	0.029	**0.090**	0.059
S_2	0.150	**0.179**	0.037
S_3	0.167	**0.149**	(0.016)
S_4	0.033	**0.080**	0.045
S_5	0.096	**0.097**	0.001
S_6	0.253	**0.185**	(0.070)
S_7	0.257	**0.189**	(0.071)
S_8	0.015	**0.031**	0.015

4.6.1 Discussion

Two approaches were explored, the first dealt with independency of each building system, and the second took into consideration the interdependency between building systems. A comparison of the results, which is presented in Table 4.15, revealed a noticeable shift in the relative weights for certain systems, noticeably the Foundations (S_1), HVAC (S_6) and Electrical (S_7) systems. This finding was discussed with the experts that provided the initial judgments to determine whether there was a logical explanation for such variations. The consensus was that the independency weights generally reflected the focus on maintenance and operation of support services in this specific building type. The foundation was given a low ranking because very few maintenance dollars are expended on that system, whereas HVAC and electrical systems demand a much larger expenditure. Also, it should be remembered that in this type of facility the electrical system (which is a grouping of electrical, fire protection, and security) contributes immensely to the overall performance.

The inclusion of interactions between building systems resulted in substantial redistribution of the priority weights. Larger variances were obtained in three systems namely Foundations, HVAC, and Electrical. In the case of the Foundations system (**S_1**), when the overall framework of the building was considered, its weight was increased (by 6%) because of the nature of its function - it provides support to all the other systems. It can be considered as an important element because of its ties to the other systems. Any failure in the foundation can severely affect the performance of most of the other systems. On the other hand, the weights for the HVAC (**S_6**) and Electrical (**S_7**) systems were also affected (they were each reduced by 7%). This reduction was due to the limited impact these systems have on the other systems. Both of these systems by nature of their function (i.e. providing a functional and comfortable working environment) are extremely important. The need for uninterrupted primary and secondary electrical power, telecommunications, thermal comfort, and indoor air quality defines the performance of a facility of this nature and this is reflected in their independent priority weights. However, the impact or contributions of these systems to other building systems are minimal and limited at best. The converse is also very true; the other systems (with the exception of the Exterior Enclosures, Roof and Internal Construction and Finishes) contribute very little to the functional performance of the HVAC and Electrical systems. At best they provide support to the mechanical, electrical and communication system integration, and distribution networks.

Both the exterior enclosures ($\mathbf{S_2}$) and the interior walls and finishes ($\mathbf{S_4}$) systems recorded increases in the order of 3.7% and 4.5%, respectively. Both provide very important utility functions and contribute substantially to the performance of all the other systems.

It was quite interesting to note that the priority weight for the Plumbing system ($\mathbf{S}_5$) reflected a marginal increase of 0.1%. This seems to infer that in this type of facility the Plumbing system is not seriously affected by the other systems, and that the contribution of other systems to the Plumbing is apparently limited, hence there has been a marginal impact on its priority weight. It was felt that the interdependency weights are a more rational reflection of the relative importance of building systems.

In this case study, just one criterion was used to develop the priority weights of the building systems, functional performance. Priorities were first developed based on the independency of the building systems. However, because of the inherent interdependency that exists between building systems, priority weights reflecting that interdependency had to be derived. The latter process provided a more realistic barometer for ascertaining the weights associated with various building systems that were specific to buildings used in this study. The capability of determining the priority weights for building systems and components that are affected by interdependency would be beneficial in identifying critical systems and components in the building environment. This type of decision analysis can help decision-makers formulate better maintenance and rehabilitation plans, since they are more aware of the interdependency between building systems and components. Furthermore, this procedure also provides a creditable basis for ascertaining the overall building condition index from the component level using the roll-up process.

4.7 Conclusions

An attempt was made here to use engineering judgment in a systematic way in conjunction with rational mathematical tools. The AHP methodology provided the structure and rigor to support a complex decision making process in facilities management through its hierarchical framework and ratio scale priority assignment. In a domain where quantitative data is inadequate, the authors had to rely on the intuition and judgments that were based on specialized experience or on general knowledge of known relationships among building systems. The compatibility between AHP functionality and the general attributes of facilities management strongly intimates the AHP's potential as a decision support tool.

The objectives determined by this study were achieved, and they are as follows:

1. Applying AHP methodology to determine relative priority weights for building systems (and components).
2. Developing a strategy for dealing with the unique situation that is applicable to building facilities in which there is a level of interdependency among building systems.
3. Subjectively assessing the magnitude of the contribution that building systems make to other systems and to themselves.
4. Utilize this application in a case study.

Chapter 5 Deterioration Modeling

5 Deterioration Modeling

5.1 Introduction

Building designers and consultants endeavor to design the best facilities with the very best systems. To achieve that objective, they select and specify the most appropriate materials and equipment to interact with the prevailing design and environmental conditions. Contractors erect and install these components using the very best technology and in accordance to design specifications. Through their collective efforts, they deliver a final product that serves its intended purpose. But despite the best efforts of these practitioners, building systems experience a process of slow deterioration in both condition and performance over time. There are several factors and mechanisms that are responsible for the general decline and ultimate demise of these systems and their inherent components. These include age, temperature variations, environmental conditions (precipitation, moisture, and humidity), number of users and intensity of use, design and construction practices and techniques, maintenance practices, material properties and operating environment (Zayed et al. 2002; Hudson et al. 1997; Madanat et al. 1995).

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.

5.1.1 Deterministic Modeling Approach

Deterministic processes are defined in both space and time by a single, defined quantity. This means that by repeating a model over and over again with the same input data we will end up with the same exact result. The assumption here is that the properties, boundary, environment, and initial conditions are well known and are not affected by any random or unknown processes, and that the systems are ideal. In reality, however, many properties of the system are not well known and are also affected by various factors and variables alluded to above. Most materials undergo changes depending on the past historical loads (physical and environmental). To account for the random phenomena it is necessary to use stochastic modeling.

5.1.2 Stochastic Modeling Approach

Nature is stochastic. The complexity of several underlying mechanisms makes it impossible to characterize this variability in model parameters deterministically for any building system or component, because a considerable amount uncertainty in model parameters exists.

The stochastic processes over time evolve in a probabilistic manner. Zayed et al. (2002) defined this process as an indexed collection of random variables (S_t) where the index t runs through a given set of nonnegative integers. A Markov chain is a special type of stochastic process in which the conditional probability of any future event, given any past event and present state $S_t = i$, 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, 1998; Abraham et al. 1999).

$$P(S_{t+1} = i_{t+1} | S_t = i_t, S_{t-1} = i_{t-1}, \ldots\ldots\ldots\ldots, S_1 = i_1, S_0 = i_0) = P(S_{t+1} = i_{t+1} | S_t = i_t) \quad (5.1)$$

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

$$P(S_{t+1} = j | S_t = i) = P_{ij} \tag{5.2}$$

The main paradox with this approach is that the determination of the values of the probability that a component is in state i at time t and that it will be in state j at time $t + 1$. Most authors assume that P_{ij} does not change over time. This approach is therefore somewhat unrealistic, since the physical deterioration of a building asset can very well accelerate due to aging and the other distresses affecting it.

The term "transition" is used when the asset moves from state i during one period to state j during the next period. Accordingly, the probability, P_{ij}, is referred to as the "transition probability." Transition probabilities are commonly displayed as an n x n matrix called a transition probability matrix 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 transition probability matrix can be written as:

$$P = \begin{bmatrix} P_{AA} & P_{AB} & P_{AC} & P_{AD} & P_{AF} \\ P_{BA} & P_{BB} & P_{BC} & P_{BD} & P_{BF} \\ P_{CA} & P_{CB} & P_{CC} & P_{CD} & P_{CF} \\ P_{DA} & P_{DB} & P_{DC} & P_{DD} & P_{DF} \\ P_{FA} & P_{FB} & P_{FC} & P_{FD} & P_{FF} \end{bmatrix} \quad (5.3)$$

The above transition probability matrix is a one-step transition. 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:

$$\boldsymbol{P^{(n)}} = \boldsymbol{P^{n}} \quad (5.4)$$

The n-step transition probability matrix is obtained by taking the $\boldsymbol{n}^{th}$ power of the one-step transition matrix (Wirahadikusunah et al. 2001, 1998; Abraham et al. 1999). Knowing the present state of any building component, or the initial state, the future condition can be predicted through the multiplication of the initial state vector and the transition probability matrix (Jaing and Sinha 1990, and Jiang et al. 1988). Therefore, if the condition rating of building components is assumed to be in state A at age 0 (when they are new), then the stage vector of the duty cycle 0 (age = 0) is given by (1, 0, 0, 0, 0) because it is known that all components must lie in state A at age 0 with a probability of 1.0 (Butt et al. 1994, 1987).

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 will have the following general structure (Butt et al. 1994, 1987):

$$P = \begin{bmatrix} p(A) & q(A) & 0 & 0 & 0 \\ 0 & p(B) & q(B) & 0 & 0 \\ 0 & 0 & p(C) & q(C) & 0 \\ 0 & 0 & 0 & p(D) & q(D) \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5.5)$$

Where ***p(i)*** = probability of a component staying in state ***i*** during the duty cycle (of one year); and ***q(i)* = 1 – *p(i)*** is the probability of the component moving down to the next state **(*i* + 1)** during one duty cycle. This means that the Transition Probability Matrix can therefore be rewritten as:

$$P = \begin{bmatrix} p(A) & 1-p(A) & 0 & 0 & 0 \\ 0 & p(B) & 1-p(B) & 0 & 0 \\ 0 & 0 & p(C) & 1-p(C) & 0 \\ 0 & 0 & 0 & p(D) & 1-p(D) \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5.6)$$

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 estimation of transition probabilities for cases in which rehabilitation is taking place represents additional difficulties, which were beyond the scope of this research.

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. Then (from Jaing et al., 1998; Jaing and Sinha 1990; Butt et al., 1994, 1987):

$$S(1) = S(0) * P$$

$$S(2) = S(1) * P = S(0) * P^2$$

$$S(3) = S(2) * P = S(0) * P^3$$

$$\cdots\cdots\cdots\cdots$$

$$S(n-1) = S(n-2) * P = S(0) * P^{(n-1)}$$

$$S(n) = S(n-1) * P = S(0) * P^n \quad (5.7)$$

Where $S(n)$ represents the condition state vector at age n.

Let R be the column vector of condition ratings, $R = [A, B, C, E, F]$. Then the estimated condition rating at age n by Markov chains is represented by the equation:

$$E(n, P) = S(n) * R \tag{5.8}$$

Where $E(n,P)$ represents the estimated condition rating at age n.

With this procedure if the transition probability matrix can be obtained, the future state of components can be predicted at any duty cycle (year) n.

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, 1998; Abraham et al. 1998; Butt et al. 1987, 1994), trunk sewers (Kleiner 2001).

5.2 Deterioration Mechanisms in Buildings

Researchers often refer to the explanatory variables and deterioration mechanisms affecting infrastructure facilities. There have been extensive research efforts to actually assess these variables in the area of transportation, with specific reference to pavement and bridges (Madanat et al. 1997; Madanat et al. 1995; Ellis et al. 1995). With specific reference to buildings, there has been ongoing research to determine the effects of various factors on the building envelope as well as on other building-related components (Flourentzou et al. 1999; Harris 1996). Within the complex building environment, it can be extremely difficult at times to attempt to isolate individual factors as being responsible for the decline in performance of some components (Hastak and Baim 2001; Mishalani and Olayẻ 1999). Invariably the rate of deterioration and associated performance is a result of several factors and their interactions. Examples of these factors and interactions are illustrated in Figure 5.1.

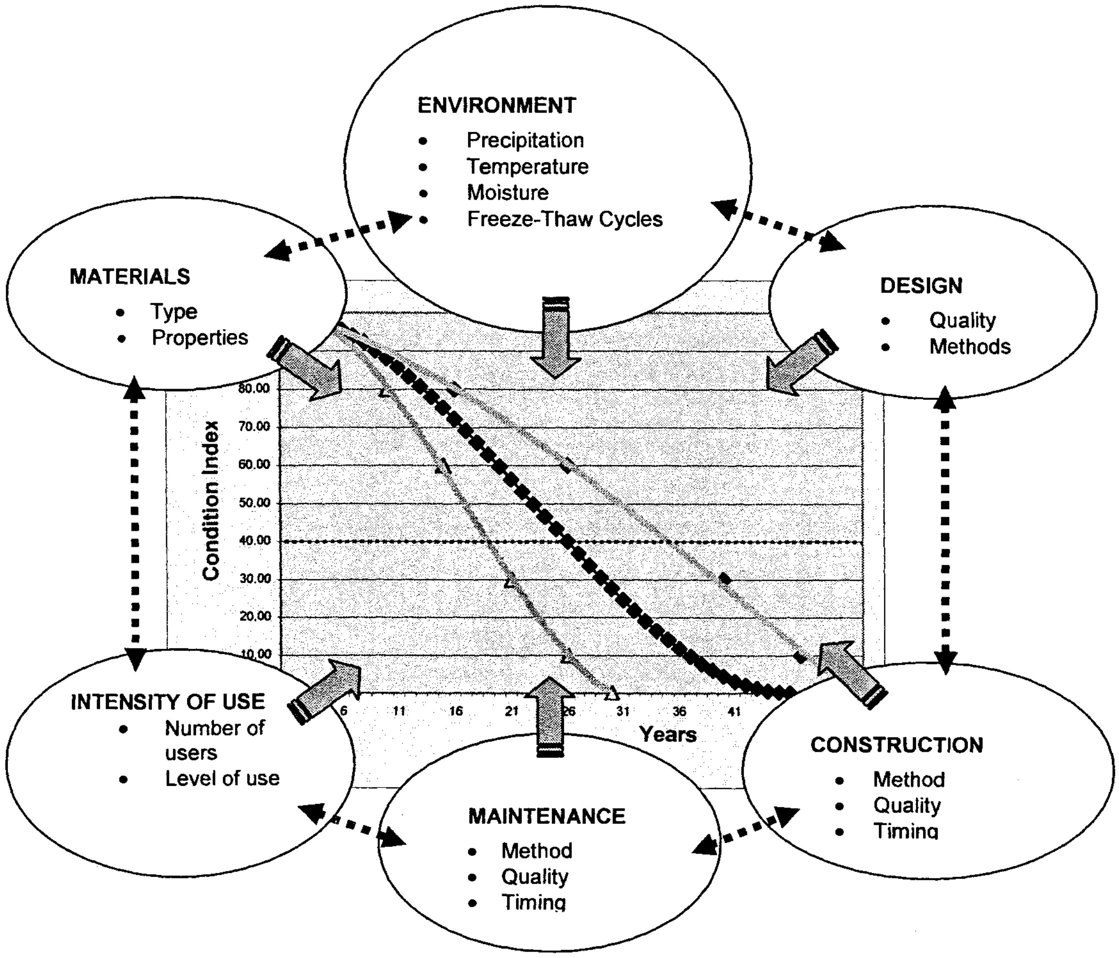


Figure 5.1 Factors and Their Interactions that can Affect Building Performance

5.3 Deterioration Modeling Approach used in the Decision Support System (DSS)

In this section the modeling approach used in the Decision Support System for Building Maintenance Management is introduced. In the proposed framework, a deterministic approach is used to model the deterioration of building components since there is very little data available for the application of the more popular stochastic models. Although a deterministic model is being utilized, some amount of flexibility will be injected into the framework to reflect realistically the constant change in the facility condition based on the many factors and unobserved variables that affect the deterioration of a facility. These variables can have a dramatic effect on the sojourn times of components in the various states. As a consequence, the proposed deterioration model allows for the influence of past or historical condition ratings on the future condition of the component. This approach presents a sound framework for making forecasts about the future conditions of a building and its components.

In the context of deterioration modeling, the Markovian assumption states that the probability that a facility's condition drops to a lower state in a given time period is independent of its deterioration during previous time periods. It has been argued that future deterioration is not independent of history, as implied by the Markov model, because facilities that have experienced deterioration in the past (due to various factors) are most likely to deteriorate faster in the future (Morocus and Rivard 2003, Harris 1996). This implies, therefore, that the probability that a facility or a component will experience a change in condition state in the future is a function of past experience. For example, a built-up roof that has experienced instances of water penetration of the roof membrane in the past (perhaps due to blisters, splits, or ridges), or a wall that has been affected by caulking wells, deteriorated caulking, or cracks in the stucco will deteriorate faster than one that has not because they are both now prone to moisture penetration.

It is assumed that if no intervention (rehabilitation or replacement) is implemented the deterioration process is unidirectional, i.e., if State A denotes "as good as new", and State F denotes "failure", then the process can only move from State i to j where $j \geq i$. A realistic representation of the deterioration of a building component is illustrated in Figure 5.2. The amount of time T_{ij} which the deterioration sojourns or holds in State i before dropping to State j is known as sojourn times or holding times. For a deterministic deterioration model, the holding times are assumed known with certainty. In a stochastic deterioration model, on the other hand, the holding times are treated as random variables.

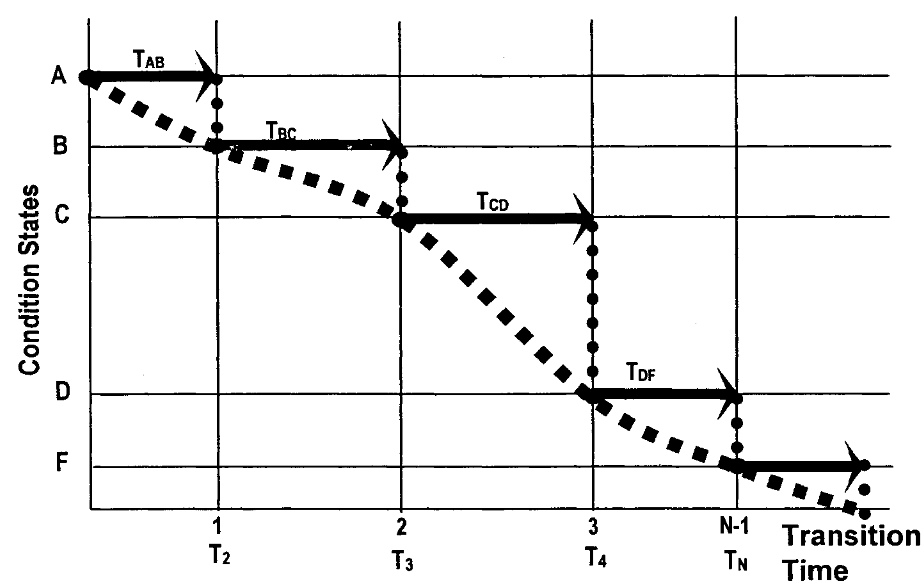


Figure 5.2 A Typical Sample Function of the Deterioration Process

The Lands and Buildings branch of the City of Edmonton is continuing to develop its database as part of a comprehensive building maintenance management system. Empirical data on past performance and condition assessment is too sparse to make any meaningful correlation on the effects of deterioration in various operating conditions. Hence, further data gathering efforts will have to be made to compile and verify the maintenance history and age data on each building component.

Because there is insufficient historical data available on the service life and condition rating of the applicable building components to populate a stochastic deterioration model adequately and to derive their parameters, experts were asked to provide three estimates of the sojourn or holding times for each of the five states for all the applicable building components. The three judgments reflect a reasonable approximation of the sojourn times of components in different operating conditions:

- Best case – excellent design and operating conditions (upper limit - UL);
- Worst case – extremely poor operating conditions (lower limit - LL);
- Average conditions – where the component is expected to last its design service life (common length of time - CL).

A literature search was conducted to ensure that the average design times were reasonably accurate. The recognition that the actual sojourn time of a component will vary within certain limits was the primary reason behind the establishment of the upper and lower bounds, especially since the deterioration factors and variables will vary from building to building (even when they are of the same building type). Furthermore, it is generally accepted that the condition of some building components significantly affects the rate of deterioration of other components. This phenomenon clearly contributes to the variability in the holding times of the affected components.

As an example, Table 5.1 shows the states and estimated sojourn times that best represent the case histories of a building component for the Arena building type. The states are based on the current condition scale being used by the City of Edmonton in their inspection and condition assessment exercises (previously discussed in Chapter 3). See **Appendix B** for the waiting times for components in a specific building type.

Table 5.1: Example of Waiting Times for a Boiler

BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			SERVICE LIFE
			LL	CL	UL	
HVAC	Boiler	A	9	12	15	45 Years
		B	5	7	11	
		C	6	9	14	
		D	6	8	10	
		F	4	9	10	
			30	45	60	

With this data it is easy to generate three deterministic deterioration curves using a fitted curve (see Figure 5.3). The two zones bounded by the curves provide asset managers with a fair gauge of the performance of components given their age, intensity of use or traffic, and applicable operating conditions.

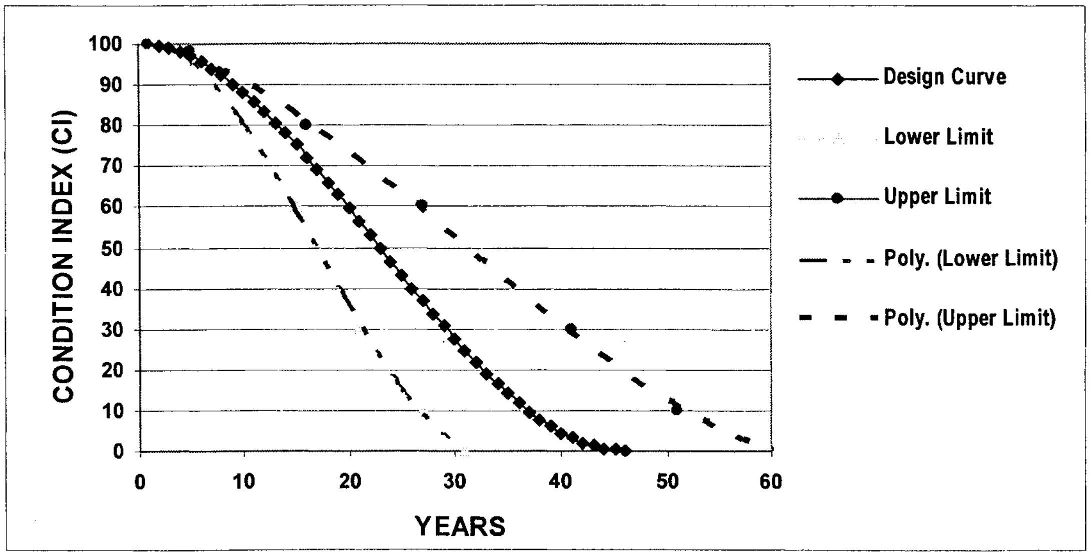


Figure 5.3 Estimated Performance Curves for Component

The annual inspections and the resultant condition rating are recorded in the DSS. This data assists in the development of a clear profile of the performance of the building component. Deterioration curves can then be generated and plotted to represent the various changes in condition of the component through the different condition states. This process facilitates the monitoring of the performance of any component over its service life as well as allowing the asset manager to estimate the remaining service life. Furthermore, the deterioration curves can yield or predict the future condition states of the component.

Four specific scenarios are demonstrated below:

1. In this scenario, a component has been inspected and monitored from the time it was commissioned. Here, the annual or bi-annual condition ratings obtained from the inspections will be recorded in the DSS. A condition profile for that component will be created that represents the general decline in performance of that component (assuming that no Maintenance, Rehabilitation, and Repair action was implemented) through its service life. This is illustrated in Figure 5.4. The actual performance curve represents 14 consecutive years of condition rating presented in Table 5.2. The resultant deterioration curve demonstrates that the performance of this component is very close to the threshold or lower limit. To forecast the future CI of the component, inspectors will be required to estimate the remaining service life of the component, based on its current condition and the immediate environment under which it is operating. This information provides the basis for the extrapolation of the actual performance curve to provide a reasonable estimate of the future performance of that component. The remaining service life as determined by the original design curve may also be used to extrapolate this information (see Table 5.5 and Figure 5.3). The application of a spline function (i.e. a

series of functions utilizing the polynomial of a specific order) is used to provide the best fitted curve. In this application, $S(t) \leq S(t+1)$ for any time t.

Table 5. 2 Actual Bi-annual CI of Component

Year	Upper Limit	Designed Perform.	Lower Limit	Actual
0	100	100	100	100
1				
2				98
3				
4	98			95
5				
6				91
7				
8				85
9			80	
10				81
11				
12		80		76
13				
14			60	71
15	80			
16				64
17				
18				59
19		60		
20			30	
21				
22				
23				
24				
25				
26	60		10	
27				
28		30		
29				
30			0	
31				
32				
33				
34				
35				
36		10		
37				
38				
39				
40	30			
41				
42				
43				
44				
45		0		
46				
47				
48				
49				
50	10			
60	0			

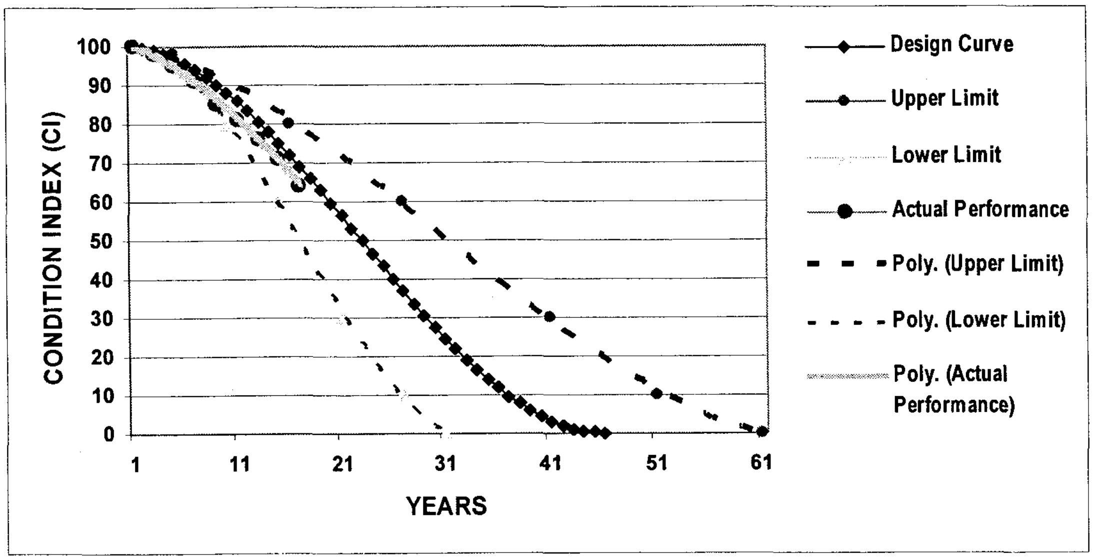


Figure 5.4 Actual Performance of Component in Comparison to Design Service Life

Table 5.3 Actual Performance of Component Combined with Estimate of Remaining Service Life

Year	Upper Limit	Designed Perform.	Lower Limit	Actual
0	100	100	100	100
1				
2				98
3				
4	98			95
5				
6				91
7				
8				85
9			80	
10				81
11				
12		80		76
13				
14			60	71
15	80			
16				64
17				
18				59
19		60		
20			30	
21				
22				
23				
24				
25				
26	60		10	
27				30
28		30		26.75
29				23.00
30			0	20.79
31				18.76
32				15.33
33				12.51
34				10.19
35				
36		10		
37				
38				
39				0
40	30			
41				
42				
43				
44				
45		0		
46				
47				
48				
49				
50	10			
60	0			

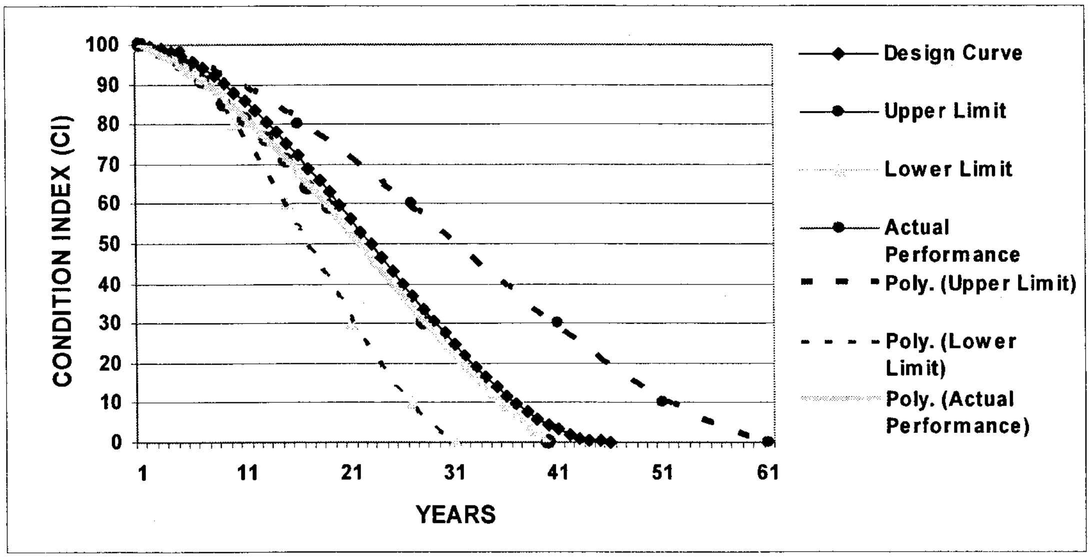


Figure 5.5 Future Performance of a Component can be Forecasted Based on Estimate of Remaining Service Life

2. In this scenario, the actual condition monitoring of the component commences many years after it is commissioned. Part of the data collection process will include conducting inspections and determining the condition ratings for components that are already operational. In situations where historical performance records of components are unavailable, the commission dates of these components (actual or estimated) in conjunction with recent inspections will suffice for the derivation of performance curves (see Figure 5.6, which was developed from data presented in

Table 5.4). In this particular case, the CI of the component is slightly above the estimated design curve. As demonstrated in the previous case, the future condition of this component can be forecast by estimating the remaining service life. Again the polynomial curve is used to best fit the data points in order to extrapolate the future performance of the component. In the example illustrated in Figure 5.7 (developed from Table 5.5), the service life of this component is projected to be 5 years better than the design service life.

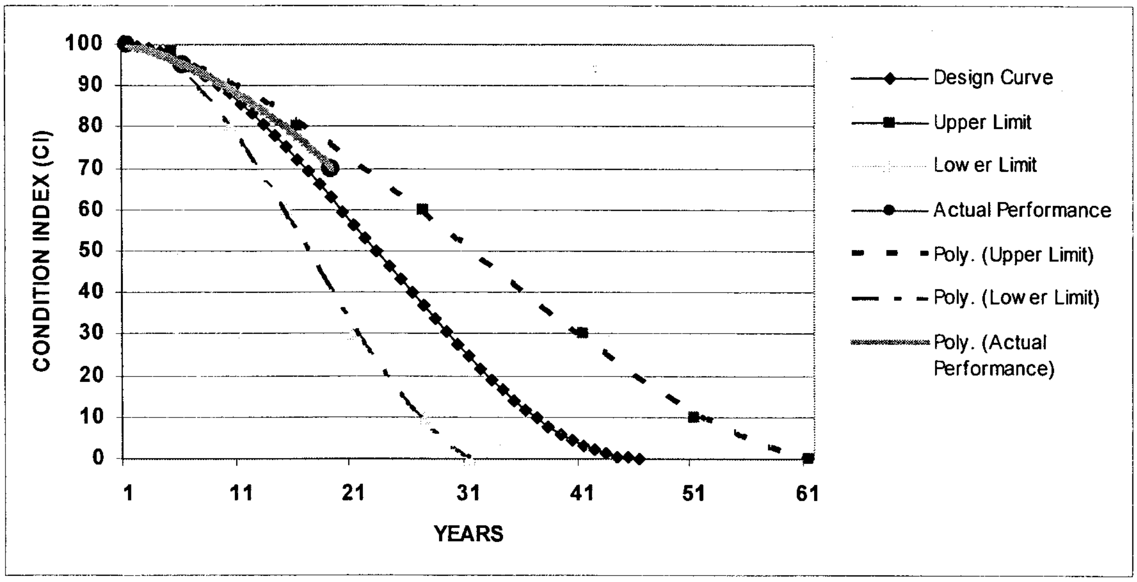


Figure 5.6 Actual Performance of Component in which Only Recent Inspections Are Available.

Table 5.4 Actual Performance of Component in which Only Limited CI Data Available

Year	Upper Limit	Designed Perform.	Lower Limit	Actual
0	100	100	100	100
1				
2				
3				
4	98			
5				95
6				
7				
8				
9			80	
10				
11				
12		80		
13				
14			60	
15	80			
16				
17				
18				70
19		60		
20			30	
21				
22				
23				
24				
25				
26	60		10	
27				
28		30		
29				
30			0	
31				
32				
33				
34				
35				
36		10		
37				
38				
39				
40	30			
41				
42				
43				
44				
45		0		
46				
47				
48				
49				
50	10			
60	0			

Table 5.5 Actual Performance of Component Combined with Estimate of Remaining Service Life

Year	Upper Limit	Designed Perform.	Lower Limit	Actual
0	100	100	100	100
1				
2				
3				
4	98			
5				95
6				
7				
8				
9			80	
10				
11				
12		80		
13				
14			60	
15	80			
16				
17				
18				70
19		60		67
20			30	66.47
21				63.3
22				62.23
23				60.16
24				
25				57.11
26	60		10	54.17
27				51.34
28		30		
29				48.65
30			0	46.10
31				43.67
32				
33				
34				
35				
36		10		
37				
38				
39				
40	30			
41				
42				
43				
44				
45		0		
46				
47				
48				
49				
50	10			
51				0
60	0			

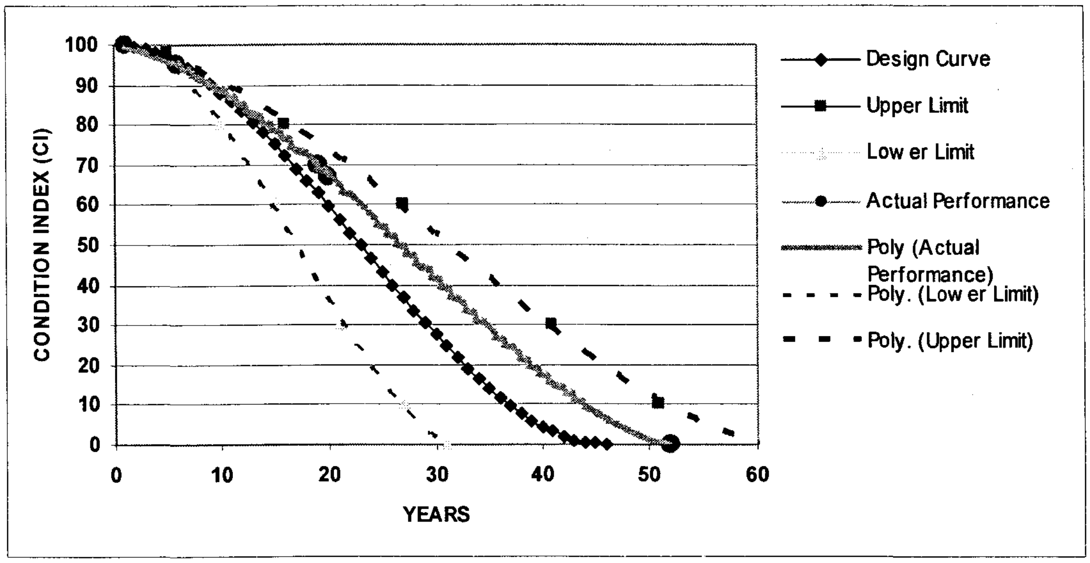


Figure 5.7 Forecasting the Performance of a Component Based on Date of Commission, a Few Inspections and an Estimate of Remaining Service Life

3. In this scenario, some form of maintenance action is executed on the component. Invariably, the maintenance action (be it major or minor rehabilitation/repairs) is performed during the state condition **C** or **D**. It is expected that the condition rating of the component will be improved on the completion of this action. Building inspectors can therefore reasonably estimate the new CI. The condition of the component prior to the execution of the maintenance action and the scope of the rehabilitation/repairs will have a bearing on the new CI. This is illustrated in Figures 5.8 and 5.9 (which are based on data presented in Tables 5.6 and 5.7, respectively). It should be noted that the remaining service life of the rehabilitated asset is determined by comparing the new estimated CI with the similar CI on the historical performance curve (before rehabilitation was executed). This will provide a good guideline for future comparisons of the asset's performance.

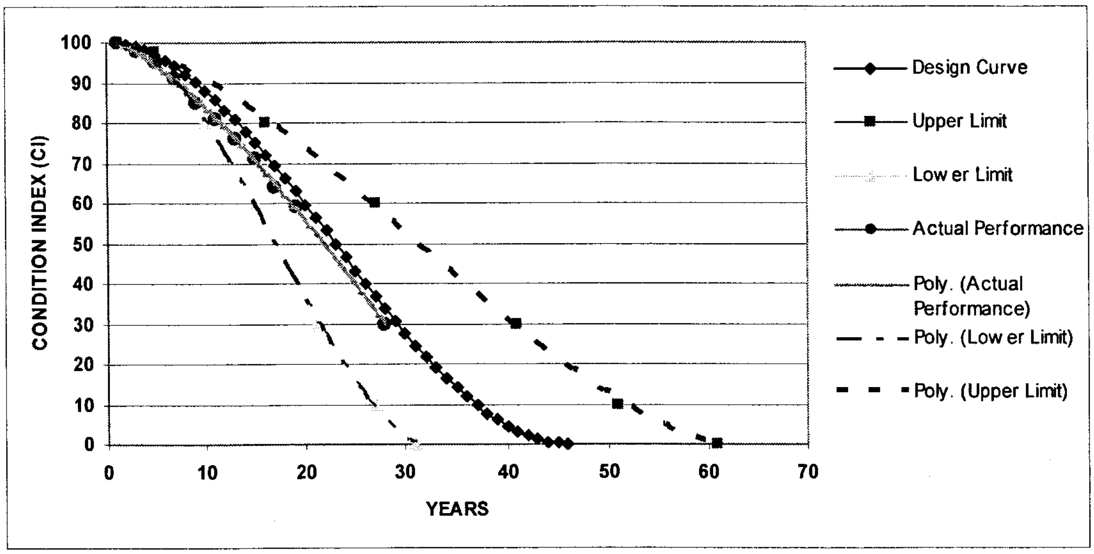


Figure 5.8 **Actual Performance of an Asset based on Yearly Inspections**

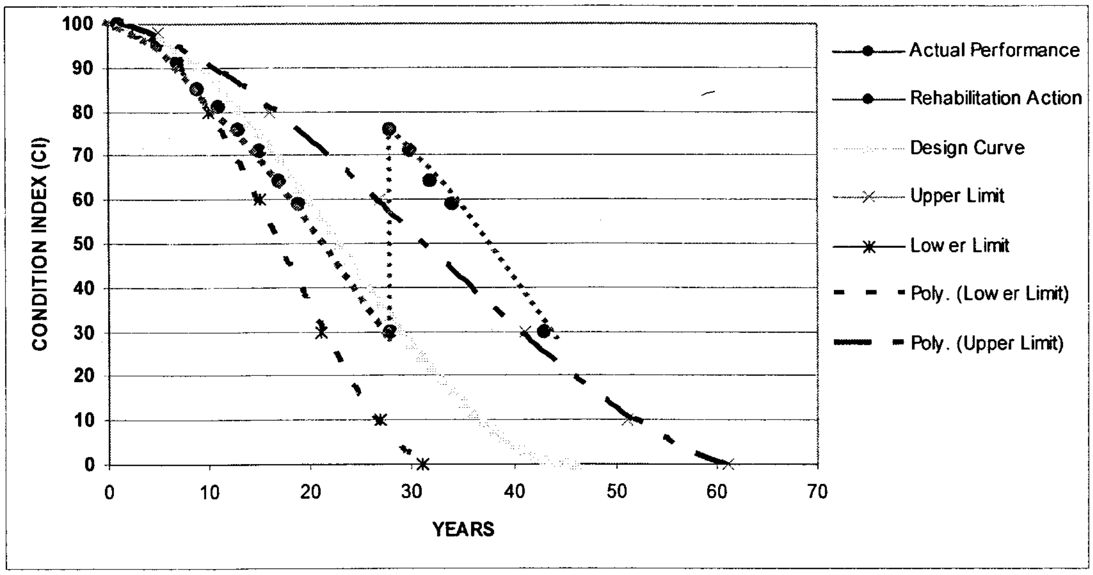


Figure 5.9 **Performance of a Rehabilitated Asset**

Table 5.6 Yearly CI of Component

Year	Upper Limit	Designed Perform.	Lower Limit	Actual
0	100	100	100	100
1				
2				98
3				
4	98			95
5				
6				91
7				
8				85
9			80	
10				81
11				
12		80		76
13				
14			60	71
15	80			
16				64
17				
18				59
19		60		
20			30	
21				
22				
23				
24				
25				
26	60		10	
27				30
28		30		
29				
30			0	
31				
32				
33				
34				
35				
36		10		
37				
38				
39				
40	30			
41				
42				
43				
44				
45		0		
46				
47				
48				
49				
50	10			
60	0			

Table 5.7 Estimated Performance of Rehabilitated Component (Estimates Based on Past Performance of Component)

Year	Upper Limit	Designed Perform.	Lower Limit	Actual	Projected Rehab.
0	100	100	100	100	
1					
2				98	
3					
4	98			95	
5					
6				91	
7					
8				85	
9			80		
10				81	
11					
12		80		76	
13					
14			60	71	
15	80				
16				64	
17					
18				59	
19		60			
20			30		
21					
22					
23					
24					
25					
26	60		10		
27				30	76
28		30			
29					71
30			0		
31					64
32					
33					59
34					
35					
36		10			
37					
38					
39					
40	30				
41					
42					30
43					
44					
45		0			
46					
47					
48					
49					
50	10				
60	0				

4. In the event that the component has been replaced, it is plausible to assume that the new CI will be 100, which represents a new component in perfect condition. The original design performance curve will be used to represent the remaining service life of the component (see Figure 5.10 developed from data in Table 5.8).

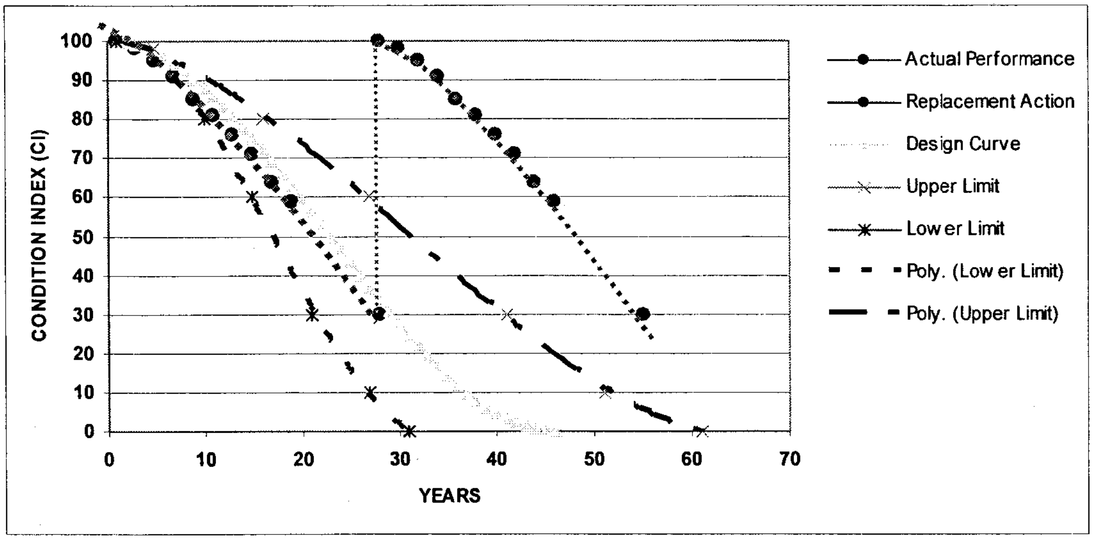


Figure 5.10 Performance of a Replaced Asset

Table 5.8 Estimated Performance of Replaced Component (Estimates Based on Past Performance of Component)

Year	Upper Limit	Designed Perform.	Lower Limit	Actual	Projected Replacement
0	100	100	100	100	
1					
2				98	
3					
4	98			95	
5					
6				91	
7					
8				85	
9			80		
10				81	
11					
12		80		76	
13					
14			60	71	
15	80				
16				64	
17					
18				59	
19		60			
20			30		
21					
22					
23					
24					
25					
26	60		10		
27				30	100
28		30			
29					98
30			0		
31					95
32					
33					91
34					
35					85
36		10			
37					81
38					
39					76
40	30				
41					71
42					
43					64
44					
45		0			59
46					
47					
48					
49					
50	10				
60	0				
61					
62					
63					30

The regular monitoring of the condition and performance of components by periodic inspections provides the basis for the collection of condition rating data on all manageable building components over their service lives and in different operating conditions. There are some distinct advantages in employing such a strategy. First, it is becomes clearly evident whether or not a component is performing above or below the expected design service life. If indications are that its performance is below, then efforts can be made to determine why this is so. Closely associated with this scenario is the possibility that components, which may have a poor condition rating, will have an adverse impact on other components.

Secondly, from the point of determining MR&R treatment requirements, it would be desirable to have a continuous record of the performance of the component and any distresses or other performance deficiencies. Thirdly, it provides data on the level of improvement that result from specific MR&R actions. Finally, the industry is currently suffering from a dearth of data on the performance of building components. Such data can be used to develop transition probability matrices for all major components for application in deterioration modeling.

5.4 Validation

A set of building inspection data collected over the last few years was used in verifying the robustness of the service life prediction model. A facility (an ambulance station) that was first inspected in May 2001 was re-inspected in June 2005. The list of building systems and components are presented along with the current condition rating data (2001) and forecasted condition ratings in **Appendix C**. The forecasted condition ratings were computed using the procedure outlined in Section 5.3 as well as using the Markov approach.

The service life frequency values gathered from experts and literature were used to develop building component curves. The initial development of three curves (representing an upper limit, a lower limit, and a most common limit) established a set of general boundaries for the performance of each building component. The condition rating data as of 2001 was inputted into the program and forecast conditions beyond the current year (of 2001) were generated. The list of inspected components is presented in **Appendix C**. Table 5.9 highlights the specific example of the HVAC building system and its components. Most of the components are in very good to fair condition, with Boiler #2 being a likely candidate for MR&R action based on the forecasted condition for next year.

The ambulance station was re-inspected in June 2005, and the list of inspected components and their condition rating data is also presented in **Appendix C**. Actual data for the HVAC system and components is presented in Table 5.10. Deterioration curves from the two sets of data were generated by the Decision Support System (DSS). These are presented in Figures 5.11 and 5.12.

Table 5.9 2001 Condition Rating Data with Forecasts for 2005, 2006, 2010, and 2020

HVAC – BUILDING SYSTEM		CI 2001	FORECAST CI 2005	FORECAST CI 2006	+ 5 YEARS	+ 10 YEARS
BUILDING COMPONENTS	**BUILDING ELEM.**					
Make Up Air Unit		95.00	76.05	69.75	42.09	11.46
Exhaust Fans		85.00	59.59	52.39	24.17	1.4
Supply & Return Ducts		95.00	86.67	85.27	79.05	69.84
Air Outlets & Inlets		85.00	68.49	63.83	44.02	20.41
Unit Heaters		95.00	76.05	69.75	42.09	11.46
Air Handling Unit		95.00	75	70.73	55.65	38.75
Boilers		80.00	65.46	34.65		
	Boiler #1	95.00	84.03	80.9	67.29	49.00
	Boiler #2	65.00	46.88	42.2	23.99	6.2
Circulation Pumps		95.00	76.05	69.75	42.09	11.46
Compressed Air Systems		85.00	63.25	57.5	34.65	10.99
		92.05	**72.1**	**62.03**	**48.55**	**29.54**

There were some minor variations between the predicted condition ratings for 2005 and the actual conditions. These variations are expected since the condition assessment procedures are to some extent "inspector dependent" and are therefore extremely subjective, especially since in most instances there are no specialized measurement devices to determine the scope of the distresses. As inspectors continue to refine their inspection techniques (inclusive of performing distress measurements) it is anticipated that there will be greater accuracy in the determination of the condition indices.

Table 5.10 2005 Condition Rating Data with Forecasts for 2006, 2010, and 2020

HVAC – BUILDING SYSTEM		CI 2005	FORECAST CI 2006	+ 5 YEARS	+ 10 YEARS
BUILDING COMPONENTS	**BUILDING ELEMENTS**				
Make Up Air Unit		74.5	70.39	42.34	6.21
Exhaust Fans		74.5	60.98	40.82	5.88
Supply & Return Ducts		74.5	71.71	59.62	43.4
Air Outlets & Inlets		74.5	70.94	52.37	25.75
Unit Heaters		76.05	71.11	48.11	11.29
Air Handling Unit		74.5	70.39	42.34	6.21
Boilers		74.47	39.94		
	Boiler #1	94.45	93.24	87.38	77.72
	Boiler #2	54.5	51.08	33.86	11.66
Circulation Pumps		74.5	70.39	42.34	6.21
Compressed Air Systems		74.5	70.97	50.55	20.67
		74.5	**71.58**	**58.53**	**40.63**

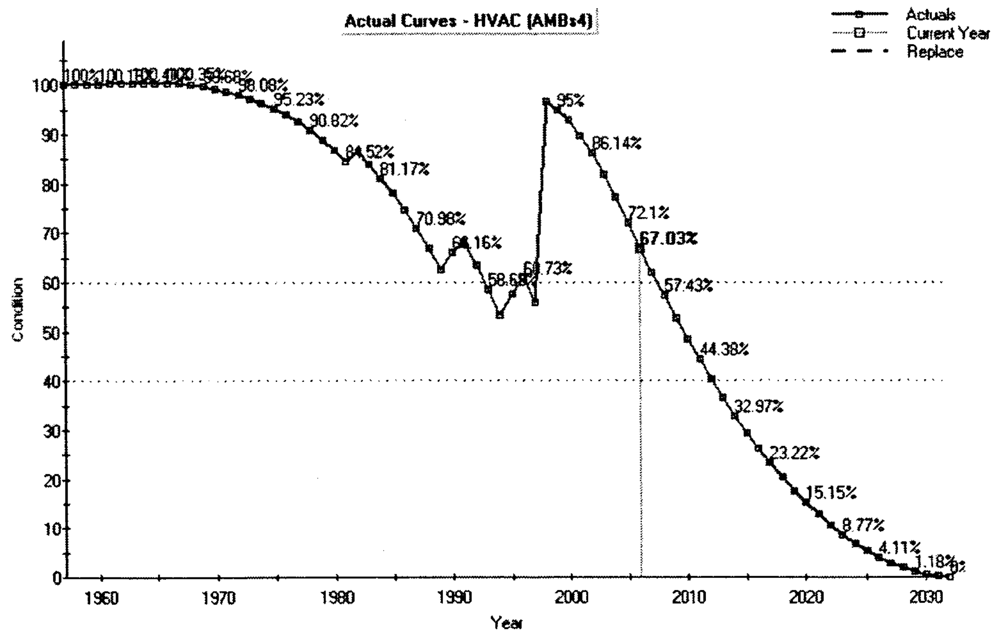


Figure 5.11 Deterioration Curve for HVAC Building System Based on 2001 Condition Rating Data

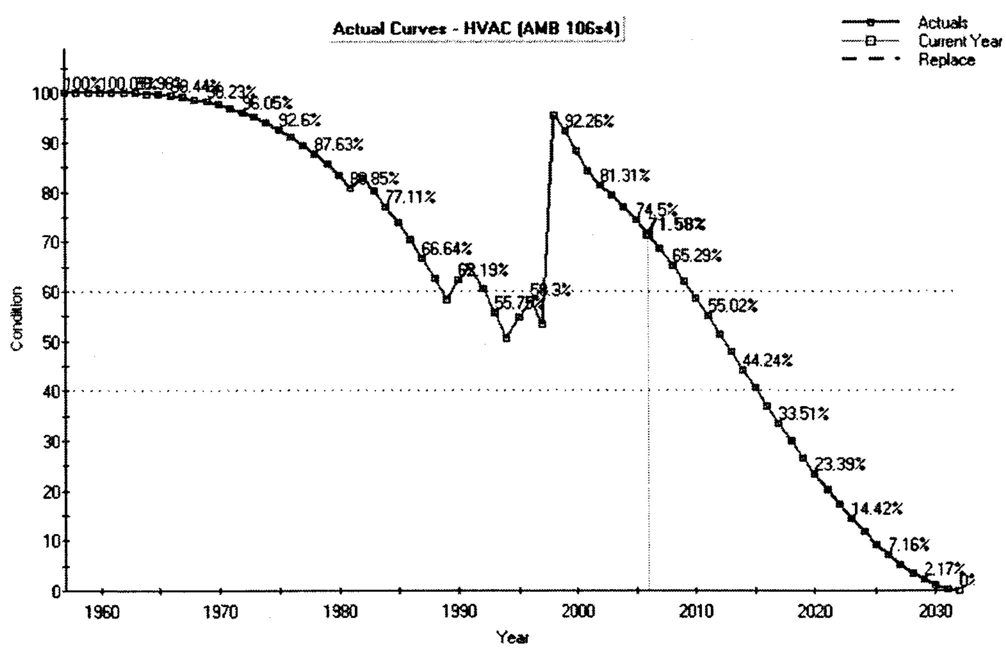


Figure 5.12 Deterioration Curve for HVAC Building System Based on 2005 Condition Rating Data

5.5 The Combined Approach

The approach adopted in this research combined the regression model with the Markov application. There is good reason for this because, in reality, the transition from one duty cycle to another within a condition state may not necessarily be constant. In the general structure of the Markov transition matrix, the deterioration from one condition state to another is constant over multiple discrete time periods. Within the highly interactive building environment, this is not an accurate representation of the performance of building components. The rate of deterioration is directly influenced by historical performance, age, and other factors, which may change constantly (Shohet and Perelstein 2004; Morcous and Rivard 2003; Hastak and Baim 2001). The numerical results obtained from the regression model, which is based on inspections, will be used to update the Markov model, and this will provide a better prediction of the deterioration of the asset. This modeling approach is much more flexible, and relaxes the rigid structure of the classic Markov approach. It utilizes the holding time estimates (UL, CL, LL) for each of the states provided by the experts, as well as the rate of deterioration derived from the regression curves generated by the condition rating data. The application of the spline function in the regression model provides a flexible framework for monitoring the performance of the building assets with points on the regression line corresponding to each condition rating. The generated graphs provide a more realistic profile of the future condition of the building asset without ignoring its historical performance and age. This approach also provides the added advantage of estimating the condition improvement in response to alternative rehabilitation and repair strategies.

5.6 Difference Between Regression and Markov Chains

Although the deterioration curves have been developed using regression, it is still necessary to use the Markov chains model to predict individual building component conditions. In fact, both regression and Markov chains models play important roles in analyzing building components. The regression model can be used to estimate the extent of condition improvement in response to alternative rehabilitation and repair strategies. However, when condition prediction is needed, the Markov chains model provides more reasonable estimates of component conditions (Jaing and Sinha 1990; Jaing et al. 1988).

The Markov probability decision process has the following advantages:

1. Future decisions are not fixed for components, but depend on the prevailing conditions in and around the building and how the component actually performs under those conditions.

2. Actions that should be taken now can be identified. Also, actions likely to be taken in the next few years can be identified with a high degree of probability.

3. It is possible to compare the expected proportions of given condition states with the actual proportions observed in the field. In this way, any major component defects can be identified and any variation in conditions can be noted.

4. A dynamic decision model has the potential for significant cost savings by selecting more appropriate and aggressive rehabilitation strategies that will satisfy performance standards.

Regression extrapolation techniques are deterministic and do not explain the variability among data points. They merely fit the best line of the data. Polynomials of different degrees and mathematical functions can be manipulated to fit the data, but when these functions are projected beyond the bounds of the data results, they can be totally misleading; hence the reason for using an estimate of next year's CI and the estimated remaining service life of the component. The Markov process imposes a rational structure on the deterioration model. It has the advantage that projections beyond the limits of the data will have the classic pattern of worsening condition with age.

5.7 Conclusions

Modeling deterioration is an essential task in managing the maintenance of infrastructure facilities, especially at the network level. Current infrastructure deterioration models have significant gaps that affect their accuracy, practicality, and versatility. The DSS not only monitors the yearly condition of any component in the building inventory, but it is also able to provide short term forecasts on the condition of components based on their current and past conditions. The DSS also demonstrates the extent to which the condition of building components can affect the overall condition of buildings. This process will greatly assist asset managers in the long term planning for capital projects. For major components, such as boilers, ice plant, chillers, and roofs, such a strategy can minimize the risks associated with the failure of these components. For components that are in zones in which they become candidates for some sort of maintenance strategy, several options are open to the asset manager:

1. Do nothing;
2. Intensify the Preventative Maintenance program;
3. Perform minor rehabilitation and repairs;
4. Perform major rehabilitation; or
5. Total replacement.

Specific costs are associated with the latter three options, and each will improve the condition rating of the component. This type of approach has another advantage, which is the ease with which they can be integrated into an optimization process.

CHAPTER 6 Optimization Model Development

6 Optimization Model Development

6.1 Introduction

When the quality of an infrastructure asset reaches an unacceptable level (or its acceptable minimum level of service), some form of action is needed to preserve the physical and functional integrity of the asset. Such remedial action might consist of Maintenance, Rehabilitation, and Replacement (MR&R), or simply increased routine maintenance to keep the asset from exceeding the level of intervention. If the asset is currently at the minimum level of service (see Figure 6.1) then it can be considered to be at a "now need." Future needs would be determined on the basis of the performance or deterioration prediction model.

If sufficient funds are available (i.e., an unconstrained budget), all maintenance needs can be addressed when they occur. The usual situation for most public agencies, however, is a continuous scarcity of financial resources available for the maintenance of buildings. The situation is exacerbated due to the state of the building assets of public agencies, in which the majority of facilities are over 30 years old according to Vanier and Rahman (2004), and their inherent systems and components are in fair to poor condition (with their condition rating ranging between **C** and **D**). In such cases, priorities have to be set on what actions or work will be undertaken, as well as where and when.

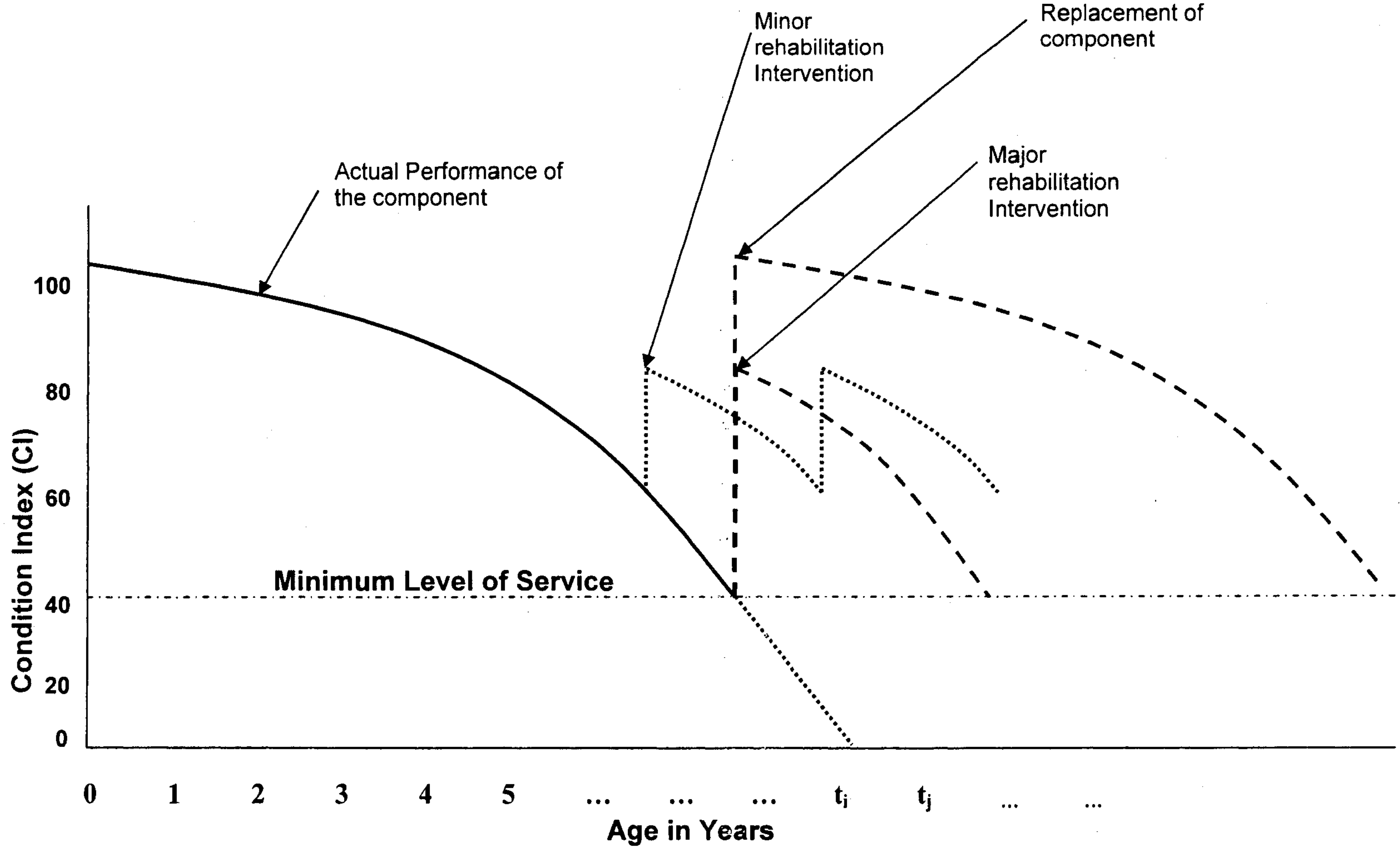


Figure 6.1 Building Component Performance with varying Maintenance, Rehabilitation and Replacement Alternative Strategies.

This research has led to quantitative and analytical tools that can be used in condition assessments, and deterioration modeling of building assets. Furthermore, this chapter focuses on the role of optimization in budgeting issues and in the development of MR&R work programs when the maintenance budget is constrained.

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. As outlined in Chapters 3 and 4, a typical building is divided into a number of systems, each of which is further subdivided into a variety of components. Building systems and components are weighted according to their relative importance.

6.2 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. These are illustrated in Figure 6.2:

- **Replacement of the component**: This option will ensure that the performance level and condition rating of the component will improve to **A** (see Table 3.1 for an explanation of the Condition Index scale for condition rating A, B, C, and D). Generally affected in situations where the component is in condition **D**, i.e., at or below the minimum level of service (refer to Figure 6.1).

- **Major Rehabilitation:** This option will significantly improve the performance and condition of the component. This may be an option of choice if maintenance funds are not available to replace the component. The exact scope or magnitude of this improvement will be determined through actual inspection; however, it is estimated that if a component has a **D** condition rating, then such an action would improve it to a **B** rating.

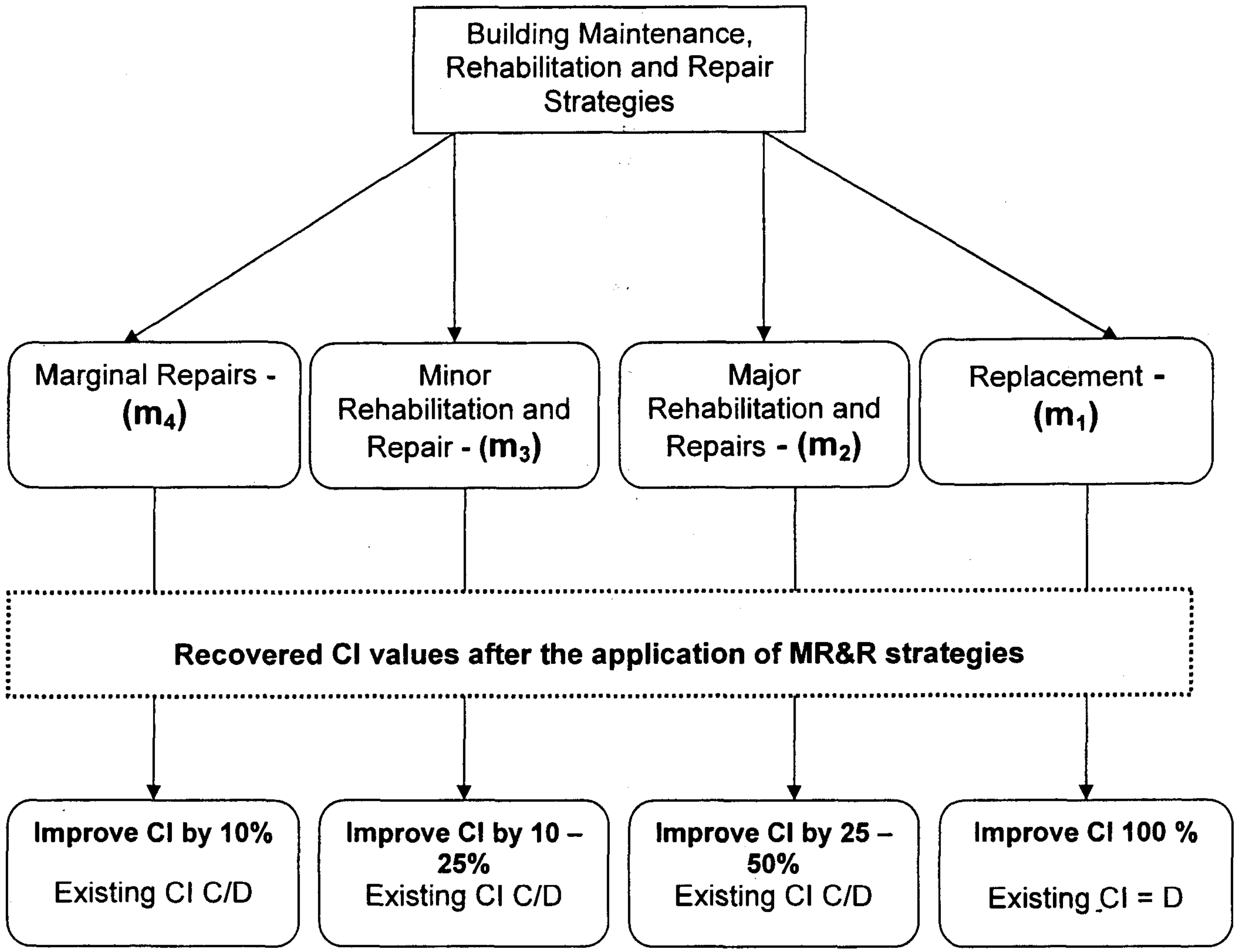


Figure 6.2 Maintenance, Rehabilitation and Replacement Strategies and the resultant improvement on Building Components.

- **Minor Rehabilitation:** This a partial rehabilitation that will improve the condition of a component marginally, say from a **D** condition rating to **C**, or from **C** to **B**. For some components, this option may be much more feasible if carried out when the component is in C rather than carrying out a major rehabilitation when the same component is in D.

- **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. Consequently, for components with a condition rating of D, this action will prevent rapid deterioration and will most likely safeguard the life of the component for a few more years.

Shohet and Perelstein (2004) suggested that each alternative strategy may be assessed according to the following quantitative criteria:

1. The amount of capital resources;
2. The level of performance to be achieved as a result of implementing the alternative;
3. The economic service life of the particular alternative;
4. The predicted annual maintenance costs;

5. The life cycle costs;
6. The duration of the rehabilitation/replacement work.

It was further suggested that qualitative criteria, such as logistics, urgency, and safety conditions, also be added to the above list.

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 (see Figure 6.2). 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. The full range of possible MR&R options available to the asset manager for any given component is detailed as follows:

- **{m_1, m_2, m_3, m_4}** – Options 1 (replace, major rehabilitation, minor rehabilitation, marginal repairs);

- {m1, m2, m3} – Option 2 (replace, major rehabilitation, minor rehabilitation only); to........
- {m1, m2} – Option 14 (replace, major rehabilitation only);
- {m1} – Option 15 (replace only).

It should be noted that, theoretically, the total number of possible MR&R options for each component is $\binom{4}{4}+\binom{4}{3}+\binom{4}{2}+\binom{4}{1}=\sum_{k=1}^{4}C(4,k)=2^4-1=15$

This can be generated to the case of ***n*** possible MR&R alternative options. In this instance, the MR&R alternatives associated with a component c_j^i of a system s_i can be selected from the set of alternatives:

$$\mathcal{A}=\{\{m_1\},\{m_1,m_2\},....................,\{m_1,m_2,....,m_n\}\}$$

$$=\{A_{j1}^i,\ A_{j2}^i,...............,A_{jn}^i\}$$

$$where\ A_{jk}^i=\{m_1,\ m_2,..................,m_k\} \tag{6.1}$$

The number of elements of $\mathcal{A}$ which is noted by cardinal ($\mathcal{A}$) can be obtained using the binominal equation:

$$\text{Cardinal }(\mathcal{A})=\sum_{k=1}^{n}\binom{n}{k}=\binom{n}{1}+\binom{n}{2}+........+\binom{n}{n}$$

$$=\frac{n!}{1!(n-1)!}+\frac{n!}{2!(n-2)!}+.........+\frac{n!}{n!0!}=2^n-1 \tag{6.2}$$

It should be noted that 0! = 1.

If an additional MR&R alternative m_0 was to be included to the original list of MR&R alternatives $\{m_1, m_2, \dots\dots\dots, m_n\}$, where m_0 represents no MR&R action will be executed on a building component during time ***t***, then the total number of alternatives will be represented as $\sum_{k=0}^{n} \binom{n}{0} = 2^n$.

(6.3)

Alternative m_0 can be applied to some structural or foundation components that may not require any MR&R action in the analysis period ***t***. A schematic of the applicable MR&R options as they apply to the various components are presented in Figure 6.3.

From a practical perspective, the number of maintenance alternatives can be significantly reduced if the asset manager selects the specific set of options that may be applicable to a component, depending on the type of component, its age and condition. This approach will result in a significant reduction in the number of decision variables available in the problem formulation.

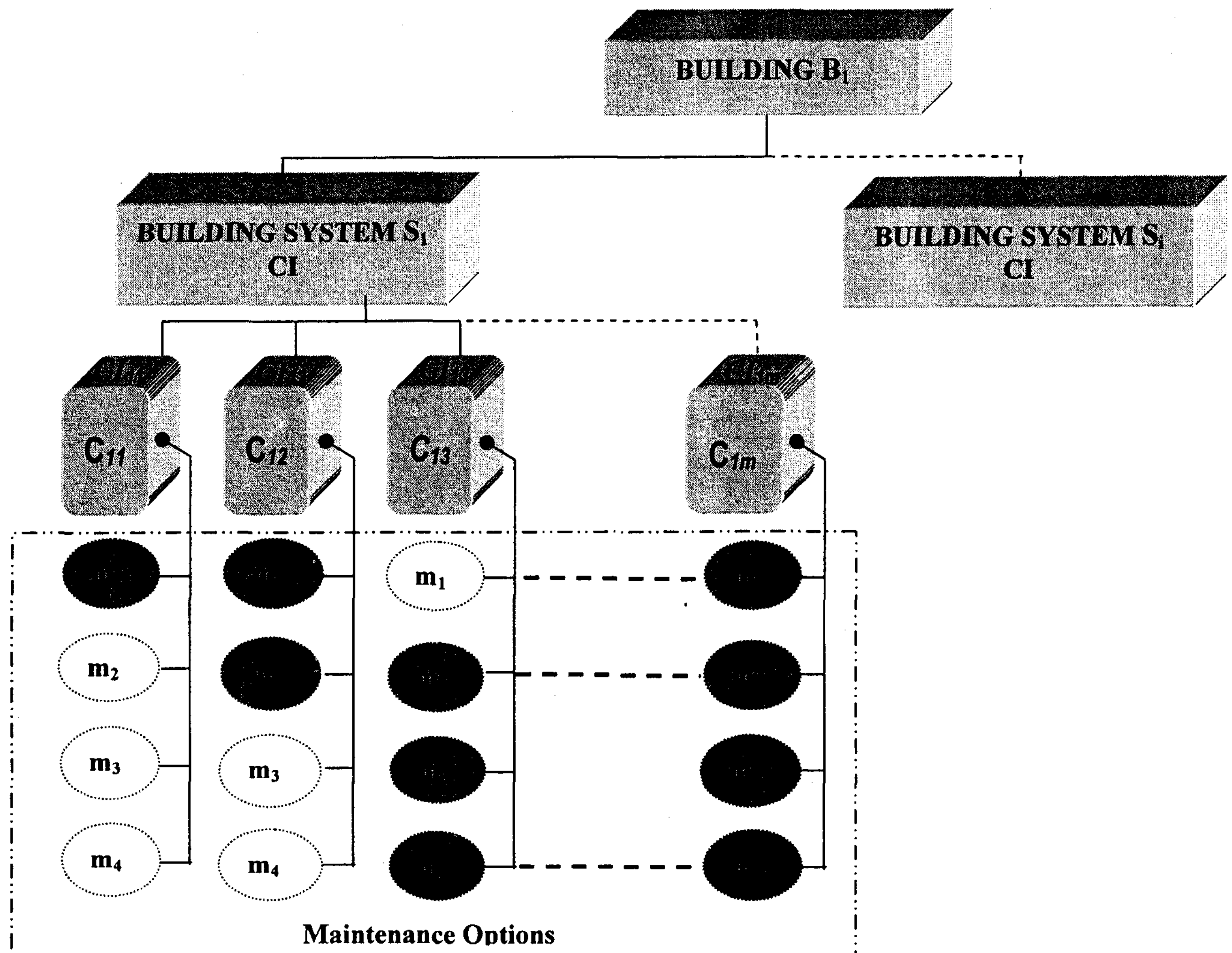


Figure 6.3 Maintenance, Rehabilitation and Replacement Options available to various components.

6.3 Development of the Optimization Model

Several computational aspects were considered in setting the objectives of the optimization model. The general approach used was a short-term optimization approach, in which the analysis is executed over a one-year period. The optimization approach used can be described as being "time-static" since the model does not consider the optimal scheduling of improvement activities over time (Guigner and Madanat 1999). The decision derived is either to perform the MR&R action this year, or do nothing and decide next year. This approach, which Guigner and Madanat (1999) describe as being myopic, does not consider the possibility that an improvement activity might have produced higher user benefits had it been delayed by a few years.

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 (Allouche et al. 2004, Guigner and Madanat 1999, Hudson et al. 1997).

The condition rating of a building at time ***t*** (where ***t*** refers to the current time) can be determined by utilizing the roll-up approach (explained in chapter 3), and is represented as follows:

$$B(t) = \sum_{i=1}^{n} w_i s_i(t) = \sum_{i=1}^{n} w_i \sum_{j=1}^{m} w_j^i c_j^i \ (t) \qquad (6.4)$$

Where B(***t***) = building CI at time ***t***;

w_i = weight of system ***i***;

s_i (***t***) = CI of system ***i*** at time (***t***);

w_j^i = weight of component ***j*** in system ***i***;

c_j^i(***t***) = CI of component ***j*** in system ***i*** at time (***t***).

6.3.1 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:

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

$$= \text{Max} \left[\sum_{i=1}^{n} \sum_{j=1}^{m} w_i s_i w_j^i c_j^1 (t+1) \right] \qquad (6.5)$$

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 (Allouche et al. 2004).

6.3.2 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**

$$\therefore \sum_{i=1}^{n}\sum_{j=1}^{m}\$C_{jk}^{i} \leq M \qquad (6.7)$$

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

Building component interconnection constraints must also be considered. The interdependency and interconnection that exist between building components may require that, logistically, any MR&R action of one component may warrant a specific action for a related component.

As indicated earlier, the asset manager in consultation with the inspector may (out of necessity) select a specific MR&R option(s) for each building component. Alternatively, the asset manager may want to determine analytically which is the most feasible option based on those that are available to him. Other constraints, such as those which follow, can be added to the optimization analysis as the asset manager explores different options or development scenarios.

(1) It may be management's policy not to allow the condition rating of some components to slip below a specific minimum level of service. For example, a designated minimum condition rating may be assigned to major building components (such as boilers, ice plants, elevators, and roofs). Since these components are critical to the function of a facility and the consequence of their failure can be quite high, they may be assigned a minimum of C. If the current condition rating of such a component is C at t and the condition at $(t + 1)$ is projected to deteriorate to D, then some improvement policy must be immediately implemented.

(2) Budget constraints may limit the costs and by extension the scope of certain candidate rehabilitation projects. The asset manager may therefore be forced to select a specific strategy that may result in a very marginal improvement in the overall performance of the component.

(3) It may be within management's long-term program to replace some components within a five-year window. Such a policy may cause the asset manager to refrain from spending limited maintenance dollars on a component at the current time; hence his or her choice may be to do nothing or to engage in minimum preventative maintenance.

(4) There may be constraints that are specific to certain components, e.g., there are components, which out of necessity cannot be rehabilitated or repaired, only replaced. Similarly, MR&R action on some components will impose similar actions on related component(s).

(5) Policy or political decisions may have some influence on spending on certain facilities.

With the cost for each MR&R being estimated, they can be expressed as follows:

$C^{i}_{jk}(t+1) \in A^{i}_{jk}$

and $A^{i}_{jk} \subset A$ (6.6)

Where:

A^{i}_{jk} represents the MR&R options $\boldsymbol{k}$ that is accorded to component $\boldsymbol{j}$ of system $\boldsymbol{i}$;

A represents all possible MR&R actions;

$C^{i}_{j.}$ represents the various MR&R options available to a specific component $\boldsymbol{j}$ within the building system $\boldsymbol{i}$.

Assuming there are four MR&R alternatives, then the various possible combinations can be illustrated as follows:

C^{i}_{j1} = m_1, m_2, m_3, m_4

C^{i}_{j2} = m_2, m_3, m_4

C^{i}_{j3} = m_3, m_4

C^{i}_{j4} = m_4

⋮

⋮

C^{i}_{j14} = m_1, m_2

C^{i}_{j15} = m_1

If the proposed solution generated by the optimization exercise is not feasible or does not meet the scrutiny and approval of the asset manager, the applicable MR&R options for different building components can be adjusted and the optimization program re-run. This type of program flexibility allows the asset manager to explore multiple "near-optimal" solutions. Each can be systematically analyzed in order to determine the one that is most suitable. This type of analysis is particularly useful when the feasibility of certain MR&R actions is being studied, since it provides asset managers with some flexibility in the decision-making process. This approach strongly illustrates the potential benefits of the DSS.

The final result of the prioritization and optimization process would be a recommended work program. This would basically be a listing of assets (components), their functional location, the type of MR&R action to be undertaken on each, and the estimated cost. The next step would be the establishment of a work schedule to allocate resources for the various work programs, and to provide quality control and quality assurance plans for the various programs.

6.4 Case Study

A case study for the Ambulance Station was used to demonstrate the application of the above formulation. The goal of the case study was to determine how best to utilize a constrained building maintenance budget of $20,000.00 on a facility that has a number of its components at the minimum level of service. A physical evaluation of the building provided the condition assessment data required for the MR&R alternatives that were utilized in the model. Priority weights were developed for each building system and component within the facility. Table 6.1 provides a listing of all building systems and their respective components for the facility under consideration, along with their individual weights, condition index, and costs associated with the various MR&R actions.

The objective of the rehabilitation program was to maximize the performance or condition of the building since the budget was fixed. Thus the objective function of the optimization model is the presented in Equation 6.5.

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

Subject to the following constraints:

a) Budget constraint ≡ $\sum_{i=1}^{n} \sum_{j=1}^{m} \$C_{jk}^i \leq M$

   This constraint limits the scope of accumulated costs for candidate projects within the available budget.

b) Limit MR&R actions to components with a condition rating that is less than C.

$\therefore \; if\; c^i_j \geq B \; then \; c^i_j = 0$

This constraint reflected the policy of the organization to implement a minimum level of service for building components, and to ensure that maintenance resources are limited to components with the greatest need.

c) Limits the selection of only one MR&R action to each candidate building component.

$\therefore C^i_{jk} = 1$

This constraint ensures that only one MR&R alternative is selected for each component.

d) This constraint facilitates the selection of a specific MR&R action for some components, where $A^i_{jk} = 1$

There are instances where the replacement of a component is the only available option. There are instances where interconnection and logistical requirements will dictate that any MR&R action on one component will require similar action on another component.

The optimization program LINDO was utilized to generate the results. There were a total of 90 decision variables in the model, because components in very good (A) and good (B) condition were not considered. This reduced the model run time to approximately seven minutes. In the model setup, the building system name and weight, component name and weight, current condition of each component, optional actions, cost corresponding to each action, action taken, estimated condition after action taken, estimated performance index (of the component after action taken), and actual cost are clearly delineated. This is presented in Table 6.1. The results of the optimization exercise are presented in Table 6.2. The following findings were observed:

1. Building systems and components that were assigned higher priority weights (e.g. roof) were the recipients of a major share of the MR&R dollars. Conversely, systems and components with lower priority weights were selected for the least costly of the MR&R alternatives (e.g., HVAC);

2. The available budget was not adequate enough to have a substantial impact on the overall condition of the facility. The current building Condition Index is 64 (on a scale of 1 – 100). The impact of the $20,000.00 upgrade would improve the building's Condition Index to 70.

The representative example is typical of many public agencies, in which the majority of facilities have been in existence for a number of years, and their inherent systems and components are in fair to poor condition (C –

D). Such situations present a real challenge to asset managers as they attempt to prioritize components. This example illustrates the potential benefits of this aspect of the DSS.

Asset managers also have the option to run the optimization program with a range of different budget options (say $30,000 to $40,000) in order to get a view of the actions that may be considered and the overall performance of the building corresponding to different budgets. Furthermore, we can also take all types of buildings into consideration using a central budget control to allocate the budget simultaneously for all systems (or components) in all buildings. This may be a more effective approach in the disbursement and management of scarce financial resources.

The physical and functional analysis of the building components provided the data required for the MR&R alternatives. These alternatives constitute the input mechanism for the DSS. This type of analysis is particularly useful when the feasibility of certain MR&R actions is being studied, since it provides asset managers with some flexibility in the decision-making process.

There may be instances in which the asset manager may choose to ignore the recommendations of the optimization process. Policy (or political) decisions made at a higher level may impose the replacement of a component when the program recommended a minor rehabilitation. Similarly, regulatory agencies may also recommend the immediate replacement of certain components when these may have been scheduled only for minor or major rehabilitation, or worse, for no maintenance action whatsoever. This change may absorb much of the scarce financial resources, and may severely reduce the effectiveness of the remaining MR&R projects that were recommended.

Table 6.1 Building Components and CI data for Arena

BUILDING	SYSTEM	SYSTEM WEIGHT	COMPONENT	COMPONENT WEIGHT	START CONDITION	OPTIONAL ACTIONS	ESTIMATED COSTS
Ambulance Station 34	HVAC	0.07	Controls System	0.03	C1	1	$1,000.00
						2	
						3	
						4	
			Dampers	0.04	C1	1	2,000.00
						2	
						3	
						4	
			Filters	0.04	C1	1	$300.00
						2	
						3	
						4	
			Unit Heater	0.05	D1	1	$5,000.00
						2	$3,000.00
						3	$1,500.00
						4	
			Humidifier	0.05	B2		
			Fans	0.04	C1	1	$2,000.00
						2	$1,000.00
						3	$500.00
						4	
			Duct	0.1	C4	1	$15,000.00
						2	$10,000.00
						3	$5,000.00
						4	$2,000.00
			Thermal Controls	0.03	C1	1	$1,000.00
						2	
						3	
						4	
			HVAC System	0.16	C1	1	$40,000.00
						2	$20,000.00
						3	$8,000.00
						4	$4,000.00
			Primary Heating	0.12	C1	1	$7,500.00
						2	$4,000.00
						3	$1,500.00
						4	$500.00
			Supply Air	0.04	C1	1	$1,000.00
						2	$500.00
						3	$300.00
						4	$100.00

		Exhaust Systems	0.04	C1	1	$1,500.00
					2	$750.00
					3	$400.00
					4	$200
		Distributing Piping	0.05	C2	1	$5,000.00
					2	$2,500.00
					3	$1,000.00
					4	$500.00
		Circulation Pumps	0.06	C1	1	$3,000.00
					2	$1,500.00
					3	$500.00
					4	$300.00
		Air Handling	0.11	B1		
		Air Inlet	0.04	C1	1	$750.00
					2	$500.00
					3	$300.00
					4	$100.00
ROOF	0.19	Roof Structure	0.37	B2		
		Flashing	0.07	B2		
		Drainage	0.11	C2	1	$5,000.00
					2	$2,000.00
					3	$1,000.00
					4	$500.00
		Vents	0.04	B2		
		Ballast	0.04	C2	1	0
					2	$600.00
					3	$200.00
					4	$100.00
		Insulation	0.13	C2	1	$0.00
					2	$1,000.00
					3	$500.00
					4	$300.00
		Membrane	0.14	C2	1	0
					2	$1,000.00
					3	$500.00
					4	$300.00
		Parapet Walls	0.07	C2	1	0
					2	$3,000.00
					3	$1,500.00
					4	$500.00
		Coping	0.03	C2	1	0
					2	$1,000.00
					3	$500.00
					4	$200.00
EXTERIOR ENCL.	0.12	Structure	0.28	B2		
		Caulking	0.08	C1	1	0
					2	$1,500.00
					3	$500.00

					4	$300.00
		Masonry	0.13	B2		
		Insulation	0.15	B2		
		Finishes	0.04	B2		
		Paint	0.06	B2		
		Windows	0.08	B2		
		Glass	0.08	B1		
		Frames	0.06	B2		
		Stone	0.04	B2		
SUPER STRUCT	0.25	Standard Foundations	0.29	B1		
		Slab on Grade	0.05	B2		
		Basement Walls	0.1	B2		
		Structural Frame	0.25	B1		
		Floor Slabs & Decks	0.15	B2		
		Roof Construction	0.16	B1		
INTERIOR CONSTR.	0.05	Finishes	0.06	B1		
		Hardware	0.09	B2		
		Paint	0.07	B1		
		Ceiling	0.2	B1		
		Carpet	0.06	B1		
		Floor Finishes	0.1	B1		
		Partitions	0.16	B2		
		Signs	0.03	B1		
		Doors	0.18	B1		
		Trim	0.04	B1		
PLUMBING	0.07	Domestic Cold Water	0.36	C1	1	$5,000.00
					2	$3,000.00
					3	$2,000.00
					4	$1,000.00
		Domestic H W Supply	0.32	C1	1	$5,000.00
					2	$3,000.00
					3	$2,000.00
					4	$1,000.00
		Plumbing Fixtures	0.14	C1	1	$7,500.00
					2	$3,000.00
					3	$2,000.00
					4	$1,000.00
		Sanit. Equip. & Sup.	0.18	C1	1	0
					2	$3,000.00
					3	$2,000.00
					4	$500.00

ELECTRICAL SYSTEM	0.07	Power Supply & Distribution	0.24	B1		
		Lighting	0.15	B1		
		Power	0.25	B1		
		Emergency Generator	0.11	B2		
		Emerg. Light Packs	0.08	B2		
		Tel. and Comm.	0.1	B1		
		Misc. Equipment	0.06	B1		
FIRE SECURITY SYSTEM	0.14	Smoke Contd. Syst	0.12	B1		
		Fan Shut Off Damper	0.09	B2		
		Garage Exhaust Syst	0.07	B1		
		Fire Sprinkler / Stand	0.18	B1		
		Fire Extinguishers	0.28	C1	1	$10,000
					2	$5,000.00
					3	$3,000.00
					4	$1,000.00
		Special Equipment	0.08	B1		
		Security	0.21	B2		
SITE SERVICES	0.05	Curbs	0.08	B1		
		Sidewalks	0.16	B1		
		Stairs	0.13	B2		
		Railings	0.12	B2		
		Handicapped Access	0.26	B1		
		Signage	0.08	A1		
		Portico / Awning	0.17	B1		

TABLE 6.2 Results of Optimization Analysis (Where 1 Represents the Action Taken)

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
HVAC	0.07	Controls System	0.03	C1	1	1000	0	A	0.95	0
					4	0	1	D	0.2	0
		Dampers	0.04	C1	1	2000	0	A	0.95	0
					4	0	1	D	0.2	0
		Filters	0.04	C1	1	300	1	A	0.95	300
					4	0	0	D	0.2	0
		Unit Heater	0.05	D1	1	5000	0	A	0.95	0
					2	3000	0	B	0.75	0
					3	1500	0	C	0.45	0
					4	0	1	D	0.2	0
		Fans	0.04	C1	1	2000	0	A	0.95	0
					2	1000	0	B	0.75	0
					3	500	0	C	0.45	0
					4	0	1	D	0.2	0
		Ducting	0.1	C1	1	15000	0	A	0.95	0
					2	10000	0	B	0.75	0
					3	5000	0	C	0.45	0
					4	2000	1	D	0.2	2000
		Thermal Controls	0.03	C1	1	1000	0	A	0.95	0
					4	0	1	D	0.2	0
		HVAC System	0.16	C1	1	40000	0	A	0.95	0
					2	20000	0	B	0.75	0
					3	8000	0	C	0.45	0
					4	4000	1	D	0.2	4000

TABLE 6.2 Contd.

HVAC contd.	0.07	Primary Heating	0.12	C1	1	7500	0	A	0.95	0
					2	4000	0	B	0.75	0
					3	1500	0	C	0.45	0
					4	500	1	D	0.2	500
		Supply Air	0.04	C1	1	1000	0	A	0.95	0
					2	500	0	B	0.75	0
					3	300	0	C	0.45	0
					4	100	1	D	0.2	100
		Exhaust Systems	0.04	C1	1	1500	0	A	0.95	0
					2	750	0	B	0.75	0
					3	400	0	C	0.45	0
					4	200	1	D	0.2	200
		Distributing Piping	0.05	C2	1	5000	0	A	0.95	0
					2	2500	0	B	0.75	0
					3	1000	0	C	0.45	0
					4	500	1	D	0.2	500
		Circulation Pumps	0.06	C1	1	3000	0	A	0.95	0
					2	1500	0	B	0.75	0
					3	500	0	C	0.45	0
					4	300	1	D	0.2	300
		Air Inlet	0.04	C1	1	750	0	A	0.95	0
					2	500	0	B	0.75	0
					3	300	0	C	0.45	0
					4	100	1	D	0.2	100

TABLE 6.2 Contd.

Roof	0.19	Drainage	0.11	C2	1	5000	0	A	0.95	0
					2	2000	1	B	0.75	2000
					3	1000	0	C	0.45	0
					4	500	0	D	0.2	0
		Ballast	0.04	C2	2	500	0	A	0.95	0
					3	200	1	B	0.75	200
					4	100	0	C	0.45	0
		Insulation	0.13	C2	1	0	1	A	0.95	0
					2	1000	1	B	0.75	1000
					3	500	0	C	0.45	0
					4	300	0	D	0.2	0
		Membrane	0.14	C2	2	1000	1	A	0.95	1000
					3	500	0	B	0.75	0
					4	300	0	C	0.45	0
		Parapet Walls	0.07	C2	2	3000	0	A	0.95	0
					3	1500	0	B	0.75	0
					4	500	1	C	0.45	500
		Coping	0.03	C2	2	1000	0	A	0.95	0
					3	500	0	B	0.75	0
					4	200	1	C	0.45	200
Exterior Enclosure	0.12	Caulking	0.08	C1	2	1500	0	A	0.95	0
					3	500	1	B	0.75	500
					4	300	0	C	0.45	0

TABLE 6.2 Contd.

Plumbing System	0.07	Domestic Cold Water	0.36	C1	1	5000	0	A	0.95	0
					2	3000	1	B	0.75	3000
					3	2000	0	C	0.45	0
					4	1000	0	D	0.2	0
		Domestic Hot Water Sup	0.32	C1	1	5000	0	A	0.95	0
					2	3000	0	B	0.75	0
					3	2000	0	C	0.45	0
					4	1000	1	D	0.2	1000
		Plumbing Fixtures	0.14	C1	1	7500	0	A	0.95	0
					2	3000	0	B	0.75	0
					3	2000	0	C	0.45	0
					4	1000	1	D	0.2	1000
		Sanitary Equipment & S	0.18	C1	2	3000	0	A	0.95	0
					3	2000	0	B	0.75	0
					4	500	1	C	0.45	500
Fire-Security System	0.14	Fire Extinguishers	0.26	C1	1	10000	0	A	0.95	0
					2	5000	0	B	0.75	0
					3	3000	0	C	0.45	0
					4	1000	1	D	0.2	1000

6.4.1 Sensitivity of Generated Optimization Results

It is important to know that any variation in the available budget will affect the allocation of scarce financial resources to the most critical and deserving components. It was therefore prudent and meaningful to perform a sensitivity analysis to investigate any variation in the results when apportioning different budget amounts to a building that may have many of its components approaching the end of their service lives.

In the above case study, the budget amount was increased from $20,000.00 to $30,000.00, and finally to $40,000.00. The optimization model was repeated with the adjusted budget constraints in an effort to determine what MR&R projects should be undertaken and the projected level of improvement in the condition of the facility if the work projects were to be implemented. The overall condition of the facility improved to 72 (in the case of a $30,000.00 budget) and 74 (in the case of a $40,000.00 budget). The results of the analysis indicated that components that had higher priority weights were consistently given the highest priority. With this type of preference, and given the high costs associated with the MR&R activity, the selected policy may not necessarily have a major impact on the overall benefit that accrues to the asset or facility. On the basis of the input budget parameters, the proposed new condition index of the facility can be established. As a consequence, policy or political decisions can be implemented to specify that at least a minimum level of service be maintained for specific public facilities and the budget allocation required to meet these minimum targets can be easily determined.

6.5 Conclusions

The physical analysis of the building components provided the required data for the MR&R alternatives. These alternatives constitute the input mechanism for the DSS. This type of analysis is particularly useful when the feasibility of certain MR&R actions is being studied, since it provides asset managers with some flexibility in the decision-making process.

The optimization model developed for application by the DSS utilizes the following information:

1. A physical inspection of the current condition of building assets (in this case building components).
2. The determination of various applicable MR&R options for each component along with their associated estimated costs.
3. Development of a quantitative model for resource allocation and using it to maximize the overall expected benefit to the building facility, while adhering to the constraints imposed by the available maintenance budget.

One of the realities of infrastructure management entails dealing with external pressures and subjective preferences on pertinent maintenance policies. Related to this reality is the necessity of dealing with changes and modifications to the maintenance budget based on circumstances outside the control of the asset manager. The optimization module is geared to deal with these changing circumstances, facilitating the re-evaluation, and reconfiguration of the maintenance budget.

Furthermore, the optimization model can also be utilized to disburse maintenance funds at the building level. The overall central budget can be systematically allocated to all buildings within the portfolio, based on the overall benefit that will accrue to the various facilities. This may be a more effective approach in the disbursement and management of scarce financial resources.

Chapter 7 System Development

7 System Development

7.1 Introduction

The research presented in this thesis culminated in the development of a Decision Support System capable of responding to the objectives explored in the previous chapters. The Decision Support System for Building Maintenance Management is an integrated building maintenance management system developed primarily for application by asset managers at the Lands and Buildings branch at the City of Edmonton. Its primary objective is to provide a series of rational, well-ordered analyses of input data so that all buildings and related facilities involved can be effectively maintained.

The DSS was developed using MS SQL Server, and has the capabilities of handling the operations of both numerical and graphic objects. It operates in the Windows environment, and is facilitated with user-friendly graphical user interfaces. It can be operated as a stand-alone system, but it was designed to interface with the CMMS on the Lands and Buildings branch, Department of Asset Management of the City of Edmonton. The operation of the DSS is divided into two parts: (1) data collection; and (2) analytical operations based on decision models.

7.2 Analytical Operations of DSS

The analytical functions of the DSS are divided into five categories, which are implemented as five function modules:

1. Database;
2. Performance Evaluation;
3. Development of Priority Weights;
4. Deterioration Modeling; and
5. Budget Forecasting and Allocation.

Figure 6.1 shows the five categories and specific functions under each category. It should be mentioned that the Budget Forecasting and Allocation module would be completed at a later date.

7.3 System Structure

The DSS uses an n-tier approach, to provide comprehensive and precise information in a dynamic and highly practical format. The three tiers of this approach involve a database, a middleware tier to provide consistency in programming the interface, and a series of interfaces that the user accesses directly. These tiers, forming the system architecture are illustrated in Figure 7.2.

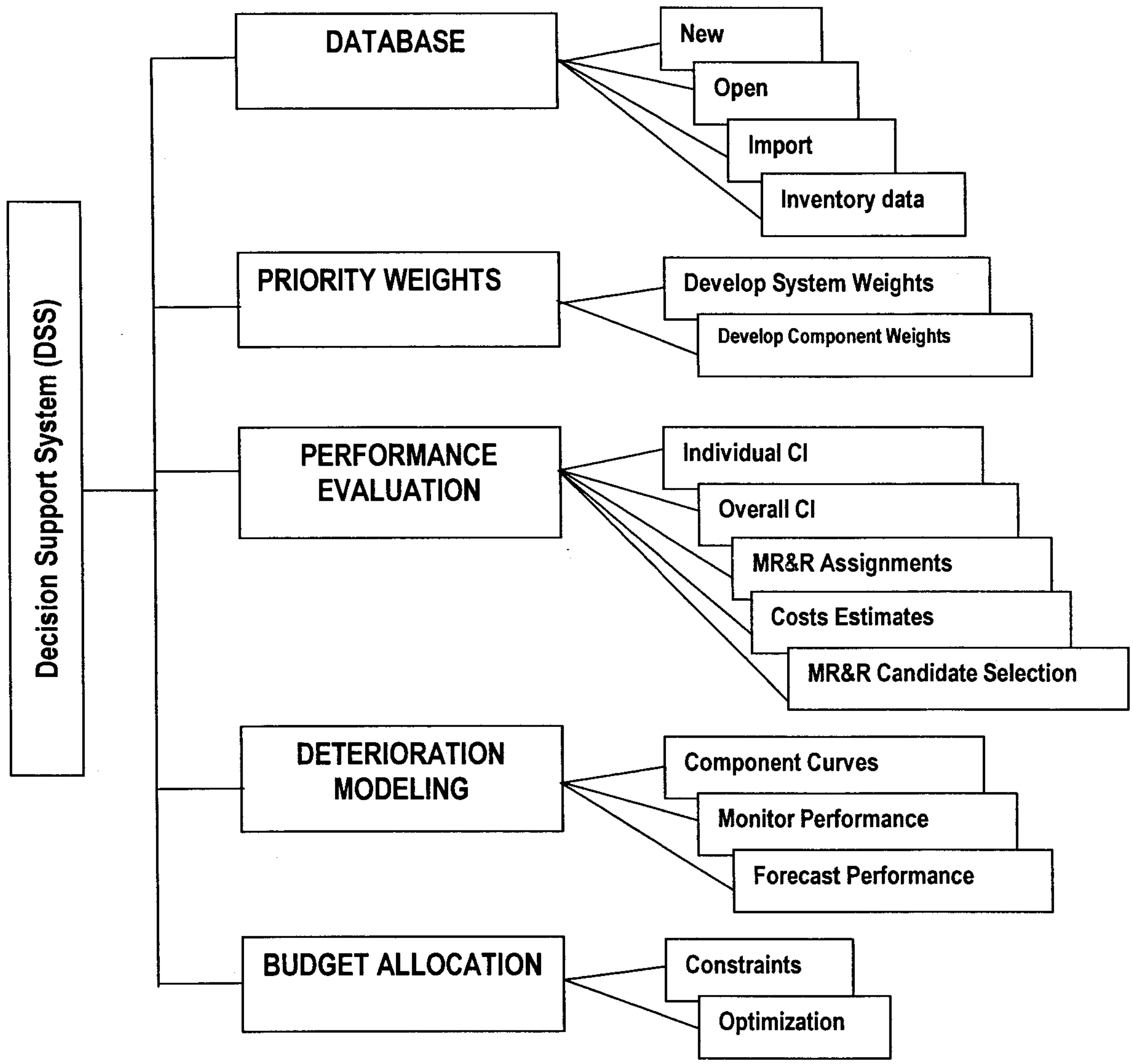


Figure 7.1 Analytical Functions in DSS

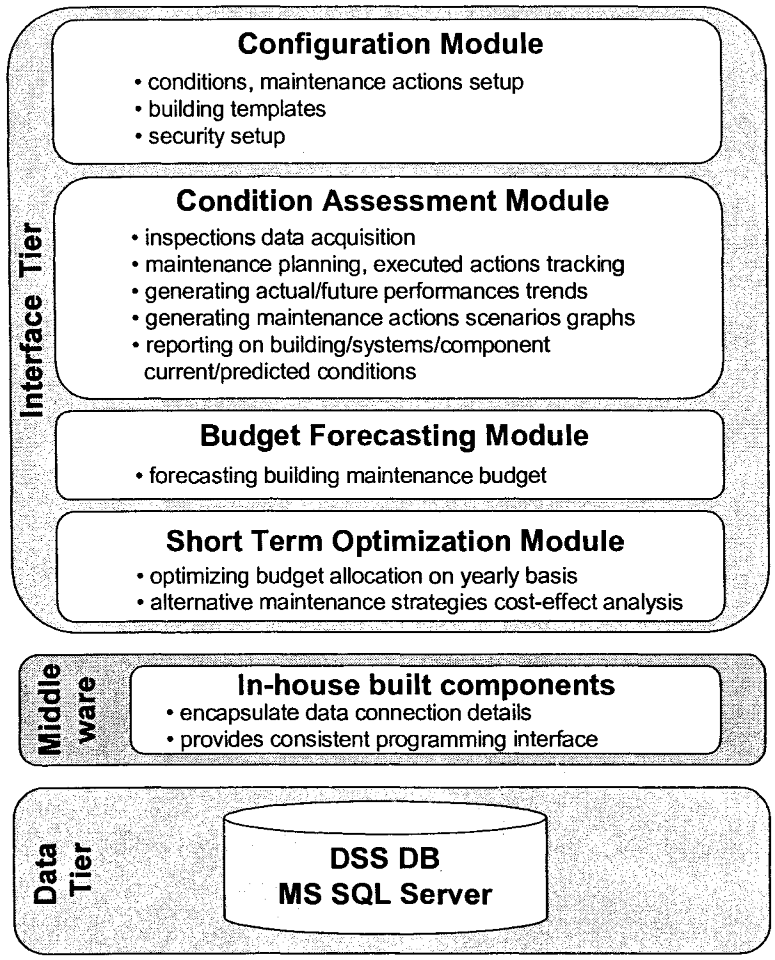


Figure 7.2 DSS for Building Maintenance - System Architecture

7.3.1 Data Tier

The data tier is the foundation of the DSS. It is the primary source for information used in the system. In collaboration with the other tiers of the DSS, the data tier is a repository for all the information inputted by the user into the database (via the interface tier), making data retrieval for any building, or any component a very simple task. The data would include:

(1) location of building facilities; (2) inventory data that provide for an accounting of the physical features and specifications of building assets; (3) condition rating data that are essential for conducting various performance-related evaluations and analyses; (4) maintenance policy and cost data; (5) priority weight values for building assets. The data tier is developed employing MS SQL Server.

7.3.2 Middleware Tier

The DSS uses a middleware employing a number of components built in-house in order to ensure there is a structured connection between the data tier and the interface tier. This middleware creates a consistent and easily controllable programming environment, which contributes to a better system design. The middleware tier is an integral part of the DSS, since it performs the task of providing a comprehensive linkage between the Data Tier and the Interface Tier.

7.3.3 Interface Tier

The interface tier comprises four modules: a configuration module, a condition assessment module, a budget-forecasting module, and a short-term optimization module (see Figure 7.2). Generally, the purpose of the interface tier is to create an electronic mediator between the user and the data in order to assist the user in the decision-making process. The interface tier facilitates access to a wide spectrum of information in a structured manner.

7.4 Configuration Module

The configuration module allows the user to perform all the preparatory work of creating the generic (or, where necessary, specific) building profiles for study and analysis. It facilitates the configuration of the building's hierarchal structure with the requisite building systems, components, and elements. A part of the model setup includes the formulation of the priority weights at each level of the hierarchy. The module is flexible enough to accommodate the modification of building profiles. The configuration module allows the user to construct a system model of the building or group of buildings for which the user must make a maintenance-related decision.

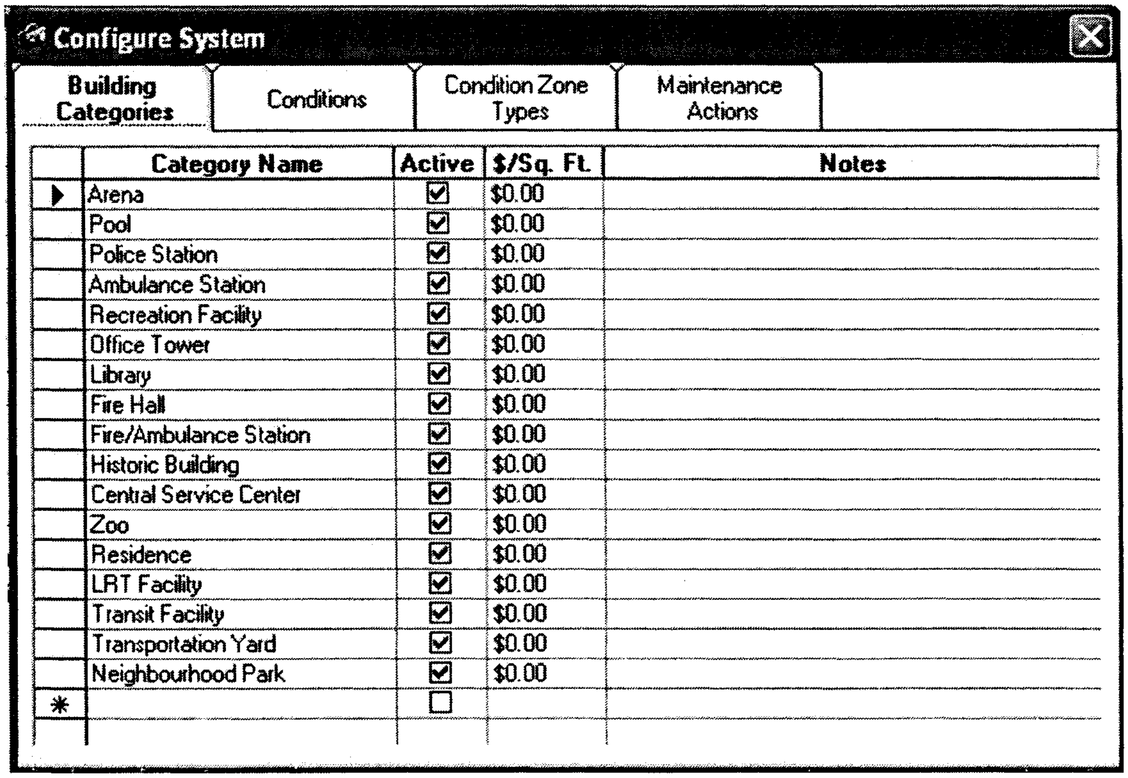
7.5 System Setup

The DSS was designed and developed as a generic system rather than an application-specific system. As a consequence, generic building profiles can be developed for each of the various building categories. The first step is to create a list of building categories. The building portfolio of the City of Edmonton comprises 17 building types that includes but is not limited to office buildings, arenas, pools, ambulance stations, fire stations, and police stations. Figure 7.3 presents a full list of the building categories. The next step entails the configuration of the condition zones for condition assessment purposes. This configuration involves the assignment of numeric ranges (e.g. 90%-100%) to lettered condition zones (e.g. Zone A) in order to denote a component's particular condition rating (please refer to Figures 7.4 and 7.5). These two configurations will set the context for the building system as a whole. In particular, the condition zones will be used extensively in condition assessment and in the estimation of CI.

Another important step in the system configuration is the development of the list of potential MR&R actions for building components that require some form of remedial action. These actions could include replacement, major rehabilitation, and minor rehabilitation as shown in Figure 7.6. Each action is expected to improve the condition of the component. It is extremely difficult to predetermine or predefine the level of improvement that will result from the maintenance action (i.e., whether it is a minor rehabilitation or a major rehabilitation). This will be determined by the current condition of the component and the scope of the work carried out. For the purpose of illustration, Figure 7.6 indicates that major rehabilitation will improve the condition of the component by 40 points, and minor rehabilitation will provide a 20-point improvement. The "do nothing" option was not included in the list for configuration purposes.

The condition zones will later be associated with these potential maintenance actions so as to ensure a consistency in the recommended MR&R action-based current recorded conditions. The configurations ensure that multiple users and those who input data into the system are using the same terms and are referring to the same conditions when they enter or utilize the system data.

The majority of the data that the user will configure in this module will be copied from an already-existing system template, which is based upon the most common systems found in the buildings. By selecting templates from the DSS template library, the user will save a great deal of effort in terms of entering configuration data.



Category Name	Active	$/Sq. Ft.	Notes
Arena	☑	$0.00	
Pool	☑	$0.00	
Police Station	☑	$0.00	
Ambulance Station	☑	$0.00	
Recreation Facility	☑	$0.00	
Office Tower	☑	$0.00	
Library	☑	$0.00	
Fire Hall	☑	$0.00	
Fire/Ambulance Station	☑	$0.00	
Historic Building	☑	$0.00	
Central Service Center	☑	$0.00	
Zoo	☑	$0.00	
Residence	☑	$0.00	
LRT Facility	☑	$0.00	
Transit Facility	☑	$0.00	
Transportation Yard	☑	$0.00	
Neighbourhood Park	☑	$0.00	
	☐		

Figure 7.3 Building Categories Setup Screen

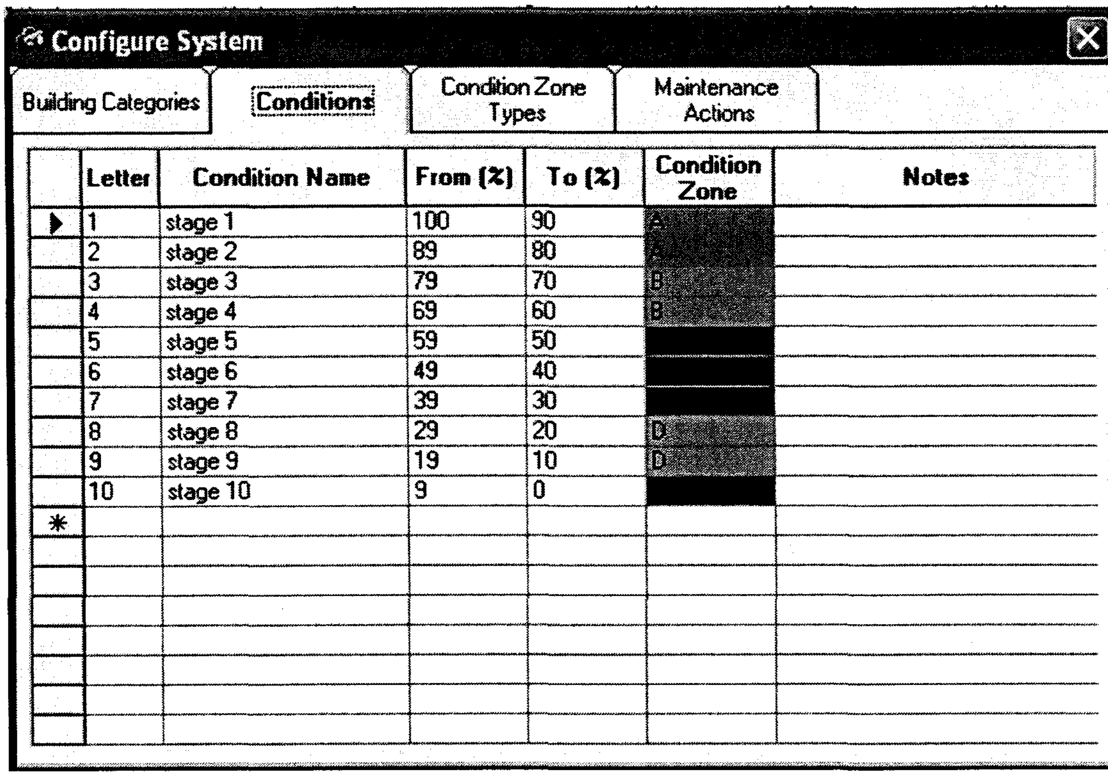


Figure 7.4 Building Conditions Setup Screen

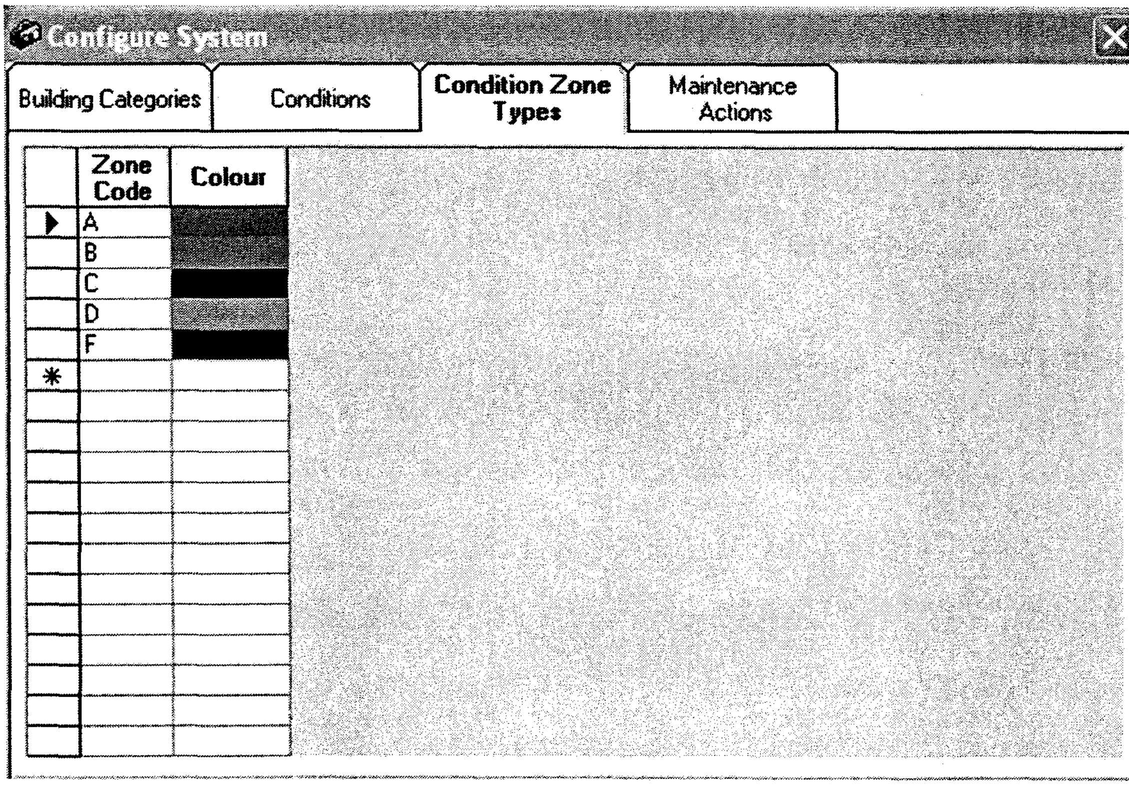


Figure 7.5 Condition Zones Setup

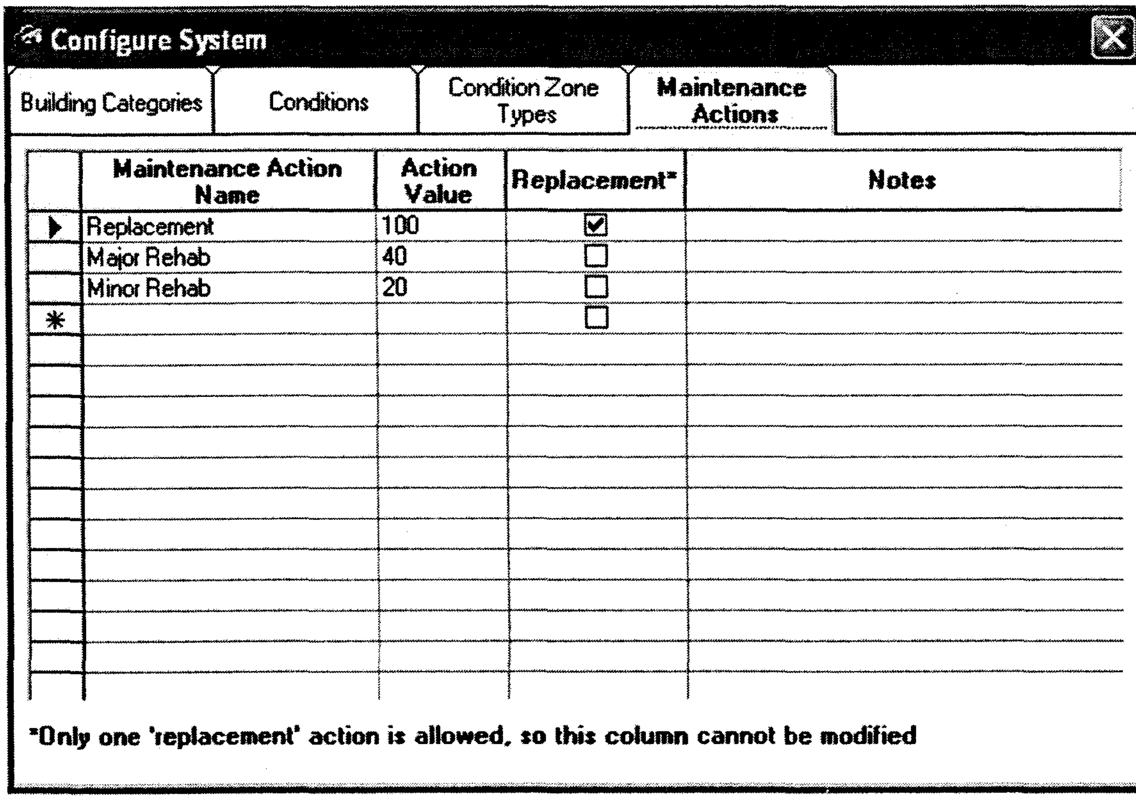


Figure 7.6 Building Maintenance Action Setup Screen

7.5.1 Creating a New Building Profile

Before creating the structure of a new building, the relevant background data and specifications must first be inputted on the description page of the building (see Figure 7.7). This generally refers to the data related to building identification and location, functional use and classification, date of original construction, physical features, material type and property data, appurtenance data, and cost data. There are primarily three ways to prepare the required profile for a new building. The user has the option of selecting from any of the following depending on what is convenient or expedient:

1. Should the new building be similar to an existing building, the user may use the "Copy-Building" function. This function copies an entire existing building hierarchy to a new building. Any changes that are required can subsequently be made. The copy function is illustrated in Figure 7.8.
2. In this option, the user may simply copy the required systems from the template library shown in Figure 7.9. This approach will save time in configuration, and may be the option of choice is situations where buildings are unique in their make-up, and have a reduced number of building systems.
3. Instead of utilizing a generic building profile or copying a profile, the user can create a building profile from the beginning. The configuration of its hierarchy of systems, components, and elements may be entered manually.

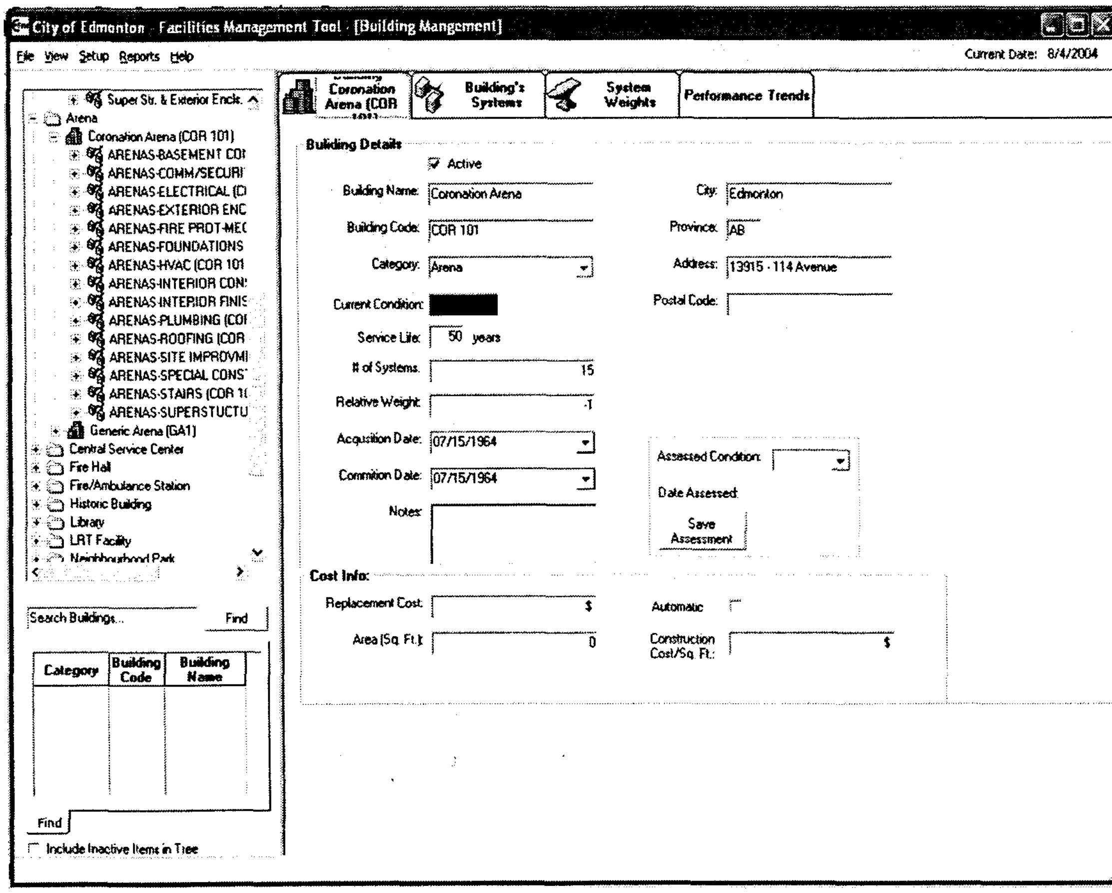


Figure 7.7 General Information Sheet for Buildings

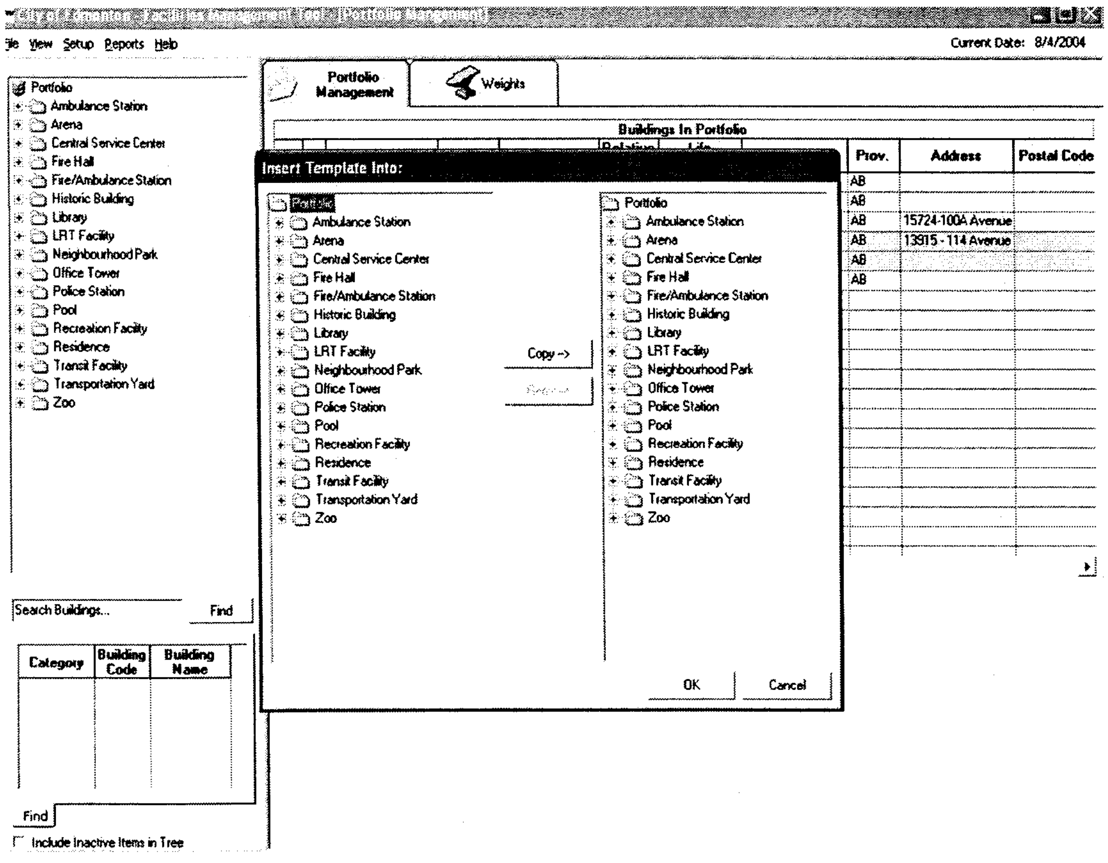


Figure 7.8 Using the Copy Function

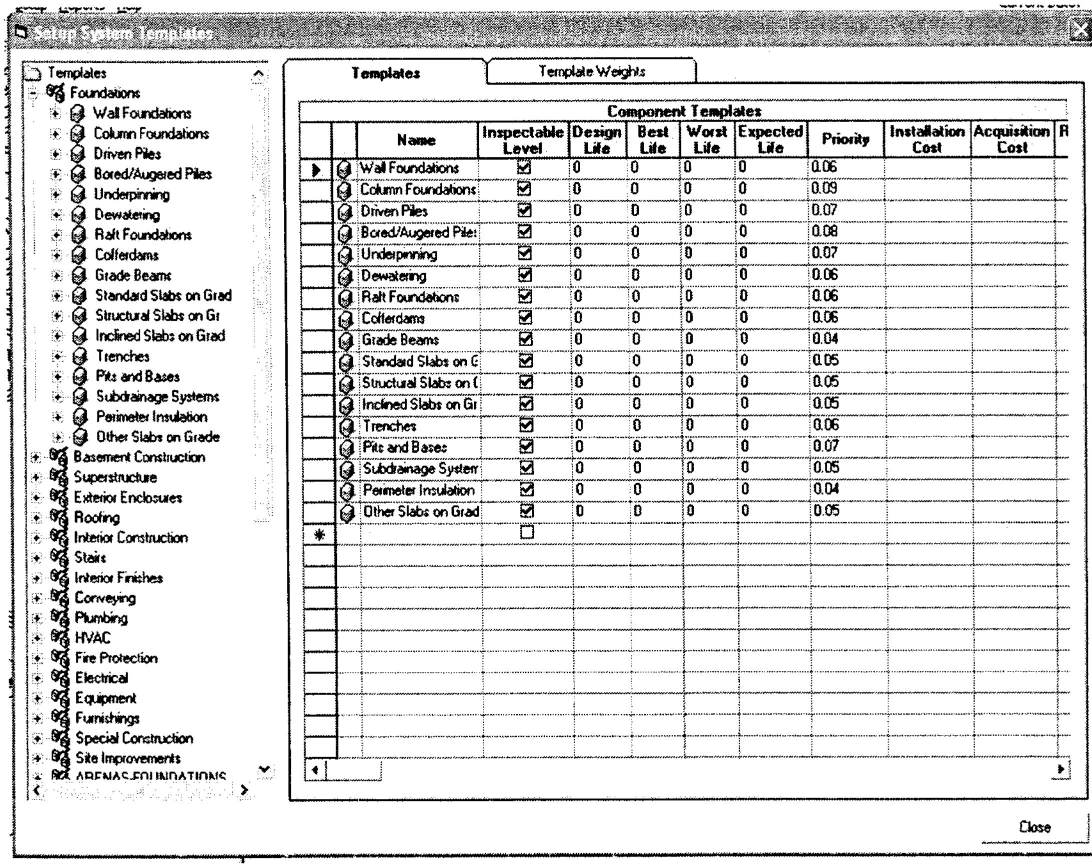


Figure 7.9 Typical Template Libraries

7.5.2 Development of Priority Weights

Having completed the creation of the building profile, the next step in the configuration process entails the development of priority weights for building systems, components, and elements, if these are required. As was demonstrated in Chapter 4, the DSS utilizes the AHP methodology in creating judgment or comparison matrices that are used in evaluating the relative importance of building assets (i.e., systems, components, or elements) based on a predefined criterion, e.g., functional performance. The input screen shown in Figure 7.10 allows the user to make subjective judgments on the relative importance of the systems that are being compared. The user has the option to enter a numeric choice or can use the dropdown menu to select from the list of linguistic choices available. Figure 7.11 illustrates the comparison matrix that results from this application. In its current stage of development, the DSS utilizes an independent approach in the formulation of priority weights.

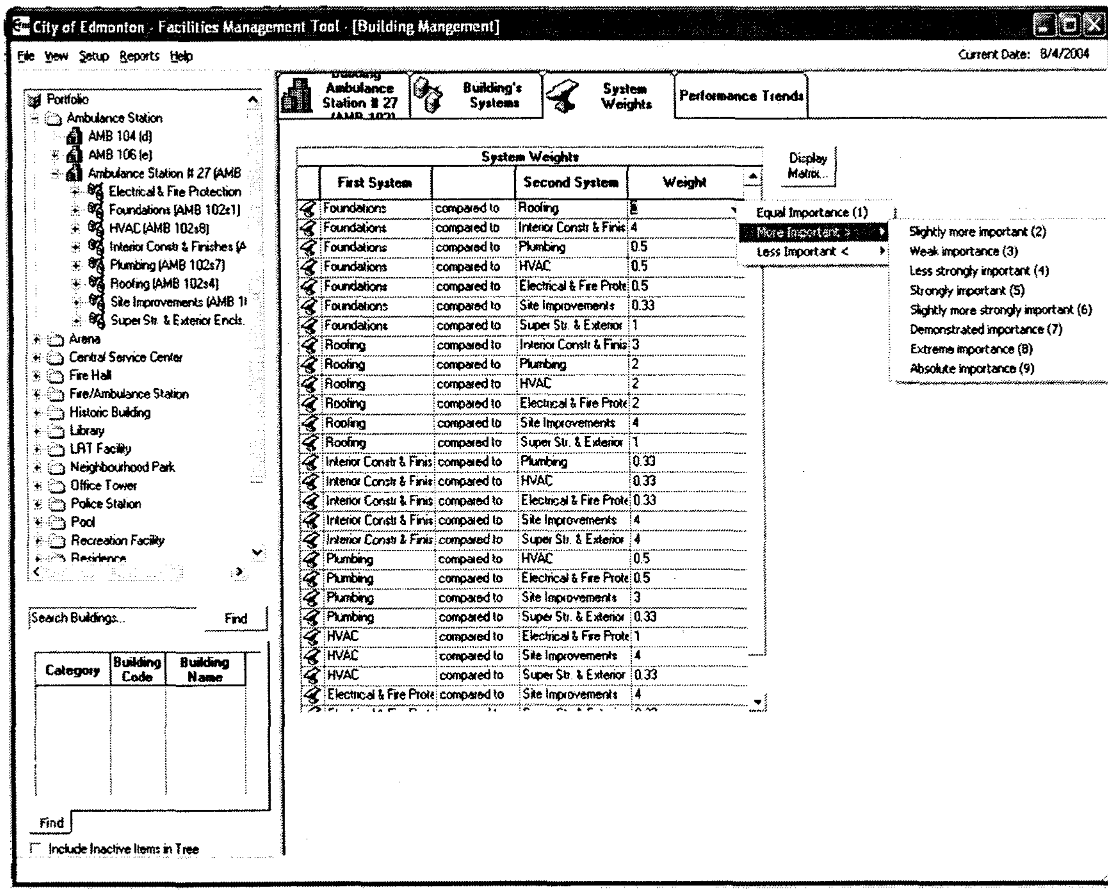
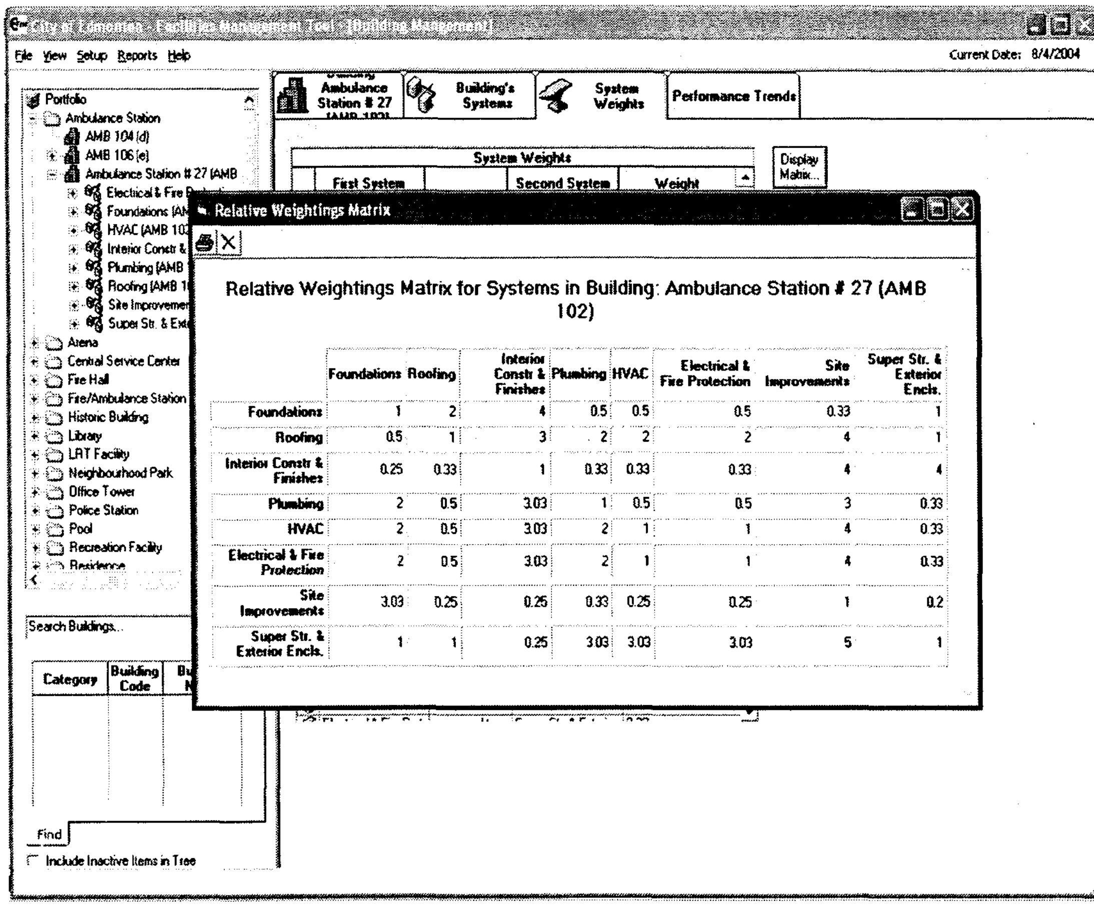


Figure 7.10 Development of the Comparison Matrix for Building Systems (Ambulance Station)



	Foundations	Roofing	Interior Constr & Finishes	Plumbing	HVAC	Electrical & Fire Protection	Site Improvements	Super Str. & Exterior Encls.
Foundations	1	2	4	0.5	0.5	0.5	0.33	1
Roofing	0.5	1	3	2	2	2	4	1
Interior Constr & Finishes	0.25	0.33	1	0.33	0.33	0.33	4	4
Plumbing	2	0.5	3.03	1	0.5	0.5	3	0.33
HVAC	2	0.5	3.03	2	1	1	4	0.33
Electrical & Fire Protection	2	0.5	3.03	2	1	1	4	0.33
Site Improvements	3.03	0.25	0.25	0.33	0.25	0.25	1	0.2
Super Str. & Exterior Encls.	1	1	0.25	3.03	3.03	3.03	5	1

Figure 7.11 Comparison Matrix for Building Systems (Ambulance Station)

7.5.3 Creation of Performance Curves

In order to develop performance curves, time-specific data on the asset's service life is required for input in the configuration module. The time estimates for the asset's service life for the three different scenarios (namely, average design-case, worst-case, or best-case scenario) until a component or element reaches a critical condition (e.g., 24% performance) will be required. Time estimates for each of the different scenarios will be obtained from experts or manufacturers. Should the years until critical condition be insufficiently defined, other conditions may be identified using the accompanying dropdown box (see Figure 7.12).

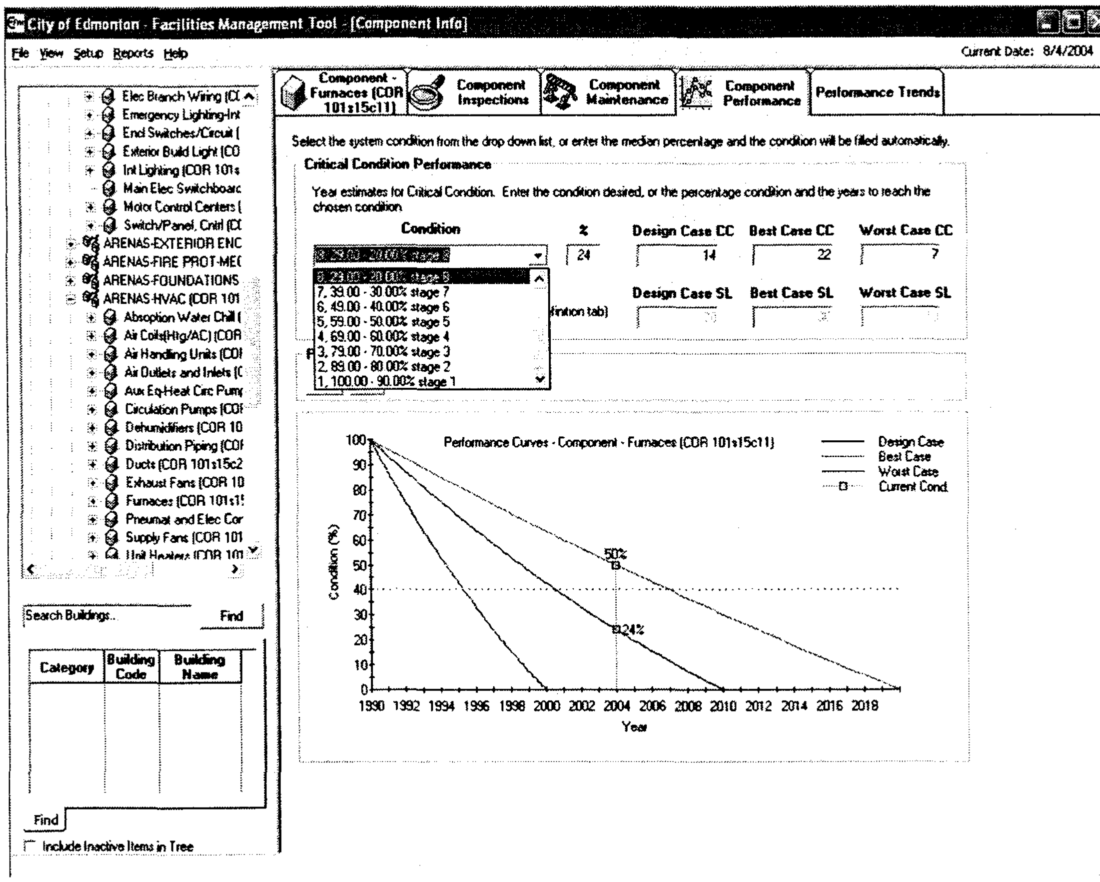


Figure 7.12 Development of Performance Curves for Building Components

7.6 Condition Assessment Module

The condition assessment module comprises a number of sub-modules. These sub-modules combine to aid the user to monitor an ongoing basis the performance of building assets (components or elements). This module facilitates the following:

1. The inputting of inspection data, the planning of maintenance work, and the tracking of already-executed actions;
2. The generation of performance trends from actual inspection data as well as projections of the future conditions of building assets;

3. The generation of performance graphs outlining the effects of various maintenance action scenarios;
4. The reporting of both current and predicted conditions for buildings, systems, components, and elements; and
5. The monitoring of annual maintenance expenditures at all levels of the building hierarchy.

Certain information is required of the user for the condition assessment module to output at full capacity. This information includes: the system or component relative priority; the general inspection accounts; the planned, proposed, and actual maintenance plans; and the planned or proposed maintenance costs. The user does not have to input information such as the building structure, the component or element-level inspection accounts, the component or element priority level, or the potential maintenance actions which could be taken. The Condition Assessment Module draws this information directly from the DSS database. The input information combines subsequently with the database information and is processed by the three sub-modules of the Condition Assessment Module: Data Acquisition, Deterioration, and Mathematical Analysis. The final output of this module involves performance graphs, actual/future performance curves, deterioration scenarios, and condition reports.

7.6.1 Data Acquisition Sub-Module

The data acquisition sub-module is a repository for the records of annual inspection of building components. The next-year condition and end-of-service-life condition may also be recorded, although this is not mandatory. Built into the system are a number of business constraints. For example, the condition recorded in year n+1 must be lesser than or equal to the condition recorded in year n, due to the influence of deterioration mechanisms. Another constraint is that inspection reports may only be entered for all periods up to the current year; at the same time, however, conditions noted in previous years can be modified. Nonetheless, an installation date of a component cannot be modified after the inspection records exist. These constraints ensure that the inspection records are as accurate and up-to-date as possible. A similar process is offered for recording maintenance actions.

A number of different maintenance action types are available within the system for the purposes of categorizing proposed MR&R action recordings. These types include: identified maintenance actions, planned maintenance actions, and executed maintenance actions. For each type of maintenance action, the user must input the cost, year, and action description, which may be selected from a list of predefined maintenance actions. Again, there are certain constraints in place and options available within the system. For example, although identified and planned maintenance action can be recorded for a future time, the executed maintenance action can only be entered for up to the current year. Also, MR&R actions can be recorded regardless of whether there is an inspection or not. These constraints and options enable the user to be as precise as possible when inputting information, as well as ensuring the precision and accuracy of output information.

7.6.2 Cost Monitoring

The data acquisition sub-module also permits the user to view running maintenance costs. The cost categories available for cross-reference include preventative and demand (emergency or breakdown) maintenances. If a component needs to be replaced, the user can select an executed maintenance action to "replace" the component or element. All information related to inspection and maintenance records is subsequently saved and made available for viewing through the "History Reports".

7.6.3 Deterioration Sub-Module

The deterioration sub-module facilitates the monitoring of the performance of the building and its respective systems, components, and elements. It generates performance curves that generally represent the deterioration of a component throughout its service life. Figures 7.13 and 7.14 demonstrate the performance curve of a component based on inspections and that of a building system, respectively. The curve maps the data points, which correspond to the condition ratings that were determined by the annual condition assessment surveys and any MR&R actions taken on components. This sub-module is also able to extrapolate the deterioration trends of the component based on its past performance and its estimated remaining service life.

By combining existing data from a number of sources with data gathered through inspections and case studies, the actual and expected performance of particular components can be determined with relative accuracy. This information is helpful since it enables users to make informed decisions regarding the likelihood of a particular component needing maintenance. This sub-module works in close collaboration with the Mathematical Analysis sub-Module.

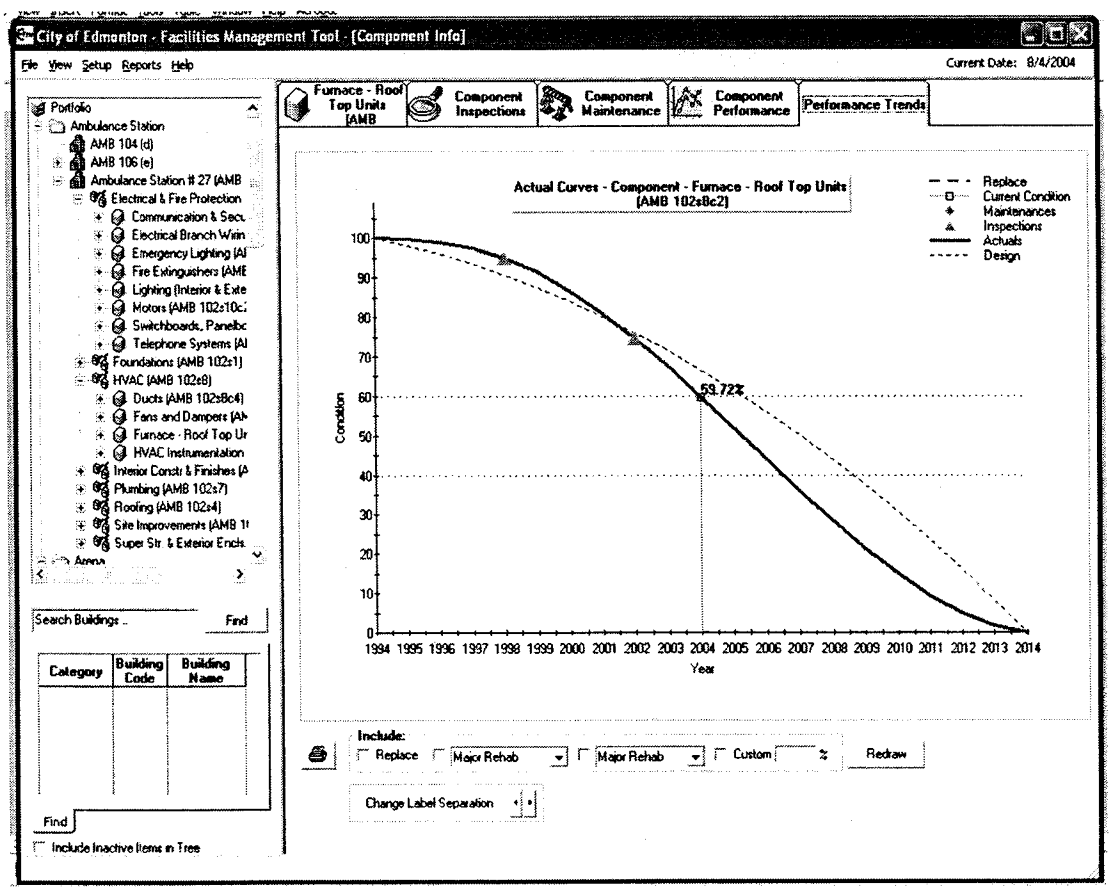


Figure 7.13 Performance Curves for a Component Based on Inspections

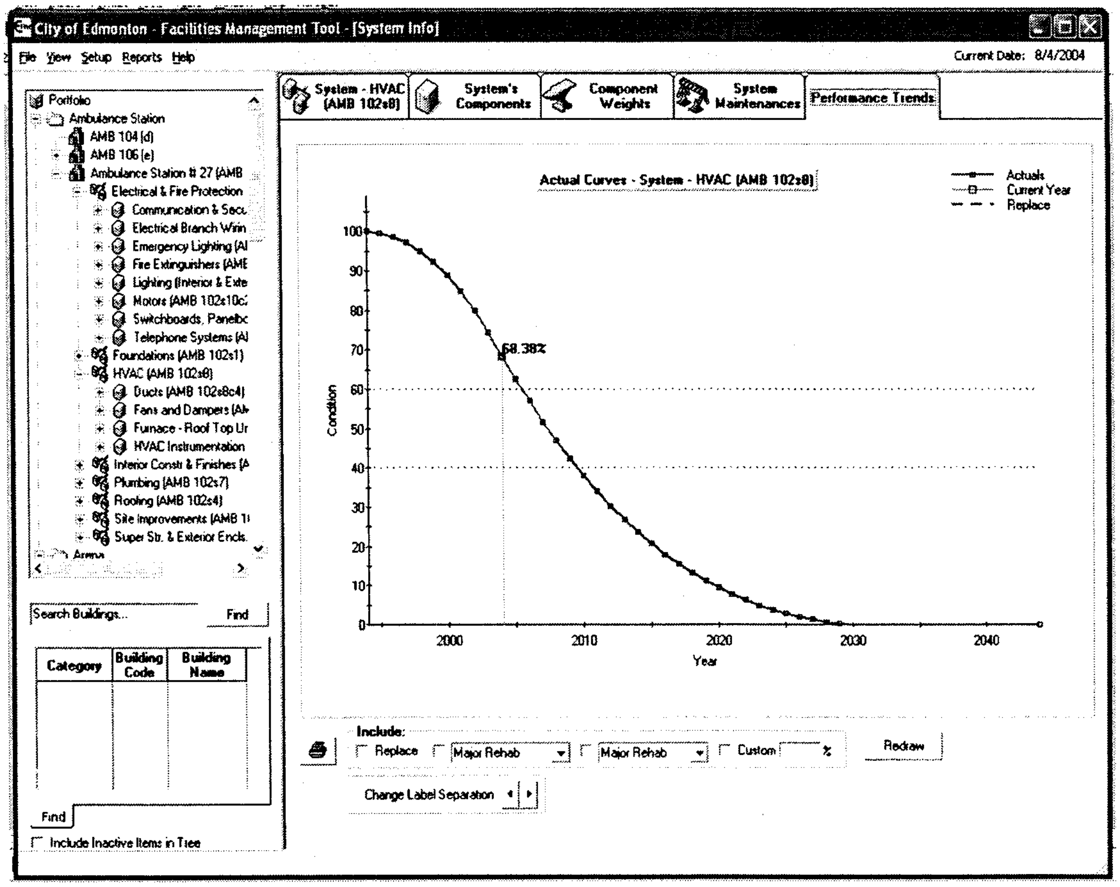


Figure 7.14 Performance Curves for a Building System Based on Inspections

7.6.4 Mathematical Analysis Sub-Module

The mathematical analysis sub-module uses MATLAB™ (The MathWorks, Inc.) to provide a best-fit curve based on the Spline function. There are a number of parameters that help to shape the methodology:

1. Condition ratings from annual inspections.
2. Initial installation point of the component.
3. Estimated remaining service life.
4. MR&R action and estimated CI that results from that action.

A simple search algorithm will select and generate the curve that best satisfies the aforementioned parameters (using the MATLAB library of curves).

If the values for next year's condition and for the estimated service life of the component or element are entered, the deterioration curve will be demonstrated by both an actual graph and a future trend graph. The actual graph is generated for the time period extending from the component's year of installation up to the current year (when the last inspection was conducted). This graph presents actual condition trends for any particular level of the building hierarchy (i.e., system, component, or element). The future trend, on the other hand, is generated by a polynomial curve, which is extrapolated from the component's current condition, next-year (estimated) condition, and expected remaining service life. If the next year condition or expected service life values have not been entered, the graph will be generated based upon inspection data and the design service life.

If a maintenance action is designated as "executed", yet there is no inspection recorded following the maintenance action, a future performance trend may be generated for that component based on its previous actual performances. The condition assessment module also provides users with the ability to consider a number of different MR&R

scenarios on components that may be nearing the end of their service life. The effect of a specific maintenance strategy upon the improvement of a system's overall condition can also be explored. This module results in proactive reporting, which enables users to determine the extent to which certain MR&R actions can affect the system's condition and how taking these actions at different times (e.g., now or later) and to different extents (e.g., do not replace the whole component, or only a certain element of it), results in condition improvement. Using the actual and future trends functions, users can determine the most efficient and effective route, balancing overall condition improvement with budget and schedule concerns.

7.7 Conclusion

The DSS for Building Maintenance Management can be considered as a venture intent upon facilitating the structuring of information for the purposes of making wise, cost-effective decisions regarding maintenance. It consists of generic structures that facilitate the representation of complex infrastructure facilities in a hierarchically decomposed framework. This representation supports the replication of different building formats and allows the reuse of the structure at any decomposition level.

In order to ensure effective decision-making, project planners must have tools available to them, which will enable comprehension of the relationships between components/elements and those categories higher up on the building hierarchy. The DSS accomplishes this by offering a balance between user-configuration and system-driven problem solving. The system offers an easy-to-use interface while retaining the complexity of the data being processed. Further development of this system can only increase the accuracy of analysis.

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.

Chapter 8 Conclusions and Recommendations

8 Conclusions and Recommendations

8.1 Introduction

This thesis attempted to investigate systematically some of the key problems facing asset managers as they try to manage their aging inventory of buildings effectively. Solutions to these problems have been proposed and developed within a multi-integrated building management Decision Support System. The Decision Support System has the potential to address some of the issues facing public agencies in their quest to manage their building asset portfolio effectively.

The questions many organizations are asking are: "What is the state of Canadian Municipal Infrastructure?" and "How much additional money is required to bring the existing infrastructure to an acceptable level?" To adequately address these issues, each of Canada's 3,500 municipalities must be able to provide answers to the following:

1. What is the current condition of my asset portfolio?
2. What is the remaining service of my building assets and how can I rationally predict their future condition?
3. What methodology can I use to prioritize my infrastructure projects and how can I proactively make decisions based on what is the best maintenance strategy to implement?

8.2 Research Contributions

8.2.1 Condition Assessment Strategy

This thesis presented an approach to assess the condition of building components. The approach allows for a consistent evaluation from year to year and from inspector to inspector. The approach is presented as logical and systematic and its use is demonstrated by a practical example.

8.2.2 Multi Criteria Evaluation of Building Systems and Components

The Analytic Hierarchy Process (AHP) provided an effective approach for dealing with multiple criteria and multiple alternative decision problems. The AHP model was successfully applied to the building hierarchy and several criteria were used to determine the relative importance of each building system/component in terms of each criterion. The formulated AHP model was able to determine the relative weight factors for building systems and components with high accuracy. The assigned weights were then used in conjunction with the CI of building components to estimate the Condition Index (CI) of the building systems and buildings using the roll-up approach. The model is flexible enough to accommodate a revaluation of building systems and component weights even among buildings of the same types.

Within the complex building environment of interconnected building systems and components, the impaired functionality of a specific component can have a debilitating impact on other components. It is important to model and approximate the magnitude of this dynamic relationship by obtaining judgments from experts on interdependency between the building systems and components.

Furthermore, in assessing the interdependency of building systems/components, this research also addressed the need to model the "self-contribution" of building systems/components. It is important to do so since the global function of a system/component may or may not be affected by the failure of other systems/components. If the failure of some systems has a minimal effect upon the performance of a system, then the self-contribution of that system is will be substantial. Conversely, if the failure of some systems has a significant effect on a system then the self-contribution will be marginal. Factoring the self-contribution phenomena into the interdependency calculations provided a more realistic representation of the priority weights of building systems/components.

The hypothesis of determining the magnitude of the self-contribution of systems/components has been verified. A novel approach of using AHP to model this self-contribution of building components facilitated the estimation of more realistic priority weights for components. Judgments of the interdependency between building systems and components will serve the purpose of clearly defining what entities have a greater weight within the building, and consequently what entity should be given priority in the planning and execution of maintenance projects and in the disbursement of limited maintenance funds.

8.2.3 Deterioration Modeling

Although several types of data are gathered from Computerized Maintenance Management Systems (CMMS), there are no systematic procedures that utilize these data to help validate and improve the accuracy of information embodied in planning and prioritizing MR&R strategies, and formulating the maintenance budget. Furthermore, very little attempt has been made to model the deterioration of entire buildings in the domain of facility management.

Deterioration modeling is a critical component of any infrastructure management program because it provides predictions of infrastructure conditions over time, which is a significant input for maintenance/rehabilitation programs. This research attempted to model the deterioration of a building's systems and components in an effort to predict the future condition of a facility, its functional systems, and components at any given age. Both the regression (deterministic) and Markov (stochastic) models were used to predict the condition rating of building components. This approach was necessary due to the lack of historical condition assessment data. The regression extrapolation model was used primarily to develop the performance profile of components based on the judgments of experts, and this facilitated the development of transition probability matrices in the Markov application. The regression model was also used to estimate the extent of condition improvement in response to alternative maintenance rehabilitation and repair strategies.

Combining the regression techniques and Markov methods facilitates a more interactive formulation deterioration process. Its application to building systems and components provides an easier framework to capture engineering expertise in monitoring the condition of building assets and forecasting the effects of maintenance, rehabilitation, and replacement treatment to facilities.

A desirable feature when planning for MR&R actions is to first specify the required performance characteristics and then to exercise the freedom to identify a variable treatment plan that achieves the performance. The application of such an approach would require the specification of performance characteristics in terms of current and future states and a variable time over which the state transition is desired to occur. The DSS provides for that flexibility in the planning process by allowing asset managers to foresee and resolve when MR&R is needed. Furthermore, it affords them the opportunity to determine which MR&R strategy is most feasible, as well as the impact such actions will have upon the performance of the asset. This type of planning approach provides a convenient framework and project level information in sufficient detail for integration with network level optimization methods.

8.2.4 Decision Support System (DSS)

With limited and shrinking funds, the need to prioritize maintenance dollars is becoming increasingly difficult. How are conditions related to overall project performance? What is the best use of available dollars? What will be the condition of my building assets in the next five or ten years?

The methodologies and procedures performed by the DSS provide an essential service in transforming raw data into information and intelligence, and essential services to administrators and decision-makers. It reduces the risk in policy and budgeting decisions with respect to MR&R projects. In the domain of facility management, the available computer maintenance management systems (CMMS) have placed a lot of emphasis on managing and scheduling work orders for maintenance and repairs, but are severely lacking in the area of condition assessment monitoring, deterioration modeling, MR&R planning, and budget optimization.

Municipalities and public agencies have consistently expressed a desire for the following:

- To be able to present budget requests with the empirical data necessary to support funding recommendations.
- To be able to set project priorities by rating facilities based on their condition and their need for attention.
- To be able to extend the useful life of facilities in response to the current funding challenges.
- To use indicators to evaluate the critical points in the life cycle of building assets in order to determine when intervention maximizes the return on investment by cost effectively extending the useful life, and by determining when it is no longer makes economic sense to continue investing in an old facility.

The key contribution of the DSS is that it adequately takes care of the above needs. Furthermore, it has the capability of providing an optimization model that integrates facility maintenance and improvement policies.

8.3 Recommendations for Further Research

8.3.1 Risk Assessment Strategy

Areas of further research include the development of a good risk assessment strategy. Such a strategy would be of immense value to asset managers, especially since they tend to operate in an environment where many major maintenance and rehabilitation projects are consistently being deferred. Analyzing the risk that a piece of equipment will fail at a crucial time (e.g., a boiler failing in the middle of winter or an ice plant failing in the middle of the hockey season) can contribute to better maintenance management policies. Such risk assessment of an analysis can be used for justification and prioritization of major maintenance capital projects. This process would include detailed portfolio assessment, the analysis of probabilities of failure, the determination of consequences of failure, and an economic analysis.

8.3.2 Further Updating of Waiting Time Parameters

As more deterioration data are collected over time, statistical procedures have to be developed for updating waiting time parameters. These procedures will be used to shift gradually from relying on expert opinion to using deterioration data. Since assets may deteriorate at different rates under various conditions, these assets and the relative data will have to be partitioned into groups comprising similar characteristics. Updating probability distribution parameters could be undertaken using a statistical method such as Bayesian updating (Ningyuan et al. 1997). Further research is required to adapt this method to the process at hand.

8.3.3 Estimating Transition Probability and Waiting Times for MR&R Strategies

The DSS will facilitate better data collection on CI monitoring of building components, and costs expenditures associated to specific MR&R actions. It will also provide more accurate data on improved conditions as a result of a specific maintenance action. Such information can be provide a mechanism for further research in the development of Transition Probability Matrices for any improvement action undertaken on major building components under well-defined operating conditions.

8.4 Conclusions

At a time when there is a scarcity of public financing resources, there is strong pressure on municipalities to be more prudent in the planning and administration of their maintenance budget. The current decision support system offers an array of facility analysis tools with the capability to project maintenance and repair requirements, determine life cycle costs, and prioritize maintenance and repair needs. Successful application of the tool will inherently depend on the proper data population of the system and the individual capabilities of the users.

The success of the decision support system lies first of all in recognizing the actual need that exists to monitor all of the building's assets. One of the successes of this project was the use of the UNIFORMAT II elemental classification structure as the desired hierarchical structure for breaking down the building into assets. It provides a consistent framework for classifying all building components as well as a system to determine the relative weights for components. Furthermore, it provided a broad-base structure for the development of the performance measurement and condition assessment process.

The benefits of this study are immeasurable. The DSS will allow asset managers to be more proactive in their maintenance management activities. They will be able to select the most cost effective maintenance strategy for each individual component. They will be able to monitor more constantly the performance of their building assets, and will be better equipped to allocate scarce resources to areas of significant need. The selection of capital planning projects will be based on a rational system of prioritization. These projects can be easily identified long before the failure of the building component.

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APPENDIX A

SAMPLE INSPECTION REPORTS

The City of Edmonton

Field Inspections Form - 2004

Building: Borden Park Pool

Conditions Legend:

A , 100.00 - 90.00% stage 1
A , 89.00 - 80.00% stage 2
B , 79.00 - 70.00% stage 3
B , 69.00 - 60.00% stage 4
C , 59.00 - 50.00% stage 5
C , 49.00 - 40.00% stage 6
C , 39.00 - 30.00% stage 7
D , 29.00 - 20.00% stage 8
D , 19.00 - 10.00% stage 9
F , 9.00 - 0.00% stage 10

Maintenance Legend:

Major Rehab	40%
Minor Rehab	20%

System/Component/Element	End of Design Life	Previous Inspected Condition	Current Condition	Next Year Condition	Remaining Service Life (yrs)	Notes
Ex Utility Doors	2030		B - stage 4			
Ex Wall Vapor/Air/Insu	1992	D - stage 8	B - stage 4			
Joint Sealers	2005		C - stage 6			
Masonry Units	2027		C - stage 5			
Paints	2005		B - stage 4			

System FOUNDATIONS						
Grade Beams	2027		C - stage 5			
Wall Foundations	2027		C - stage 5			
Struct Slabs on Grade	2012		C - stage 5			

System HVAC						
Air Outlets and Inlets	2015		B - stage 4			
Circulation Pumps	2017		B - stage 3			
Supply & Return Air Ducts	2052		B - stage 4			
Exhaust Fans	2019		B - stage 3			
Furnaces - Furnace #1	2015		C - stage 5			
Furnaces - Furnace #2	2015		C - stage 5			
Furnaces - Furnace #3	2019		B - stage 3			
Furnaces - Space Heater	2010		B - stage 4			

The City of Edmonton

Field Inspections Form - 2004

Building: Borden Park Pool

Conditions Legend:

A , 100.00 - 90.00% stage 1
A , 89.00 - 80.00% stage 2
B , 79.00 - 70.00% stage 3
B , 69.00 - 60.00% stage 4
C , 59.00 - 50.00% stage 5
C , 49.00 - 40.00% stage 6
C , 39.00 - 30.00% stage 7
D , 29.00 - 20.00% stage 8
D , 19.00 - 10.00% stage 9
F , 9.00 - 0.00% stage 10

Maintenance Legend:

Major Rehab 40%
Minor Rehab 20%

System/Component/Element	End of Design Life	Previous Inspected Condition	Current Condition	Next Year Condition	Remaining Service Life (yrs)	Notes
Int Wall Painting	2007		B - stage 4			
Plaster Wall Finishes	2015		B - stage 4			
Tile Floor Finishes	2021		B - stage 4			
Tile Wall Finishes	2021		B - stage 4			
System PLUMBING						
Backflow Devices	2009		B - stage 3			
Basins	2025		C - stage 5			
Domestic Water Heaters - Domestic Water	2015		C - stage 5			
Domestic Water Heaters - Domestic Water	2021		A - stage 2			
Domestic Water Heaters - Domestic Water	2015		C - stage 5			
Piping Insulation	2013		B - stage 4			
Rain Water Drain Pipe	1992	D - stage 8	C - stage 5			
Sanitary Waste/Vent Pipe	1992	D - stage 8	C - stage 5			
Showers	2031		B - stage 3			
Urinals	2020		C - stage 5			
Mixing Valves	2012		B - stage 4			
Domestic Water and Piping Sys	1992	B - stage 4	B - stage 4			
Water Closets	2028		B - stage 3			
Sink	2025		B - stage 4			

Edmonton

The City of Edmonton

Field Inspections Form - 2004

Building: Borden Park Pool

Conditions Legend:

A , 100.00 - 90.00% stage 1
A , 89.00 - 80.00% stage 2
B , 79.00 - 70.00% stage 3
B , 69.00 - 60.00% stage 4
C , 59.00 - 50.00% stage 5
C , 49.00 - 40.00% stage 6
C , 39.00 - 30.00% stage 7
D , 29.00 - 20.00% stage 8
D , 19.00 - 10.00% stage 9
F , 9.00 - 0.00% stage 10

Maintenance Legend:

Major Rehab 40%
Minor Rehab 20%

System/Component/Element	End of Design Life	Previous Inspected Condition	Current Condition	Next Year Condition	Remaining Service Life (yrs)	Notes
Pool Heating System	2014		B - stage 4			
Meter/Reg. Equip. - Water/Gas	2017		B - stage 4			
Pool Circulation System	2022		B - stage 3			
Pool Water Treatment	2017		B - stage 3			
Pool Filtration System	2017		C - stage 5			
System INTERIOR CONST						
Int Fixed Partitions	2002	C - stage 7	B - stage 4			
Int Swinging Doors	2020		B - stage 4			
Lockers	2020		B - stage 4			
Pedestrian Cont Device	2020		B - stage 4			
Storage Shelving	2010		C - stage 5			
Toilet/Bath Accessories	2010		C - stage 5			
System INTERIOR FINISH						
Ceiling Paneling	2013		B - stage 4			
Concrete Floor Finish	2017		B - stage 4	C - stage 5	10	
Floor Painting	2006		C - stage 5			
Gypsum Board Wall Fin	2016		B - stage 4			
Int Ceiling Painting	2007		B - stage 4			

APPENDIX B

WAITING TIMES FOR COMPONENTS IN AN ARENA

Table B.1: Estimates of Waiting Times for Building System – **FOUNDATIONS**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
FOUNDATIONS	Slab on Grade	A	5	10	15	75 – 100 years
		B	10	15	20	
		C	20	25	35	
		D	10	15	20	
		F	5	10	10	
	Basement Wall Construction	A	5	10	15	75 – 100 years
		B	10	15	20	
		C	20	25	35	
		D	10	15	20	
		F	5	10	10	
	Wall Foundations	A	5	10	15	75 – 100 years
		B	10	15	20	
		C	20	25	35	
		D	10	15	20	
		F	5	10	10	
	Column Foundations	A	5	10	15	75 – 100 years
		B	10	15	20	
		C	20	25	35	
		D	10	15	20	
		F	5	10	10	
	Concrete Grade Beams	A	5	10	15	75 – 100 years
		B	10	15	20	
		C	20	25	35	
		D	10	15	20	
		F	5	10	10	

Table B.2: Estimates of Waiting Times for Building System – **SUPERSTRUCTURE**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
SUPERSTRUCTURE	Floor Structural Frame	A	5	10	15	75 – 100 years
		B	10	15	20	
		C	20	25	35	
		D	10	15	20	
		F	5	10	10	
	Columns Supporting Floors	A	5	10	15	75 – 100 years
		B	10	15	20	
		C	20	25	35	
		D	10	15	20	
		F	5	10	10	
	Roof Construction	A	5	10	15	75 – 100 years
		B	10	15	20	
		C	20	25	35	
		D	10	15	20	
		F	5	10	10	
	Firestopping and Fire Proofing	A	1	2	5	10 years
		B	2	3	5	
		C	2	2	6	
		D	1	2	3	
		F	1	1	1	
	Expansion Control	A	1	2	5	10 years
		B	2	3	5	
		C	2	2	6	
		D	1	2	3	
		F	1	1	1	
	Structural Interior Walls	A	5	10	15	75 – 100 years
		B	10	15	20	
		C	20	25	35	
		D	10	15	20	
		F	5	10	10	

Table B.3: Estimates of Waiting Times for Building System – **EXTERIOR ENCLOSURES**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
EXTERIOR ENCLOSURES	Exterior Walls	A	5	10	15	75 – 100 years
		B	10	15	20	
		C	20	25	35	
		D	10	15	20	
		F	5	10	10	
	Exterior Wall Interior Skin	A	5	8	10	50 years
		B	8	12	15	
		C	10	20	25	
		D	5	6	6	
		F	2	4	4	
	Exterior Protection Devices	A	2	4	5	20 years
		B	4	5	6	
		C	6	7	8	
		D	2	2	3	
		F	1	2	3	
	Balcony Walls and Railings	A	5	10	15	75 yaers
		B	10	15	20	
		C	20	25	35	
		D	10	15	20	
		F	5	10	10	
	Exterior Windows	A	3	5	8	40 years
		B	7	10	12	
		C	12	15	18	
		D	6	7	8	
		F	2	3	4	
	Exterior Doors	A	3	5	8	40 years
		B	7	10	12	
		C	12	15	18	
		D	6	7	8	
		F	2	3	4	
	Expansion Control	A	1	2	5	10 years
		B	2	3	5	
		C	2	2	6	
		D	1	2	3	
		F	1	1	1	

Table B.4: Estimates of Waiting Times for Building System – **ROOFING**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
ROOFING	Built-up Bituminous Roofing	A	2	3	4	20 years
		B	3	5	7	
		C	6	7	10	
		D	2	3	5	
		F	2	2	4	
	Roof and Deck Insulation	A	5	8	10	50 years
		B	10	12	15	
		C	15	18	25	
		D	7	8	15	
		F	3	4	10	
	Flashing	A	3	5	8	40 years
		B	7	10	12	
		C	10	15	18	
		D	4	7	8	
		F	1	3	4	
	Roof Drain	A	3	5	8	40 years
		B	7	10	12	
		C	10	15	18	
		D	4	7	8	
		F	1	3	4	
	Roof Specialties	A	3	5	8	40 years
		B	7	10	12	
		C	10	15	18	
		D	4	7	8	
		F	1	3	4	
	Traffic Toppings and Paving	A	3	5	8	40 years
		B	7	10	12	
		C	10	15	18	
		D	4	7	8	
		F	1	3	4	
		A				
		B				
		C				
		D				
		F				

Table B.5: Estimates of Waiting Times for Building System – **INTERIOR CONSTRUCTION**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
INTERIOR CONSTRUCTION	Interior Fixed Partition	A	5	10	15	75 years
		B	12	15	20	
		C	15	25	35	
		D	10	15	20	
		F	8	10	10	
	Interior Demountable Partitions	A	3	4	6	25 years
		B	4	5	6	
		C	7	8	10	
		D	4	5	5	
		F	2	2	3	
	Interior Windows	A	3	5	6	30 years
		B	5	7	10	
		C	8	10	15	
		D	3	5	6	
		F	1	3	3	
	Interior Doors	A	3	5	6	30 years
		B	5	7	10	
		C	8	10	15	
		D	3	5	6	
		F	1	3	3	
	Compartments and Cubicles	A	3	5	6	35 years
		B	6	8	10	
		C	10	12	14	
		D	4	6	7	
		F	2	4	3	
	Pedestrian Control Devices	A	3	5	8	30 years
		B	3	5	10	
		C	7	10	15	
		D	4	6	10	
		F	3	4	7	
	Lockers	A	3	5	6	30 years
		B	5	7	10	
		C	8	10	15	
		D	3	5	6	
		F	1	3	3	

Table B.6: Estimates of Waiting Times for Building System – **STAIRS**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
STAIRS	Stair Construction	A	3	5	8	40 years
		B	7	10	12	
		C	10	15	18	
		D	4	7	8	
		F	1	3	4	
	Stair Finishes	A	3	4	5	25 years
		B	5	6	8	
		C	7	9	10	
		D	3	3	4	
		F	2	3	3	
	Balustrades	A	3	5	7	30 years
		B	5	8	10	
		C	7	10	13	
		D	3	4	6	
		F	2	3	4	

Table B.7: Estimates of Waiting Times for Building System – **INTERIOR FINISHES**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
INTERIOR FINISHES	Wall Finishes - Concrete	A	5	4	5	25 Years
		B	7	6	8	
		C	3	9	10	
		D	2	3	4	
		F	3	3	3	
	Wall Finishes - Tile	A	5	4	5	25 Years
		B	7	6	8	
		C	3	9	10	
		D	2	3	4	
		F	3	3	3	
	Interior Wall Painting	A	1	2	5	10 Years
		B	2	3	5	
		C	2	2	6	
		D	1	2	3	
		F	1	1	1	
	Floor Finishes - Concrete	A	5	4	5	25 Years
		B	7	6	8	
		C	3	9	10	
		D	2	3	4	
		F	3	3	3	
	Floor Finishes - Tile	A	5	4	5	25 Years
		B	7	6	8	
		C	3	9	10	
		D	2	3	4	
		F	3	3	3	
	Wood Flooring	A	3	6	8	35 Years
		B	5	7	10	
		C	8	10	15	
		D	5	7	10	
		F	4	5	7	
	Carpet Flooring	A	1	2	5	10 Years
		B	2	3	5	
		C	2	2	6	
		D	1	2	3	
		F	1	1	1	

Table B.7 Contd.: Estimates of Waiting Times for Building System – **INTERIOR FINISHES**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
INTERIOR FINISHES	Ceiling – Acoustical Finish	A	1	2	3	15 Years
		B	2	4	5	
		C	4	6	7	
		D	2	2	4	
		F	1	1	1	
	Ceiling – Plaster Veneer	A	1	2	3	15 Years
		B	2	4	5	
		C	4	6	7	
		D	2	2	4	
		F	1	1	1	
	Interior Ceiling Painting	A	1	2	5	10 Years
		B	2	3	5	
		C	2	2	6	
		D	1	2	3	
		F	1	1	1	

Table B.8: Estimates of Waiting Times for Building System – **CONVEYING**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
CONVEYING	Elevators	A	3	3	5	25 yrs
		B	4	5	7	
		C	7	8	10	
		D	4	5	6	
		F	2	2	2	
	Wheelchair Lifts	A	3	3	5	25 yrs
		B	4	5	7	
		C	7	8	10	
		D	4	5	6	
		F	2	2	2	
	Escalators & Moving Walks	A	3	3	5	25 yrs
		B	4	5	7	
		C	7	8	10	
		D	4	5	6	
		F	2	2	2	
	Dumbwaiters	A	2	3	5	20 yrs
		B	3	5	7	
		C	6	7	10	
		D	3	4	6	
		F	1	1	2	
	Hoists	A	2	3	5	20 yrs
		B	3	5	7	
		C	6	7	10	
		D	3	4	6	
		F	1	1	2	

Table B.9: Estimates of Waiting Times for Building System – **PLUMBING**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
PLUMBING	Fixtures – Water Closets	A	3	6	8	35 yrs
		B	5	7	10	
		C	8	10	15	
		D	5	7	10	
		F	4	5	7	
	Fixtures - Urinals	A	2	5	7	25 yrs
		B	4	7	9	
		C	6	8	10	
		D	2	3	5	
		F	1	2	4	
	Fixtures - Lavatories	A	3	6	8	35 yrs
		B	5	7	10	
		C	8	10	15	
		D	5	7	10	
		F	4	5	7	
	Fixtures - Sinks	A	3	5	7	40 yrs
		B	7	10	12	
		C	10	15	17	
		D	3	7	10	
		F	2	3	4	
	Fixtures - Basins	A	3	5	8	30 yrs
		B	5	8	10	
		C	7	10	13	
		D	4	5	6	
		F	1	2	3	
	Fixtures - Showers	A	3	5	7	40 yrs
		B	7	10	12	
		C	10	15	17	
		D	3	7	10	
		F	2	3	4	
	Domestic Water Distribution	A	3	6	8	35 yrs
		B	5	7	10	
		C	8	10	15	
		D	5	7	10	
		F	4	5	7	
	Domestic Water Heater	A	3	5	6	20 yrs
		B	4	5	6	
		C	5	6	7	
		D	2	3	4	
		F	1	1	1	

Table B.9 CONTD.: Estimates of Waiting Times for Building System – **PLUMBING**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
PLUMBING	Waste and Vent Piping	A	3	5	7	40 yrs
		B	7	10	12	
		C	10	15	17	
		D	3	7	10	
		F	2	3	4	
	Rain Water Drainage	A	3	5	7	40 yrs
		B	7	10	12	
		C	10	15	17	
		D	3	7	10	
		F	2	3	4	
	Backflow Devices	A	1	2	3	15 yrs
		B	2	4	5	
		C	4	6	7	
		D	2	2	4	
		F	1	1	1	
	Sump Pumps	A	3	4	6	20 yrs
		B	3	5	7	
		C	5	7	10	
		D	3	3	5	
		F	1	1	2	
	Valves	A	1	2	3	15 yrs
		B	2	4	5	
		C	4	6	7	
		D	2	2	4	
		F	1	1	1	
	Circulation Pumps	A	1	2	3	15 yrs
		B	2	4	5	
		C	4	6	7	
		D	2	2	4	
		F	1	1	1	

Table B.10: Estimates of Waiting Times for Building System – **HVAC**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
HVAC	Pipes and Tubes	A	3	6	8	35 yrs
		B	5	7	10	
		C	8	10	15	
		D	5	7	10	
		F	4	5	7	
	Boilers	A	3	6	8	35 yrs
		B	5	7	10	
		C	8	10	15	
		D	5	7	10	
		F	4	5	7	
	Furnaces	A	3	4	6	20 yrs
		B	3	5	7	
		C	5	7	10	
		D	3	3	5	
		F	1	1	2	
	Chillers	A	3	4	6	20 yrs
		B	3	5	7	
		C	5	7	10	
		D	3	3	5	
		F	1	1	2	
	Cooling Towers	A	2	5	7	25 yrs
		B	4	7	9	
		C	6	8	10	
		D	2	3	5	
		F	1	2	4	
	Refrigerant Compressors and Condensers	A	1	2	3	15 yrs
		B	2	4	5	
		C	4	6	7	
		D	2	2	4	
		F	1	1	1	
	Heat Pumps	A	1	2	3	15 yrs
		B	2	4	5	
		C	4	6	7	
		D	2	2	4	
		F	1	1	1	
	Air Handling Units	A	3	4	6	20 yrs
		B	3	5	7	
		C	5	7	10	
		D	3	3	5	
		F	1	1	2	

Table B.10 CONTD.: Estimates of Waiting Times for Building System – **HVAC**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
HVAC	Fans	A	2	4	5	20 yrs
		B	3	5	6	
		C	6	7	10	
		D	3	3	6	
		F	1	1	3	
	Ducts and Accessories	A	3	5	8	30 yrs
		B	5	8	10	
		C	7	10	13	
		D	4	5	6	
		F	1	2	3	
	Terminal and Packaged Units	A	2	4	5	20 yrs
		B	3	5	6	
		C	6	7	10	
		D	3	3	6	
		F	1	1	3	
	Humidifiers	A	1	2	3	15 yrs
		B	2	4	5	
		C	4	6	7	
		D	2	2	4	
		F	1	1	1	
	Dehumidifiers	A	1	2	3	15 yrs
		B	2	4	5	
		C	4	6	7	
		D	2	2	4	
		F	1	1	1	
	Unit Heaters	A	1	2	3	15 yrs
		B	2	4	5	
		C	4	6	7	
		D	2	2	4	
		F	1	1	1	
	HVAC Instrumentation and Controls	A	2	4	5	20 yrs
		B	3	5	6	
		C	6	7	10	
		D	3	3	6	
		F	1	1	3	

Table B.11: Estimates of Waiting Times for Building System – **FIRE PROTECTION**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
FIRE PROTECTION	Sprinklers	A	3	5	7	30 yrs
		B	5	7	10	
		C	7	10	12	
		D	3	5	7	
		F	2	3	4	
	Standpipes	A	2	3	5	20 yrs
		B	3	5	6	
		C	6	7	10	
		D	3	4	6	
		F	1	1	3	
	Fire Extinguisher, Cabinets and Accessories	A	2	5	7	25 yrs
		B	4	7	9	
		C	6	8	10	
		D	2	3	5	
		F	1	2	4	
	Other Fire Protection Systems	A	2	5	7	25 yrs
		B	4	7	9	
		C	6	8	10	
		D	2	3	5	
		F	1	2	4	

Table B.12: Estimates of Waiting Times for Building System – **ELECTRICAL**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
ELECTRICAL	Transformers	A	3	5	7	40 years
		B	7	10	12	
		C	10	15	17	
		D	3	7	10	
		F	2	3	4	
	Switchboards, Panel boards and Control Centers	A	3	5	7	40 years
		B	7	10	12	
		C	10	15	17	
		D	3	7	10	
		F	2	3	4	
	Circuit Breakers	A	3	5	7	40 years
		B	7	10	12	
		C	10	15	17	
		D	3	7	10	
		F	2	3	4	
	Interior Electrical Distribution Transformers	A	3	5	8	30 years
		B	5	8	10	
		C	7	10	13	
		D	4	5	6	
		F	1	2	3	
	Motor Control Centers	A	3	5	8	30 years
		B	5	8	10	
		C	7	10	13	
		D	4	5	6	
		F	1	2	3	
	Electrical Branch Wiring	A	5	5	8	40 years
		B	8	10	12	
		C	10	15	18	
		D	5	6	7	
		F	2	4	5	
	Interior Lighting	A	3	5	8	30 years
		B	5	8	10	
		C	7	10	13	
		D	4	5	6	
		F	1	2	3	
	Exterior Building Lighting	A	3	5	8	30 years
		B	5	8	10	
		C	7	10	13	
		D	4	5	6	
		F	1	2	3	

Table B.12 CONTD.: Estimates of Waiting Times for Building System – **ELECTRICAL**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
ELECTRICAL	Detection and Alarm	A	2	3	5	20 years
		B	3	5	6	
		C	6	7	10	
		D	3	4	6	
		F	1	1	3	
	Security Access and Surveillance	A	2	3	5	20 years
		B	3	5	6	
		C	6	7	10	
		D	3	4	6	
		F	1	1	3	
	Voice and Data Systems	A	2	3	5	20 years
		B	3	5	6	
		C	6	7	10	
		D	3	4	6	
		F	1	1	3	
	Public Address and Music Systems	A	2	3	5	20 years
		B	3	5	6	
		C	6	7	10	
		D	3	4	6	
		F	1	1	3	
	Television Systems	A	2	2	3	15 years
		B	2	3	5	
		C	4	6	7	
		D	1	3	4	
		F	1	1	1	
	Other Communication and Security Sys.	A	2	3	5	20 years
		B	3	5	6	
		C	6	7	10	
		D	3	4	6	
		F	1	1	3	

Table B.13: Estimates of Waiting Times for Building System – **EQUIPMENT**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
EQUIPMENT	Vending Equipment	A	2	3	5	20 years
		B	3	5	7	
		C	5	7	10	
		D	3	3	5	
		F	2	2	3	
	Food Service Equipment – Soda Fountain	A	2	3	5	20 years
		B	3	5	7	
		C	5	7	10	
		D	3	3	5	
		F	2	2	3	
	Food Service Equipment – Range Hoods	A	2	3	5	20 years
		B	3	5	7	
		C	5	7	10	
		D	3	3	5	
		F	2	2	3	
	Freezers	A	2	3	5	20 years
		B	3	5	7	
		C	5	7	10	
		D	3	3	5	
		F	2	2	3	
	Scoreboards	A	2	3	5	20 years
		B	3	5	7	
		C	5	7	10	
		D	3	3	5	
		F	2	2	3	

Table B.14: Estimates of Waiting Times for Building System – **SITE SERVICES**

BUILDING TYPE: ARENA						
BUILDING SYSTEM	COMPONENT	STATE	TRANSITION TIMES			EXPECTED SERVICE LIFE
			LL	CL	UL	
SITE SERVICES	Roads	A	2	3	6	20 years
		B	3	4	8	
		C	6	8	12	
		D	2	3	5	
		F	2	2	4	
	Curbs and Gutters	A	2	3	5	20 years
		B	3	5	7	
		C	5	7	10	
		D	3	3	8	
		F	2	2	5	
	Parking lots	A	2	3	6	20 years
		B	3	4	8	
		C	6	8	12	
		D	2	3	5	
		F	2	2	4	
	Exterior Steps and Ramps	A	3	5	7	30 years
		B	5	8	10	
		C	7	12	15	
		D	3	3	5	
		F	2	2	3	
	Fences and Gates	A	3	5	7	30 years
		B	5	8	10	
		C	7	12	15	
		D	3	3	5	
		F	2	2	3	
	Exterior Signs	A	2	3	5	20 years
		B	3	5	7	
		C	5	7	10	
		D	3	3	8	
		F	2	2	5	
	Site Furnishings	A	2	3	5	20 years
		B	3	5	7	
		C	5	7	10	
		D	3	3	8	
		F	2	2	5	
	Landscaping	A	3	5	7	30 years
		B	5	8	10	
		C	7	12	15	
		D	3	3	5	
		F	2	2	3	

APPENDIX C

BUILDING CONDITIONS DATA FOR AMBULANCE STATION

Building Conditions Report Generated from 2005 Inspection Data

Conditions Report:

Category Name:	Ambulance Station
Building Name:	AMB 106

Name	Current Condition (2005)	Next Year Condition	+ 5 Years	+10 Years
AMB 106: Ambulance Station #34	66.81	63.93	51.54	35.29
AMB 106s1: Foundations	46.12	44.08	35.4	24.14
AMB 106s1c1: Slabs on Grade	39.84	38.44	32.79	25.59
AMB 106s1c2: Walls	54.5	51.56	38.26	20.79
AMB 106s1c3: Grade Beams	54.5	51.56	38.26	20.79
AMB 106s2: Roofing	88.32	84.64	68.59	47.21
AMB 106s2c1: Roof Drainage	94.67	92.7	82.29	63.56
AMB 106s2c2: Membrane Roofing(ballast/insu)	84.5	78.67	53.29	22.8
AMB 106s2c3: Flashing/Sheet Metal	84.5	79.01	56.37	29.54
AMB 106s2c4: Roof Penetrations	99.12	98.58	95.17	88.05
AMB 106s2c5: Roof Sealants	84.5	79.01	56.37	29.54
AMB 106s2c8: Parapet Walls/Coping	84.5	79.56	61.71	43.37

AMB 106s3: Plumbing	65.15	62.1	49.39	33.36
AMB 106s3c1: Domestic Water Heaters	64.5	34.32	0	0
AMB 106s3c1e1: Water Heater #1	74.5	71.01	51.72	23.5
AMB 106s3c1e2: Water Heater #2	54.5	50.63	29.14	4.15
AMB 106s3c2: Piping Insulation	74.5	70.83	50.18	20.43
AMB 106s3c3: Sanitary Waste & Vent Piping	54.5	51.21	35.04	13.89
AMB 106s3c4: Domestic Water/Piping Systems	64.5	61.07	43.59	19.49
AMB 106s3c11: Backflow Devices	74.5	71.29	55.88	34
AMB 106s3c12: Rain Water Drain Pipe	54.5	51.21	35.04	13.89
AMB 106s3c13: Domestic Water Circ. Pump	74.5	70.83	50.18	20.43
AMB 106s3c8: Plumbing Fixtures	66.5	35.39	0	0
AMB 106s3c8e1: Water Closets	64.5	61.07	43.59	19.49
AMB 106s3c8e2: Urinals	54.5	50.73	30.83	6.68
AMB 106s3c8e3: Sinks	64.5	61.07	43.59	19.49
AMB 106s3c8e4:	74.5	71.11	54.26	30.23

Showers				
AMB 106s3c8e5: Basins	74.5	71.11	54.28	30.25
AMB 106s4: HVAC	74.5	71.58	58.53	40.63
AMB 106s4c1: Make Up Air Unit	74.5	70.39	42.34	6.21
AMB 106s4c2: Exhaust Fans	74.5	69.68	40.82	5.88
AMB 106s4c3: Supply & Return Ducts	74.5	71.71	59.62	43.4
AMB 106s4c4: Air Outlets & Inlets	74.5	70.94	52.37	25.75
AMB 106s4c5: Unit Heaters	74.5	71.11	48.11	14.29
AMB 106s4c7: Air Handling Unit	74.5	70.39	42.34	6.21
AMB 106s4c8: Boiler - Hot Water Heat	74.47	39.94	0	0
AMB 106s4c8e1: Boiler #1	94.45	93.24	87.38	77.72
AMB 106s4c8e2: Boiler #2	54.5	51.08	33.86	11.66
AMB 106s4c9: Circulation Pumps	74.5	70.39	42.34	6.21
AMB 106s4c10: Compressed Air Systems	74.5	70.97	50.55	20.67
AMB 106s5: Electrical System	67.15	65.55	56.45	41.1
AMB 106s5c1: Switchboards, Panelboards	66.41	64	54.17	41.41

AMB 106s5c2: Electrical Branch Wiring	64.5	63.87	56.44	39.81
AMB 106s5c3: Lighting (Interior & Exterior)	27.86	19.06	0	0
AMB 106s5c4: Emergency Lighting	74.5	72.7	55.3	23.69
AMB 106s5c6: Raceway &Boxes	64.5	62.99	49.11	23.45
AMB 106s5c7: Conductors&Cables	64.5	63.87	56.44	39.81
AMB 106s5c8: Main Elec. Switchboards	95	95.57	94.85	88.21
AMB 106s5c9: Elec. Branch Circ. Paneling	54.5	53.66	45.42	28.51
AMB 106s5c10: Motor Control Centers	74.5	73.22	60.94	36.35
AMB 106s5c11: Encl. Switches/Circuit	74.5	73.99	68.37	55.3
AMB 106s5c12-1: Telepnone equip/sys	77.77	75.33	64.32	47.7
AMB 106s6: Site Improvement/Services	63.41	60.35	47.75	32.08
AMB 106s6c1: Ext. Signage	74.5	71.4	55.2	31.09
AMB 106s6c2: Planters/landscape	64.5	61.05	43.55	19.46
AMB 106s6c3: Site Drainage	54.5	50.66	30.66	6.63

AMB 106s6c4: Barrier Free Access	74.5	71.4	55.2	31.09
AMB 106s6c5: Pedestrain Paving	44.5	40.57	20.82	1.31
AMB 106s6c7: Parking Lot	54.5	51.55	38.22	20.76
AMB 106s6c7-1: Fence	74.5	70.59	49.5	19.99
AMB 106s7: Exterior Enclosures	57.74	54.3	41.13	26.37
AMB 106s7c1: Mansonry Wall Const.	64.5	61.87	51.26	38.19
AMB 106s7c2: Portland Cement Plast.	7.05	3.56	0	0
AMB 106s7c3: Expansion Control	61.33	59.05	49.27	35.62
AMB 106s7c4: Joint Sealers	54.5	50.29	26.64	1.71
AMB 106s7c5: Painting	74.5	67.25	30.81	0
AMB 106s7c6: Ext. Wall Vapor/Insul.	64.5	60.24	36.96	8.07
AMB 106s7c7: Windows	64.5	61.17	43.88	19.7
AMB 106s7c10: External Doors	67.83	36.12	0	0
AMB 106s7c10e1: Entrance Doors	74.5	71.1	54.24	30.21
AMB 106s7c10e2: Utility Doors	54.5	50.65	30.63	6.62
AMB 106s7c10e3: Overhead Doors	74.5	71.4	55.2	31.09

AMB 106s8: Superstructure	52.83	50.24	39.63	26.55
AMB 106s8c1: Expansion Control	54.5	51.95	41.98	30.27
AMB 106s8c2: Floor Const.	44.5	41.96	31.96	20.39
AMB 106s8c3: Insulation/Air Barrier	54.5	51.95	41.98	30.27
AMB 106s8c4: Roof Struct. Frame	54.5	51.95	41.98	30.27
AMB 106s8c5: Columns/Supporting Roof	54.5	51.95	41.98	30.27
AMB 106s8c6: Interior Wall-Sup. Roof	54.5	51.95	41.98	30.27
AMB 106s9: Interior Const.	65.23	63.39	53.83	38.7
AMB 106s9c1: Int. Fixed Partitions	47.06	45.54	39.28	31.08
AMB 106s9c2: Interior Doors	74.5	75.35	64.15	32.43
AMB 106s9c4: Lockers	84.5	82.25	68.55	45.1
AMB 106s9c6: Stair Const.	47.06	45.54	39.28	31.08
AMB 106s9c7: Toilet Partitions/Access	74.5	70.83	50.18	20.43
AMB 106s9c8: Ceiling Const.	74.5	70.02	35.42	0
AMB 106s9c9: Floor Const.	54.5	50.29	26.64	1.71
AMB 106s10: Interior Finishes	68.13	65.17	52.48	35.9

AMB 106s10c1: Wall Finishes	56.5	30.01	0	0
AMB 106s10c1e1: Concrete Wall Finishes	44.5	41.46	27.63	10.71
AMB 106s10c1e2: Plaster Wall Finishes	44.5	41.46	27.63	10.71
AMB 106s10c1e3: Gypsum Board Wall Fin.	84.5	82.78	73.84	59.25
AMB 106s10c1e4: Tile Wall Finishes	44.5	40.43	18.83	0
AMB 106s10c1e5: Int. Wall Painting	64.5	59.38	28.61	0
AMB 106s10c2: Floor Finishes	62	33.06	0	0
AMB 106s10c2e1: Concrete Floor Finishes	54.5	50.61	30.55	6.59
AMB 106s10c2e2: Tile Floor Finishes	84.5	82.4	70	48.8
AMB 106s10c2e3: Resiliant Flooring	64.5	61.02	38.76	8.67
AMB 106s10c2e5: Floor Painting	44.5	40.63	16.88	0
AMB 106s10c3: Ceiling Finishes	79.5	42.43	0	0
AMB 106s10c3e1: Ceiling Paneling	74.5	69.68	40.82	5.88

AMB 106s10c3e2: Int. Ceiling Painting	84.5	81.02	57.28	20.68
AMB 106s10c4: Furnishings/Millwork	74.5	71.31	55.95	34.08
AMB 106s11: Other Equipment Mechanical	66.77	62.75	47.4	30.3
AMB 106s11c1: Food Storage/Freezer	59.05	54.29	32.7	0
AMB 106s11c2: Food Serv-Concess Equip.	74.5	70.12	45.67	13.2
AMB 106s12: Fire/Security	74.64	71.32	57.2	38.97
AMB 106s12c1: Detection/Fire Alarms	74.5	70.12	45.67	13.2
AMB 106s12c2: Smoke Alarm	74.5	71.38	50.36	18.16
AMB 106s12c3: Security Access/Surv.	74.5	69.28	34.2	0
AMB 106s12c4: Security Access	75.36	71.63	56.16	35.63
AMB 106s12c6: PA & Music Systems	74.5	69.28	34.2	0
AMB 106s12c7: Fire Extinguishers/Cabinets	74.5	70.37	46.27	13.47

Building Conditions Report Generated from 2001 Inspection Data

Category Name:	Ambulance Station
Building Name:	AMB: Ambulance Station 106

Name	2001 Condition	Current Condition (2005)	+ 5 Years	+10 Years
AMB: Ambulance Station 106		57.92	38.2	22.76
AMBs1: Foundations	65	55.48	43.41	30.05
AMBs1c1: Slabs on Grade	65	56.02	44.47	32.69
AMBs1c2: Walls	65	56.02	44.47	32.69
AMBs1c3: Grade Beams	65	52.3	44	35.07
AMBs2: Roofing	41.2	21.04	3.4	0
AMBs2c1: Roof Drainage	35	6.78	0	0
AMBs2c2: Membrane Roofing(ballast/insu)	35	6.78	0	0
AMBs2c3: Flashing/Sheet Metal	45	18.93	0	0
AMBs2c4: Roof Penetrations	55	70.69	56.9	40.52
AMBs2c5: Roof Sealants	45	18.93	0	0
AMBs2c6: Parapet Walls/Coping	45	35.19	23.64	13.25
AMBs3: Plumbing	77.89	61.54	41.24	24.97
AMBs3c1: Domestic Water Heaters	85	65.16	0	0

AMBs3c1e1: Water Heater #1	95	80.78	54.02	25.73
AMBs3c1e2: Water Heater #2	75	49.53	17.09	0
AMBs3c2: Piping Insulation	75	52.78	19.09	0
AMBs3c3: Sanitary Waste & Vent Piping	65	48.6	27.72	10.14
AMBs3c4: Domestic Water/Piping Systems	85	86.86	75.66	61.37
AMBs3c5: Backflow Devices	85	71.93	52.49	32.15
AMBs3c6: Rain Water Drain Pipe	65	48.6	27.72	10.14
AMBs3c7: Domestic Water Circ. Pump	85	62.33	30.63	6.1
AMBs3c8: Plumbing Fixtures	77	60.17	0	0
AMBs3c8e1: Water Closets	75	57.36	33.36	12.37
AMBs3c8e2: Urinals	65	45.57	21.59	4.19
AMBs3c8e3: Sinks	75	57.36	33.36	12.37
AMBs3c8e4: Showers	85	70.28	48.11	25.7
AMBs3c8e5: Basins	85	70.26	48.08	25.68
AMBs4: HVAC	92.05	72.1	48.55	29.54
AMBs4c1: Make Up Air Unit	95	76.05	42.09	11.46
AMBs4c2: Exhaust Fans	85	59.59	24.17	1.4
AMBs4c3: Supply & Return Ducts	95	86.67	79.05	69.84

AMBs4c4: Air Outlets & Inlets	85	68.49	44.02	20.41
AMBs4c5: Unit Heaters	95	76.05	42.09	11.46
AMBs4c6: Air Handling Unit	95	76.05	42.09	11.46
AMBs4c7: Boiler - Hot Water Heat	80	65.46	0	0
AMBs4c7e1: Boiler #1	95	84.03	67.29	49
AMBs4c7e2: Boiler #2	65	46.88	23.99	6.2
AMBs4c8: Circulation Pumps	95	76.05	42.09	11.46
AMBs4c9: Compressed Air Systems	85	63.25	34.65	10.99
AMBs5: Electrical System	83.55	66.81	47.94	30.94
AMBs5c1: Switchboards, Panelboards	85	71.51	51.9	31.67
AMBs5c2: Electrical Branch Wiring	75	58.96	37.1	16.94
AMBs5c3: Lighting (Interior & Exterior)	75	39.23	2.51	0
AMBs5c4: Emergency Lighting	75	52.57	23.29	2.97
AMBs5c5: Raceway &Boxes	75	59.18	37.37	17.11
AMBs5c6: Conductors&Cables	75	64.5	46.41	25.65
AMBs5c7: Main Elec. Switchboards	100	96.9		
AMBs5c8: Elec. Branch	85	74.34	60.04	45.07

Circ. Paneling				
AMBs5c9: Motor Control Centers	85	68.56	47.8	28.27
AMBs5c10: Encl. Switches/Circuit	85	74.34	60.04	45.07
AMBs5c11: Telepnone equip/sys	85	71.99	52.58	32.22
AMBs6: Site Improvement/Services	76.9	62.02	43.43	27.43
AMBs6c1: Ext. Signage	95	85.5	68.19	47.86
AMBs6c2: Planters/landscape	85	72.03	52.63	32.26
AMBs6c3: Site Drainage	65	46.73	23.85	6.15
AMBs6c4: Barrier Free Access	85	71.51	51.9	31.67
AMBs6c5: Pedestrain Paving	55	33.91	9.47	0
AMBs6c6: Parking Lot	65	51.59	34.07	17.72
AMBs6c7: Fence	85	68.65	44.21	20.53
AMBs7: Exterior Enclosures	82.2315	60.19	39.5	23.41
AMBs7c1: Mansonry Wall Const.	75	54.29	45.78	36.58
AMBs7c2: Portland Cement Plast.	75	62.76	45.85	28.71
AMBs7c3: Expansion Control	75	64.42	48.22	30.75
AMBs7c4: Joint Sealers	65	32.67	2.03	0
AMBs7c5: Painting	95	62.47	18.19	0

AMBs7c6: Ext. Wall Vapor/Insul.	75			
AMBs7c7: Windows	95	86.7	71.49	53.23
AMBs7c8: External Doors	77.55	63.56	45.03	28.74
AMBs7c8e1: Entrance Doors	85	72.03	52.63	32.26
AMBs7c8e2: Utility Doors	65	47.14	24.24	6.28
AMBs7c8e3: Overhead Doors	85	71.51	51.9	31.67
AMBs8: Superstructure	64.6	55.01	43.3	30.11
AMBs8c1: Expansion Control	65	56.82	46.44	35.79
AMBs8c2: Floor Const.	55	45.99	34.93	24.16
AMBs8c3: Insulation/Air Barrier	65	56.82	46.44	35.79
AMBs8c4: Roof Struct. Frame	65	56.82	46.44	35.79
AMBs8c5: Columns/Supporting Roof	65	56.82	46.44	35.79
AMBs8c6: Interior Wall-Sup. Roof	65	56.82	46.44	35.79
AMBs9: Interior Const.	81.2	59.01	40.26	24.8
AMBs9c1: Int. Fixed Partitions	65	56.82	46.44	35.79
AMBs9c2: Interior Doors	95	71.89	44.93	22.36
AMBs9c3: Lockers	95	72.78	48.13	27.73
AMBs9c4: Stair Const.	65	56.82	46.44	35.79

AMBs9c5: Toilet Partitions/Access	95	65.03	36.49	11.77
AMBs9c6: Ceiling Const.	100	82.72		
AMBs9c7: Floor Const.	65	7.05	0	0
AMBs10: Interior Finishes	81.0625	62.88	41.43	24.66
AMBs10c1: Wall Finishes	68	50.1	0	0
AMBs10c1e1: Concrete Wall Finishes	55	40.75	23.08	8.4
AMBs10c1e2: Plaster Wall Finishes	55	40.75	23.08	8.4
AMBs10c1e3: Gypsum Board Wall Finishes	100	97.84		
AMBs10c1e4: Tile Wall Finishes	55	26.87	1.64	0
AMBs10c1e5: Int. Wall Painting	75	44.31	9.45	0
AMBs10c2: Floor Finishes	81.25	65.43	0	0
AMBs10c2e1: Concrete Floor Finishes	75	46.8	23.91	6.17
AMBs10c2e2: Tile Floor Finishes	100	97		
AMBs10c2e3: Resiliant Flooring	75	71.5	44	8.17
AMBs10c2e4: Floor Painting	75	44.31	9.45	0
AMBs10c3: Ceiling Finishes	90	64.26	0	0
AMBs10c3e1: Ceiling	85	59.59	24.17	1.4

Paneling				
AMBs10c3e2: Int. Ceiling Painting	95	68.94	35.23	9.09
AMBs10c4: Furnishings/Millwork	85	71.7	52.17	31.89
AMBs11: Other Equipment Mechanical	85	63.5	38.14	20.43
AMBs11c1: Food Storage/Freezer	85	63.5	31.67	6.37
AMBs11c2: Food Serv-Concess Equip.	85	63.5	31.67	6.37
AMBs12: Fire/Security	90.1	64.19	37.09	18.87
AMBs12c1: Detection/Fire Alarms	85	63.5	31.67	6.37
AMBs12c2: Smoke Alarm	95	76.05	42.09	11.46
AMBs12c3: Security Access/Surv.	85	50.07	10.65	0
AMBs12c4: Security Access	95	83.12	65.76	44
AMBs12c5: PA & Music Systems	85	50.07	10.65	0
AMBs12c6: Fire Extinguishers/Cabinets	85	62.33	30.63	6.1