A KNOWLEDGE-BASED DECISION SUPPORT SYSTEM IN RELIABILITY-CENTERED MAINTENANCE OF HVAC SYSTEMS

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A Knowledge-Based Decision Support System in Reliability-Centered Maintenance of HVAC Systems

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Abstract

Studies have shown that in large physical systems, it is possible to eliminate or reduce costly machine failures, equipment downtime, lost production and decreased revenues by keeping abreast of the most effective and current maintenance techniques available.

The purpose of this thesis is to propose a multi-faceted approach to maintenance which can address the short comings of conventional approaches to maintenance.

The proposed methodology combines the reliability-centered maintenance technique (RCM), a fault tree analysis, a database system, and the Weibull analysis. The integration of these techniques produces an innovative system which increases the reliability and availability of the system. To the author's knowledge, this integrated approach has not been done before.

As an example, the heating, ventilating and air conditioning (HVAC) of large buildings was used to illustrate this methodology. Failure data was collected from the Biotechnology, Arts and Administration Extension and Earth Resources Buildings of

Memorial University of Newfoundland (CERR) over a six year period. The data included the time to failure and failure modes for each component within the central HVAC system. The collected data was used to quantify the reliability of the system. A probabilistic analysis based on the Weibull distribution was used to analyze the time to failure data.

Using reliability-centered maintenance to identify the causes and impact of failures. the information acquired was used to develop fault trees. Failure modes identified in the fault trees were coded as identifiers to be used in a knowledge-based system for improving the reliability and availability of the system and its components.

It was shown that system reliability can be improved by increasing the reliability of each component utilizing the proposed multi-faceted approach. Failure data analysis enabled us to quantify the reliability for many sub-components within the major components that constitute the HVAC system.

It is concluded that the developed knowledge-based system enables us to troubleshoot causes of failure at a much faster rate and this will decrease the down time and increase the availability of the system.

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List of Symbols, Abbreviations, and Acronyms

A(T)	Availability
AFFPA	Air Filter Failure
AHU#	Air Handling Unit Number
ARTS/EXT	Arts and Administration Building Extension of MUN
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
ATAA	Air Transport Association of America
Cause_ID	Cause Identification
CCC^2	Square of 90% Critical Correlation Coefficient
CCSF	Computer Control System Failure
CDF	Cumulative Distribution Function
CERR	Earth Resources Building of Memorial University of Newfoundland
CSF	Cooling System Failed
EP	Electric- pneumatic
EPRF	Electric-pneumatic Relay Failure
f(t)	failure density
F(t)	failure distribution
FAA	Federal Aviation Agency
FAD	Fresh Air Damper
FDNO	Fan Does Not Operate

List of Symbols, Abbreviations, and Acronyms - continued

FN	Fan Noise
FPS	System Failure due to Freeze Protection System being Activated
GVU	General Ventilating Unit
h(t)	hazard function
HAF	High Air Flow
HSF	Heating System Failed
HVAC	Heating, Ventilating and Air Conditioning
ISAF	Insufficient Air Flow
LMU	Laboratory Makeup Unit
LVU	Laboratory Ventilating Unit
m_M	mean times to perform maintenance
m_R	mean times to perform the repair
MRB	Maintenance Review Board
MSG	Maintenance Steering Group
MTI	Maintenance Technology International of Calgary
MUN	Memorial University of Newfoundland
n/s	Number of units under study and number of units that are suspended
PCHP	Power Consumption High
PMP	Premature Failure

List of Symbols, Abbreviations, and Acronyms - continued

Problem_ID	Problem Identification
r	Correlation coefficient, used to measure the strength of a linear relationship between two variable
R(t)	reliability = 1-F(t)
R(t) AF	Reliability for Air Filter
R(t) CCSF	Reliability for Computer Control System
R(t) CFP	Reliability for Coil Freeze Protection System
R(t) CS	Reliability for Cooling System
R(t) FA	Reliability for Fan Assembly
R(t) FAD	Reliability for the Fresh Air Damper
R(t) FAN	Reliability for Fan
R(t) FB	Reliability for Fan Belts
R(t) FBG	Reliability for Fan Bearing
R(t) FM	Reliability for Fan Motor
R(t) FVV	Reliability for Fan Vortex Vane
R(t)HS	Reliability for Heating System
R(t)S	Reliability for the System
RCM	Reliability Centered Maintenance
SHL	Space Humidity Low
SPH	Static Pressure High
SPL	Static Pressure Loss

List of Symbols, Abbreviations, and Acronyms - continued

symptoms_ID	Symptoms Identification
t	failure time
T_e	the expected time to perform emergency maintenance
T_m	the expected time to perform minimal repair
T_s	the expected time to perform scheduled maintenance
VAV	Variable Air Volume
W/rr	Weibull analysis using least square method
WIF	What IF
WO#	Work order number
β	slope or shape parameter of Weibull distribution
e	2.718281828, the base for natural logarithms
η	characteristic life or scale parameter of the Weibull distribution in time unit

Chapter 1 Introduction

1.1 Problem Identification

1.1.1 Need for an Integrated Approach to the Maintenance of Large Systems

Large systems such as the heating, ventilating and air conditioning system (HVAC) in a large building, such as a hospital or university, normally consist of thousands of components that are interconnected. Failure of such systems can be catastrophic especially in intensive care wards, operating rooms, or in sensitive research laboratories. It is essential that such systems are properly maintained and work reliably. By keeping abreast of the most effective and current maintenance techniques available, we can eliminate or reduce costly machine failures, equipment downtime, lost production and decreased revenues. Statistics published by Maintenance Technology International of Calgary (MTI) (n.d.) have identified large unnecessary expenditures resulting from a lack of maintenance. In Canada, five billion dollars are spent because of poor lubrication practices which can be easily resolved, but which are ignored because maintenance personnel tend to think these problems are normal. In addition, two hundred billion dollars are lost annually by North American companies due to wear caused by inadequate maintenance.

Other factors that contribute to high maintenance costs are inappropriate inspection schedules, incorrect servicing, poor cost accounting, improper use of preventive maintenance techniques, poor lubricant selection and application, poor contamination control methods and inadequate use of maintenance staff.

In recent years, industry expectation of maintenance and maintenance techniques has changed enormously. During the 1940's and the 1950's, the policy was "fix it when it breaks". During the 1960's and the 1970's, the techniques used were scheduled overhauls (Moubray, 1991) with planning and control of work being achieved using big and slow computers. In the meantime, industry demanded higher plant availability, longer equipment life, and lower costs. During the 1980's and 1990's, the industry expectations shifted towards higher plant availability and reliability, greater safety, better product quality, less damage to the environment, longer equipment life, and greater cost effectiveness. To meet the new demands, new maintenance techniques have been developed, including: condition monitoring, design for reliability and maintainability, hazard studies, and failure modes and effects analyses. Other techniques such as expert systems, multiskilling, and teamwork have not been used effectively because very often they are used in isolation from each other. There have been many research papers written on maintenance of individual pieces of equipment using specific techniques but detailed maintenance studies of large systems are limited and are usually confined to specific projects for specific industries. There is a need to study the integration of design, construction, operation, maintenance and redesign of large systems using a number of currently available techniques. This integrated approach is supported by Moore and Rath (1999) and Tesdahl and Tamlingson (1998).

In view of the urgent need for a rational approach to maintenance of large systems, this thesis proposes a multi-faceted approach to maintenance which will prove to be more reliable than current practices.

1.1.2 Current Problems with HVAC Systems

In Canada, every built environment has a Heating, Ventilating and Air-Conditioning system in place. Hospital operating rooms, for example, require special HVAC systems to maintain positive pressure and to stop bacteria from contaminating the internal environment. On the other hand, laboratory HVAC systems maintain negative pressure in order to avoid bacteria propagation to other areas. The HVAC systems for office towers became a major concern in recent years because of the Indoor Air Quality issue as stated by Morey (1988) and Chow (1987). The number of related complaints has increased with the construction of tighter sealed buildings, the growing use of synthetic materials, and the application of energy conservation measures that reduce the amount of outside air being circulated. Modern office equipment (photocopiers, laser printers, computers etc.), cleaning products, and the outdoor air pollution can also increase the levels of indoor air contamination. The reactions to indoor contaminants have led to the phenomenon of sick building syndrome. Therefore, there is a definite need to ensure that HVAC systems are functioning properly at all times during the occupancy period and that unscheduled shutdowns are minimized.

Maintenance experts who are capable of analyzing and solving HVAC problems are in short supply. Most engineers learn through on-the-job training in this area. The HVAC area requires solid fundamental knowledge of applied thermodynamics, heat transfer, fluid mechanics, and fluid power. Further, at the operator level, training is limited by the absence of solid fundamentals in the training programs. As a result, most of the HVAC systems are poorly operated or maintained, and many owners and end users do not believe they can work as efficiently as promised.

1.1.3 Maintenance Aspects of HVAC Systems

Smith (1993) states that, in most locations, proactive maintenance is less than sufficient in current practice. In order to ensure increased productivity and efficiency, there must be a proper proactive maintenance program in place. The need for repetitive correction is a concern as many companies do not have a system in place to track down recurring problems. Rather than finding the source of the problem, only the apparent symptom is corrected. Broussard (1994) described the methodology used to preserve failure data and then used it in conducting Root Cause Failure Analysis (RCFA). This is a very important step used for continuous quality improvement in the maintenance of systems. Often times, maintenance is carried out in a haphazard fashion and areas that should be of concern are overlooked in favour of obvious problems. In addition, within companies, maintenance practices in one area will vary significantly from those in another area (i.e., separate buildings). Maintenance practices within an organization should be consistent.

At times, maintenance is carried out by people who are not thoroughly familiar with the intended function of each component. As a result, they do not maintain equipment functions at their designed levels. Scheduled maintenance can often be both unnecessary and conservative. Maintenance items lower on a scale of importance may get much attention due to the ease of doing it, whereas those areas requiring more attention and hence more work, are relegated to a less consistent schedule. Likewise a company may avoid preventative maintenance as it may be erroneously perceived as too great a cost.

If preventative maintenance is to be successful, it must be visible and recorded on an operating time basis. Hence, it can be referenced for its effectiveness and altered to suit the actual maintenance that is required over time. A company should set up its own maintenance program which exceeds or falls short of manufacturer's recommended maintenance input based on actual operating conditions. There is often a variance between maintenance of similar units.

There should be standard procedures and checkpoints in place for maintenance of identical units. Predictive maintenance methodology presently is currently rarely used in HVAC systems.

Reliability-Centered Maintenance methodology that requires a combination of engineering and technical skills, as well as management awareness and motivation, offers the most systematic and efficient process to address an overall programmatic approach to optimization of HVAC systems. A solution to many of the problems associated with the HVAC systems would reduce sickness, create a better working environment, reduce energy consumption, and lower maintenance cost. Therefore, there is an immediate need to develop an expert system to help owners and users optimize the function of HVAC systems.

1.2 Aims and Objectives

To address the common maintenance problems stated in Section 1.1, the aim of this work is to integrate RCM (Reliability-Centered Maintenance) techniques with a knowledge-based system techniques to provide decision-support for optimizing HVAC systems availability, and lowering maintenance costs. The detailed objectives of this thesis are:

- To apply the RCM maintenance program which simultaneously reduces both the probability of critical failure in HVAC systems and maintenance costs by reducing scheduled maintenance.

- To develop a decision-support tool for optimized operational and maintenance procedures.

- To provide a tool to enable maintenance personnel to understand the functions and performance standards of installed HVAC systems.

- To provide a tool to promote total integration of design, construction, set up commissioning, operation and maintenance of HVAC systems.

- To promote predictive and preventive maintenance tasks in lieu of the conventional definite time span maintenance.

1.3 Outline of Thesis

The background of the thesis has been presented in the previous section along with the objectives of the study. The following chapter reviews the relevant literature as it relates to RCM, fault tree analysis, planned maintenance, conditional based maintenance and redesign, the new paradigm for maintenance management, the root cause failure analysis, and to knowledge-based systems.

Application of RCM to acquire the functions and performance standards of the installed HVAC system will identify the intended function and the functional failure mode, and at the same time observe the cause and effect of the failure mode. The acquired information from RCM is transformed into graphical representation using a fault tree. This graphical representation is easy to use by the operation and maintenance personnel. Based on the fault tree, mathematical models are developed to determine the component failure caused by the various failure modes. The failure modes are coded and stored in a data base system. The coded failure modes are combined with Weibull analysis using collected failure data to predict the probability of failure. This method quantifies the failure mode based on actual usage and therefore is more scientific than the scheduled maintenance method. The developed data base system can be used as a decision tool for trouble shooting. To illustrate this methodology, failure data was collected and analysed from HVAC systems located in three buildings at Memorial University of Newfoundland. This established the parameters for Weibull distribution and the failure modes for the knowledge-based system. The results of the analysis point out the impact of design and construction on the reliability of the system, and how this affects the maintenance and operation of the system. This analysis also points out the misuse of conditional based techniques and how effective use of predictive and conditional based techniques can be used to optimize the system reliability.

Chapter 2 Review of Literature

In order to fulfill the research objectives outlined in Section 1.2, a review of literature was necessary to gain the state of the art knowledge in this particular area. This chapter summarizes the literature review in maintenance cost, RCM, Expert Systems, and optimization techniques as related to the development of a RCM Expert System.

2.1 Maintenance Cost

Estimating maintenance costs was discussed by Howell and Kluczny (1982) who pointed out that two approaches may be used by HVAC maintenance decision makers to derive the necessary maintenance cost information: the Engineering Requirements Method and the Historical Data Method. The Engineering Requirements Method establishes the type and timing of the maintenance effort from an engineering analysis of the system components. Using this approach, the rate of component deterioration must be calculable in order to arrive at reliable estimates of system failure costs. Unfortunately, this method is very difficult to implement due to the high cost of performing engineering analyses, and the lack of reliability specifications from vendors. The second approach is to rely on historical data to project future costs. The data may be the experience of a single user analyzing his or her own data or it may be the accumulated experience of many users sharing their data in a data base. This method offers a practical alternative to the Engineering Requirements Method for most HVAC owner/operators. Unfortunately, it is not without its own disadvantages such as the availability, accuracy, and consistency of historical data.

Dohrmann and Alereza (1986) obtained maintenance costs and HVAC system information from 342 buildings located in 35 states in the United States. In 1983 U.S. dollars, data collected showed a mean HVAC system maintenance cost of $\$3.40/m^2$ per year, with a median cost of $\$2.60/m^2$ per year. The age of the building has a statistically significant but minor effect on HVAC maintenance costs. When analyzed by geographic location, the data revealed that location does not significantly affect maintenance costs. Analysis also indicated that building size is not statistically significant in explaining cost variation. The equation of Dohrman & Alereza is given by:

C = total annual building HVAC maintenance cost ($\$/m^2$)

$$= \$3.59/m^2 + 0.019n + h + c + d \quad \textbf{(2.1)}$$

where,

$\$3.59/m^2$	=	base system maintenance costs
0.019	=	age adjustment factor
n	=	age in years
h	=	heating system adjustment factor h
c	=	cooling system adjustment factor c
d	=	distribution system adjustment factor d

Values for adjustment factors h, c, and d can be obtained from the 1999 ASHRAE Handbook (SI) on page 35.4.

The estimate can be adjusted to current dollars by multiplying the maintenance cost estimate by the current Consumer Price Index (CPI) divided by the CPI in July 1983. In July 1983, the CPI was 100.1. Monthly CPI statistics are recorded in Survey of Current Business (U.S. Department of Commerce). The estimating method is limited to one equipment variable per situation. That is, the method can estimate maintenance costs for a building having either a centrifugal chiller or a reciprocating chiller, but not both. Assessing the effects of combining two or more types of equipment within a single category requires a more complex statistical analysis.

Wolfson Maintenance (1998) states that decisions made at an early stage in the concept and design of an item in a plant can have significant effects on the cost of running that piece of equipment throughout its life (Figure 2.1).

In the preliminary design review stage, 15% to 35% of the life cycle costs have been determined. In the concept design review stage, 25% to 40% of the life cycle costs have been determined In the critical design review stage, 95% of the life cycle costs have been determined.

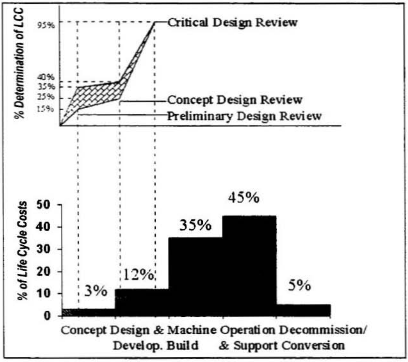


Figure 2.1 **Life Cycle Costs**

The designer must be aware of the consequences of his/her decisions. If for instance, a bearing is installed in an inaccessible position, that bearing will certainly have to be changed a number of times during the life time of the equipment. Due to the difficulty of access, excessive replacement costs will be incurred. If this inaccessible position is unavoidable, the installation of a top quality and/or an oversize bearing, will increase the purchase costs but may reduce the overall life cycle cost. The same applies during the operating life in the purchasing of spare parts, maintenance tools, and training of operators and maintainers.

2.2 Reliability-Centered Maintenance (RCM)

2.2.1 Overview

Reliability is the probability that a plant or component will not fail to perform according to certain specifications during a given time period working in a stated environment. Reliability-Centered Maintenance (RCM) implies that the maintenance function must be focused on assuring reliability in equipment and systems. RCM calls for an analysis for determining maintenance needs.

RCM grew from studies carried out during the development of the Boeing 747. This work showed that the failure modes of aircraft components are randomly dominated. At this time aircraft maintenance was based predominately on flying hours, therefore, a new method of maintaining aircraft was considered appropriate.

The RCM approach assumes no prior knowledge of the components, a so-called zero-based or first principles approach. Each component in the aircraft was systematically analyzed to identify their failure modes (causes of failure) and appropriate maintenance tasks were then assigned. Moubray (1991) states that this analysis is carried out by asking the following seven questions about each asset:

(1) What are the functions and associated performance standards of the asset in its present operating context?

(2) In what ways does it fail to fulfill its functions?

(3) What causes each functional failure?

(4) What happens when each failure occurs?

(5) In what way does each failure matter?

(6) What can be done to prevent each failure?

(7) What if a suitable preventive task cannot be found?

These questions are required in order to fully capture the information needed to design the appropriate maintenance regime.

2.2.2 Development of RCM

In the late 1950's, the FAA (Federal Aviation Agency),which was responsible for regulating airline maintenance practices in the U.S.A., was frustrated by experiences showing that it was not possible to control the f(t) (failure density) of certain unreliable types of engines by any feasible changes in either the content or frequency of scheduled overhauls. In 1960 a task force was formed consisting of representatives from both the FAA and airlines to investigate the capabilities of preventive maintenance. As a result, a FAA/Industry

Reliability Program was established, the mandate of which was to develop a program towards the control of reliability through an analysis of the factors that affect reliability. This approach was a direct challenge to the traditional concept that the length of time between successive overhauls of an item was an important factor in controlling its failure rate. The findings of this study were :

1. Scheduled overhaul has little effect on the overall reliability of a complex item unless the item has a dominant failure mode (cause of failure).

2. There are many items for which there is no effective form of scheduled maintenance.

A rudimentary decision-diagram technique was devised in 1965 and in June 1967 a paper on its use was presented at the ATA Commercial Aircraft Design and Operation Meeting. The recommendations were included in ATA (1969).

In 1974, the United States Department of Defence commissioned United Airlines to prepare a report on the processes used by the civil aviation industry to prepare maintenance programs for aircrafts. The resulting report, known as MSG-1 (Maintenance Steering Group), was used by special teams of industry and FAA personnel to develop the first scheduled-maintenance program based on the principles of Reliability-Centered Maintenance. Use of the decision-diagram technique led to further improvements which were incorporated two years later in a second document, MSG-2. The objective of the techniques outlined in MSG-1 and MSG-2 was to develop a scheduled-maintenance program that assured the maximum safety and reliability at the lowest cost. Commenting on the MSG-1 and MSG-2 documents, Nowlan and Heap's 1978 report stated that:

> "Although the MSG-1 and MSG-2 documents revolutionized the procedure followed in developing maintenance programs for transport aircraft, their application to other type of equipment was limited by their brevity and specialized focus. In addition, the formulation of certain concepts was incomplete. For example, the decision logic began with an evaluation of proposed tasks, rather than an evaluation of the failure consequences that determine whether they are needed, and if so, their actual purpose. The problem of establishing task intervals was not addressed, the role of hidden-function failure was unclear, and the

treatment of structural maintenance was inadequate. There was also no guidance on the use of operating information to refine or modify the initial program after the equipment entered service or the information systems needed for effective management of the on-going program. All these shortcomings, as well as the need to clarify many of the underlying principles led to analytic procedures of broader scope and their crystallization into the logical discipline now known as Reliability-Centered Maintenance."

RCM is known as MSG-3 within the aviation industry, and to this date it remains the process used to develop and refine maintenance programs for all major types of aircrafts.

Currently three versions of the RCM decision diagram are in wide use. The first is shown on pages 91 and 92 of the report by Nowlan and Heap (1978). The second version of the decision diagram is the official MSG-3 version currently used by the civil aviation industry. It is shown as the

"System/Powerplant Logic Diagram" on pages 6 and 7 of the Maintenance Program Development Document published by the ATAA (Air Transport Association of America) (1988). In recent years, the environment became more and more of an issue. In 1990, the addition of the question, "Does this failure mode cause a loss of function or other damage which could breach any known environmental standard or regulation?" to the RCM decision diagram warranted changing its name to RCM 2.

2.2.3 What is Reliability-Centered Maintenance?

The Reliability Centered Maintenance process involves the application of a number of investigative procedures to each of the selected systems.

Foremost among these is the determination of the functions and associated performance standards of the system in its current operating context. This includes the full range of functions (primary, secondary, protective devices, and superfluous functions): the inherent reliability or built-in capability of the system: other standards including product quality, safety, energy efficiency and operating environment: operating occupancy patterns: and operating context (i.e., stand-alone versus stand-by duty).

Functional failure - or the manner in which, and the extent to which, a system fails to meet a desired standard of performance, whether the failure be partial or total - must likewise be investigated. Having ascertained the manner and extent of failure, it then becomes critical to identify the probable root cause(s) of the particular functional failure mode. Failure modes, and the operating context in which they occur, should be indicated.

The process of analyzing the extent and the effects of a failure must cover the full spectrum from the evidence (if any) that a failure has occurred through to the procedures necessary to effect repair. Full consideration must be given to the actual or the potential threat to safety or to the environment, the anticipated range of potential effects on production and operational activity, and the actual or potential physical damage resulting from the failure. The consequences of a functional failure will depend, to some extent, on whether the failure is obvious or hidden but, in either case, there will be potential effects relating to safety and the environment, operational activities and non-operational activities.

Predictive and corrective maintenance must be accompanied by effective preventive maintenance procedures, including on-condition tasks, restoration tasks, and replacement tasks. An equally important component is the establishment of a course of action to pursue in the event that no suitable preventive maintenance activity can be identified. This may include default actions such as reassessing the system design or even redesigning the system, in part or in its entirety.

2.2.4 Difference Between RCM and Planned Maintenance

RCM is a process used to determine the maintenance requirements of any physical asset in its operating context by identifying the functions of the asset, the causes of failures, and the effects of the failures. RCM advocates Condition Base Maintenance (CBM) and reassessing the system design (Redesign). Planned maintenance involves identifying (1) what inspection and/or servicing tasks are to be done and (2) when each task should be done to retain the functional capabilities of operating equipment or systems. Planned maintenance usually does not include on-condition monitoring or the reassessment of system design. Planned maintenance is the most widely used form of maintenance. It is based on the concept that every item on a piece of complex equipment has a "right age" at which complete overhaul is necessary to ensure safety and operating reliability. It is most effective if implemented as equipment begins to wear out and failure probability increases. Planned maintenance tasks are often grouped together into maintenance downtime or windows to minimize the total number of planned maintenance stoppages per year. This strategy is seriously flawed because the majority of industrial failure modes are random in nature and so maintenance tasks based on time will have limited effect in improving equipment performance.

CBM relies on the fact that the majority of failures do not occur instantaneously but develop over a period of time as shown in Figure 2.2 P-F Curve.

The P-F curve shows how a failure starts. deteriorates to the point at which it can be detected (the potential failure point "P"). if it is not detected and corrected. continues to deteriorate - usually at an accelerated rate - until it reaches the point of functional failure ("F"). The P-F interval can be known as the "Lead Time To Failure". CBM involves recording some measurement that gives an indication of machine condition (e.g., temperature increase on an insulation surface. vibration increase on a bearing housing). An investigation can then be carried out to identify the exact problem.

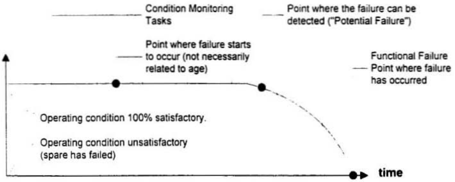


Figure 2.2 P-F Curve

Redesign (or design out) can prove to be a very effective method of solving a recurring problem. However it can easily be inappropriately utilized. Putting in a more powerful motor due to frequent tripping may be an ill-thought out reaction to malpractice by an operator, whilst simple instruction may solve the same problem. Before considering designing out a problem, it is important to identify exactly what the root cause of the problem is. Having identified the root cause, is it possible to monitor the condition at this problem area? If so, it may be cost effective to monitor the condition and take action as necessary. If this is not the case, can the problem be redesigned? If it can, what will this involve and can it have any adverse effects elsewhere? Once the procedure has been thoroughly developed, the redesign procedure should be accepted. Finally, redesign implies that mistakes or oversights were made during the original design of the equipment.

Wolfson Maintenance (1998) stated the advantages and disadvantages of planned maintenance, CBM, and redesign and are listed in Table 2.1.

Table 2.1 Comparison of Planned maintenance, CBM, and Redesign (After Wolfson, 1998)

	Planned Maintenance	CBM	Redesign
Advantages	- Failure reduced. - Labor used cost-effectively. - Maintenance planned well in advance (provision for labour and material).	- Maximizes equipment availability. - Some forms of inspection utilizing human senses can be inexpensive. - Allows shutdown before severe damage occurs. - Production can be modified to extend unit life. - Cause of failure can be analyzed. - Maintenance can be planned - Labour can be organized. - Spares can be assembled.	- Some minor design out projects can be inexpensive and guaranteed to work. - A recurring problem can be completely resolved.
Dis-advantages	- Maintenance activity and costs increased. - Unnecessary and invasive maintenance is carried out. - Applicable only to age related deterioration. - Maintenance sometimes induces failures (infant mortality).	- Vibration monitoring, Thermograph and Oil Debris Analysis require specialized equipment and training. A company must carefully choose the correct technique. A period of time will be required for trends to develop and then machine condition can be assessed.	- The root cause of the problem may get missed in the exercise. - Larger design out projects can prove to be very expensive - Production can be disrupted for a considerable period of time with larger projects. - The expected result may not materialize. - Solving a problem in one area may overload and cause problems in another.

2.2.5 Extending the RCM Method to Other Complex and Critical Systems

In response to the problem, airplane designers began to develop design features that mitigated failure consequences - that is, how to design airplanes that were "failure tolerant". Further, RCM has been applied to both the aircraft and the offshore platform industries resulting in cost reductions with no decrease in reliability. However, a better understanding of the failure process in the complex equipment has actually improved reliability by making it possible to direct preventive tasks at specific evidence of potential failures. Based on the findings of years of study by the aircraft industry, such as the MSG-1 program for the Boeing 747, United Airline expended only 66,000 man hours on major structural inspections before reaching a basic interval of 20,000 man hours for the first heavy inspections of this airplane. Under traditional maintenance policies, it took more than 4 million man hours to arrive at the same structural inspection interval for the smaller and less complex Douglas DC-8. Cost reductions of this magnitude are of obvious importance to any organization responsible for maintaining large fleets of complex equipment. Tesdahl and Tomlingson (1998) stated that the 21st Century will usher in a broader need for equipment management, a cradle to grave strategy to preserve equipment functions, avoid the consequences of a failure and ensure the productive capacity of equipment. They also asserted that RCM should be applied to the mining industry. It is beneficial to apply RCM to other industries such as the HVAC industry to minimize cost, increase availability and improve environmental conditions.

2.2.6 Mathematical Aspects of Reliability-centered Maintenance

There are three main mathematical aspects of Reliability-Centered Maintenance discussed by H.L. Resnikoff (1978). The first corresponds to the partitioning of the system into sets of items that are functionally related by means of the consequences of their failure. The second is the formal expression of the costs of maintenance and consequences of failure in common terms of direct and imputed costs. The principal purpose of the maintenance policy designer is to minimize the maintenance/failure cost function. The third mathematical aspect models the iterative procedure used in the Reliability-Centered Maintenance program to minimize the total cost function.

2.2.7 Combining Total Productive Maintenance and RCM

Total Productive Maintenance (TPM) was developed in Japan and is a strategy for improving productivity through improved maintenance and related practices. TPM calls for: restoring equipment to a like-new condition, operator involvement in maintaining equipment, improving maintenance efficiency and effectiveness, training people to improve their job skills, equipment management and maintenance prevention, and the effective use of preventive and predictive maintenance technology. Moore and Rath (1999) pointed out that a combination of TPM and RCM efforts has lead to an improved process for facilitating teamwork between the maintenance and production functions, to improved equipment reliability and uptime, and to lower operating costs.

2.2.8 Maintenance Management - A New Paradigm

Moubray (n.d.) summarized fifteen of the most important areas of changes which have occurred in the field of physical asset management over the past fifteen years in his paper named Maintenance Management - A New Paradigm. The old and the new paradigms are compared in the following table:

Table 2.2 Comparison of Old and New Paradigms (after Moubray)

Maxim	Old Paradigm	New Paradigm
Maxim 1:	Maintenance is about preserving physical assets.	Maintenance is about preserving the function of assets.
Maxim 2:	Routine maintenance is about preventing failures.	Routing Maintenance is about avoiding, reducing, or eliminating the consequences of failure.
Maxim 3:	The primary objective of the maintenance function is to optimize plant availability at minimum cost.	Maintenance affects all aspects of business effectiveness and risk - safety, environmental integrity, energy efficiency, product quality and customer service, not just plant availability and cost.

Maxim	Old Paradigm	New Paradigm
Maxim 4:	Most equipment becomes more likely to fail as it gets older.	Most failures are not more likely to occur as equipment gets older.
Maxim 5:	Comprehensive data about failure rates must be available before it is possible to develop a really successful maintenance program.	Decisions about the management of equipment failures will nearly always have to be made with inadequate hard data about failure rates.
Maxim 6:	There are three basic types of maintenance: predictive, preventive, and corrective.	There are four basic types of maintenance: predictive, preventive, corrective, detective.
Maxim 7:	The frequency of condition-based maintenance tasks should be based on the frequency of the failure and/or failure the criticality of the item.	The frequency of condition-based maintenance tasks should be based on the failure period (also known as the "lead time to failure" or "P-F interval"
Maxim 8:	If both are technically appropriate, fixed interval overhauls/replacements are usually both cheaper and more effective than condition-based maintenance.	If both are technically appropriate, condition-based maintenance is nearly always both cheaper and more effective than fixed interval overhauls / replacements throughout the life of the asset.
Maxim 9:	Serious incidents / catastrophic accidents which involve multiple equipment failures are usually the result of "bad luck" or "acts of God", and are hence unmanageable.	To a considerable extent, the likelihood of a multiple failure is a manageable variable, especially in protected systems.
Maxim 10:	The quickest and surest way to improve the performance of an existing "unreliable" asset is to upgrade the design.	It is nearly always more cost-effective to try to improve the performance of an unreliable asset by improving the way it is operated and maintained, and only to review the design if this cannot deliver the required performance.

Maxim	Old Paradigm	New Paradigm
Maxim 11:	Generic maintenance policies can be developed for most types of physical asset.	Generic policies should only be applied to identical assets whose operating context, functions and desired standards of performance are also identical.
Maxim 12:	Maintenance policies should be formulated by managers and maintenance schedules drawn up by suitably qualified specialists or external contractors (a top-down approach).	Maintenance policies should be formulated by the people closest to the assets. The role of management is to provide the tools to help them make the right decisions, and to ensure that the decisions are sensible and defensible.
Maxim 13:	The maintenance department on its own can develop a successful, lasting maintenance program.	A successful, lasting maintenance program can only be developed by maintainers and users of the assets working together.
Maxim 14:	Equipment manufacturers are in the best position to develop maintenance programs for new physical assets.	Equipment manufacturers can only play a limited (but still important) role in developing maintenance programs for new assets.
Maxim 15:	It is possible to find a quick, one-shot solution to all our maintenance effectiveness problems.	Maintenance problems are best solved in two stages: 1) change the way people think, 2) get them to apply their changed thought processes to technical / process problems - one step at a time.

2.3 Fault Tree Analysis (FTA)

A Fault tree is a graphical representation of causal relations obtained when a system hazard is traced backward to search for its possible causes. Fault tree analysis was developed by H.A. Watson of Bell Telephone Laboratories in 1961 - 62 during an Air Force study contract for the Minuteman Launch Control System. The first published paper concerning Fault Tree was published by Haasl (1965) at the 1965 Safety Symposium sponsored by the University of Washington and the Boeing Company. Lambert (1973) described Systems Safety Analysis and Fault Tree Analysis. Fussell (1976) declared the value of a fault tree to be as follows:

- Directing the analysis to ferret out failures.
- Pointing out the aspects of the system important to the failure of interest.
- Providing a graphical aid in giving visibility to those in systems management who are removed from systems design changes.
- Providing options for qualitative and quantitative systems reliability analysis.
- Allowing the analyst to concentrate on one particular system failure at a time.
- Providing an insight into system behavior.

Detail fault tree construction can be found in Henley and Kumanoto (1992). The application of fault tree analysis is described in more detail in Chapter 4.

2.4 Root Cause Failure Analysis (RCFA)

Root Cause Failure Analysis is a simple discipline process used to investigate, rectify and eliminate equipment failure. Latino (1998) stated that industry statistics show that approximately $60 billion (US) is spent annually on industrial training. Many firms are involved and competent in providing training in the area of Root Cause Failure Analysis. However, statistics show that only about 20% of the people trained ever utilize their new learning in the field.

Also Latino (1998) discussed the personality traits required for the individual chosen to train and lead RCFA. The RCFA method is a means to accurately determine the root causes of an undesirable event. The process consists of preserving failure data, ordering the analysis team, analyzing the data, communicating findings and recommendations, and tracking for bottom-line results. He also stressed that true "Root Cause" Failure Analysis will identify not only the physical causes of failure, but also the flawed human decisions that lead to errors of omission and errors of commission, such as flawed procedures, training systems and purchasing system.

Latino (1998) states that RCM coupled with RCFA covers all the basics in moving towards total Failure Avoidance. RCM may be necessary to gain control of an operation, however, it is time consuming and expensive up front. RCM's returns are not realized quickly.

RCFA is applied in real time. It deals with today's problems and eliminates them from being tomorrow's problems. Bottom-line results can be immediate if recommendations are acted on quickly. RCFA can be proactive when accepted chronic failures that comprise the maintenance budget are eliminated from recurring.

2.5 Expert Systems

An expert system is an intelligent computer program. It is a highly specialized piece of software that attempts to mimic the function of an expert, or group of experts, to solve complex problems in a given field (domain) of applications. Waterman (1986) provides a good description of expert systems. Details concerning inference engines can be found in Giarratano and Riley (1994).

The major components in an expert system can be listed as follows:

- Knowledge Base: contains the facts, relationships, and heuristics about a domain of application. The knowledge base can have many formats which can be chosen by system designers. The most common formats are:

- production rules (IF - THEN rules)
- Frames
- Semantic Networks

- Inference Engine: It contains the inference and control strategies. It implements a search and pattern-matching operation. Basic Inference mechanisms are:
  - Forward chaining - a searching strategy that starts from the basic facts, and proves additional facts progressively. It works forward to achieve the desired goal.
  - Backward Chaining - a searching strategy that starts from a hypothesis, and then looks for facts which support the hypothesis until the hypothesis is proved or disproved.

- User interface, and

- Interface to outside world.

At present, there are many expert system shells available on the market. A shell is nothing more than an inference engine plus additional user interface routines. Shells make the development of expert systems much easier because they save considerable effort in building interfaces, pattern matchers, search algorithms, modules for uncertain reasoning, explanation facilities, rule/object editors, and tracing and debugging facilities. Most of the available shells provide both Forward and Backward chaining capabilities.

The procedure in building an expert system is as follows:

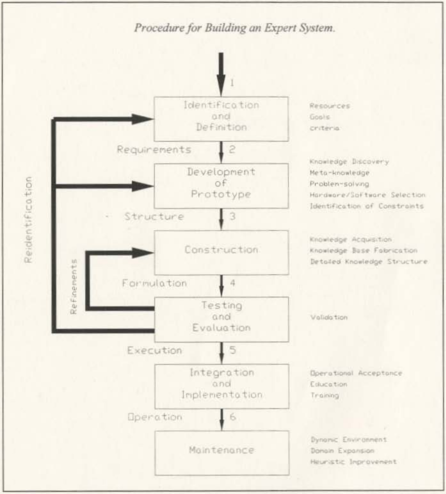


Figure 2.3 Procedure for Building an Expert System

Whitehead and Roach (1987) developed an expert system based on Causal Reasoning. In their paper, they describe the application of a model-based diagnosis to a real problem, diagnosis of faults in the Mark 45 lower hoist.

In HOIST, a system for hypothetical reasoning, WIF (What IF), models the functionality of all the components thereby creating a "causal model" of the Mark 45 lower hoist. It is computer accessible and can identify single or multiple components whose failure could explain the given hoist misbehaviour.

The findings were listed as follows:

A. An expert system that reasons from first principles (i.e., causal reasoning) and requires a specification of the functionality of the device's components to diagnose faults can be developed without the use of a domain expert or "shallow rules".

B. The problems of conventional expert systems are identified as follows:

   - First, shallow reasoning is incapable of handling unanticipated faults.
   - Second, significant lag time exists between initial construction of a device and the development of a conventional expert system for maintenance.

- Third, devices commonly go through a series of design modifications, and it is unclear whether a shallow reasoning fault advisor is still correct after such modification.

Qualitative physics is the study of the behaviour of the world in inexact terms. It has been suggested that humans perceive, understand, and generate expectations about physics of the world in an imprecise form. WIF is a hypothetical reasoning system that can be used to model causality. Causality is the study of how to represent what happens as a result of some action. Qualitative physics and causal reasoning are strongly related.

Their paper did not include the quantitative aspects of functional failure as required in RCM. However, it clearly pointed out the limitation of conventional expert system.

2.6 Integrated Mathematical and Knowledge-based System

Feldman, et al (1992) developed an integrated Mathematical and Knowledge-based maintenance delivery system which illustrated a practical approach to the knowledge acquisition process. It demonstrated how a knowledge-based system could become the framework for incorporating operation's research and analytical approaches into designing a decision support system. The developed system is used to develop appropriate actions for maintaining smelt pots in a continuous process production facility at an Aluminum Company of America (Alcoa) plant.

The findings were listed as follows:

- The requirements of the system are easy to use for production personnel. The system can be easily modified and extended by the engineering staff and delivered on a PC-compatible personal computer.

- A knowledge-based system and mathematical analysis can be integrated into a single replacement policy system.

2.7 Optimization

Barlow and Hunter (1960) described two preventive maintenance policies using elementary renewal theory to obtain optimum policies. Policy I can be defined as: perform preventive maintenance after t_0 hours of continuing operation without failure. If the system fails before t_0 hours have elapsed, perform maintenance at the time of failure. Preventive maintenance is then rescheduled. For this policy, it is assumed that the system is as good as new after any type of maintenance or replacement is performed. Policy II is defined as: perform preventive maintenance on the system after it has been operating for a total time, t_* hours regardless of the number of intervening failures. It is assumed that after each failure only minimal repair is made and the system failure rate is not disturbed.

The findings were listed as follows:

- Under certain reasonable restrictions, Policy I and II have unique solutions which can be computed and their efficiencies (availability) compared.

- The optimal t_0 and t_* for policy I and II respectively, depend only on the ratios T_e/T_s and T_m/T_s respectively, where:

  T_e - the expected time to perform emergency maintenance

  T_s - the expected time to perform scheduled maintenance

  T_m - the expected time to perform minimal repair

- If $T_e = T_s$ and $T_m > T_s/\mu q(\mu)$, then Policy I is better than Policy II.

- If $T_e = T_s$, and F is $N(\mu, \sigma)$ and $\mu/\sigma > \sqrt{2\pi}\, T_s/2T_m$, then policy I is better than Policy II.

- Policy I is most useful in maintaining simple equipment or systems. However, Policy II may be more applicable for the HVAC system.

Barlow and Hunter (1960) developed their policy based on the assumptions that the planning horizon is infinite, all failure events are independent, and in case of preventive maintenance, failures are removed by replacement.

Before any maintenance strategy is considered, the patterns of failure based on conditional probability of failure against operating age for various components in the system must be analyzed in detail. This is well explained by Moubray (1991).

Referring to Figure 2.4, Pattern A is the well-known bathtub curve. It begins with a high incidence of failure (known as infant mortality or burn-in) followed by a constant failure rate, then a wear-out zone. Pattern B shows constant or slowly increasing failure probability, ending in wear-out zone. Pattern C shows slowly increasing probability of failure, but there is no identifiable wear-out age. Pattern D shows low failure probability when the item is new or just out of the shop, then a rapid increase to a constant level, while Pattern E shows a constant probability of failure at all ages (random failure). Pattern F starts with high infant mortality, which drops eventually to a constant or very slowly increasing failure probability.

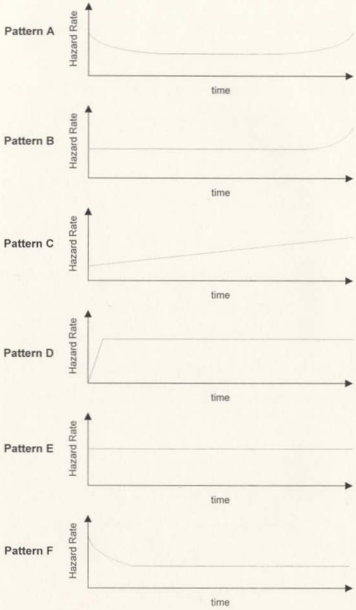


Figure 2.4 Failure Patterns

Studies done on civil aircrafts showed that 4% of the items conform to Pattern A. 2% to B. 5% to C. 7% to D. 14% to E and no fewer than 68% to Pattern F. Although percentages in which these patterns occur in aircrafts is not necessarily the same as in HVAC industry. there is no doubt that as equipment grows more complex. we will see more and more of the Patterns E and F because of the increased usage of electronics equipment in the aircrafts.

These findings contradict the belief that there is always a connection between reliability and the operating age of an item. This belief led to the idea that the more often an item is overhauled. the less likely it is to fail. Nowadays. this is seldom true. Unless there is a dominant age related failure mode. age limits do little or nothing to improve the reliability of complex items. In fact. scheduled overhauls can actually increase overall failure rates by introducing infant mortality into otherwise stable systems.

Ramani (1985) performed an analysis of optimum maintenance polices. In this study. a solution of the well-known age-based maintenance model is derived using the semi-Markov approach. The effects of the model parameters on the results are then discussed.

The findings are listed as follows:

- The semi-Markov approach to the classical age-based maintenance model is more appealing to engineers used to the state space approach than the renewal theory concepts introduced by Barlow and Hunter (1960).

- Markov model approach is only good for non-deteriorating systems where the time to failure of the system is exponentially distributed. This method cannot be used to determine optimum policies.

- Semi-Markov model can be used to handle a class of stochastic systems with non-exponential distributions.

- The optimum policy is independent of the probability distributions of the repair and maintenance times - only the mean durations are of interest.

- If the hazard rate is constant or decreasing, there is no optimum solution because the unit either is unchanged or improves with time. Replacing an unfailed unit with a new unit is not efficient. This is very similar to the assertion in Patterns E and F of failure based on conditional probability of failure.

- The optimum maintenance interval is a function of ratio ((m_R) mean time to perform the repair) / ((m_M) mean time to perform maintenance). and not the actual values of m_R and m_M.

The Semi-Markov model was discussed with the following stated assumptions:

- When not under preventive maintenance, the system is assumed to be in one of two states: working or failed.

- That after preventive maintenance or after a repair following a failure, the system returns to as good as new conditions.

- Time is reset to zero, when the system is returned to service after maintenance or repair.

That the system returns to as good as new conditions is not a very good assumption and will increase the probability of failure if the failure pattern belongs to Pattern A and Pattern F.

The literature review on expert system in RCM for aircraft systems has provided detailed knowledge which can be generalized and applied to other large systems such as HVAC systems. In the following chapter, the application of RCM to HVAC systems will be discussed.

Chapter 3 Application of RCM

This chapter describes the eight steps for implementing RCM to HVAC systems (see Figure 3.1). The RCM method reviews each asset in its operating context by asking the following questions:

(1) What are the functions and associated performance standards of the asset in its present operating context?

(2) In what ways does it fail to fulfil its functions?

(3) What causes each functional failure?

(4) What happens when each failure occurs?

(5) In what way does each failure matter?

(6) What can be done to prevent each failure?

(7) What if a suitable preventive task cannot be found?

Tesdahl and Tomlingson (1997) describe 8 logical steps for implementing RCM. These steps are shown in Figure 3.1. The application of these steps to a component of the HVAC system is described as follows:

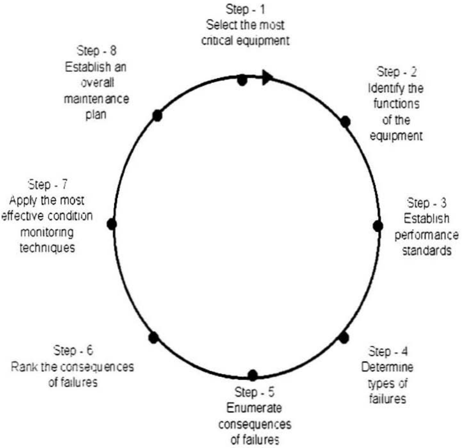


Figure 3.1 Implementing RCM in Eight Logical Steps (after Tesdahl & Tomlingson, 1997)

The implementation steps include:

1. Select the Most Critical Equipment - Let's assume that the most critical equipment in a particular HVAC operation is the fresh air intake louver.

2. Identify the Functions of the Most Critical Equipment - What, exactly does the fresh air intake louver do in its operating context? The primary functions of the fresh air intake louver can be stated as follows:

    - to allow adequate fresh air intake to the HVAC system.

    - to stop snow and rain from getting into the HVAC equipment.

    - to provide aesthetics for the building architecture.

    - to keep unwanted people or animals from the HVAC system.

3. Establish Performance Standards - How well must the fresh air intake louver perform in the conditions under which it operates? The louver must be able to, for example:

- Allow 5,000 litre/sec of quality fresh air to the HVAC system with maximum pressure drop of 2.5 mm during all weather conditions for periods of 24 hours, stopping only for system shut down.

4. Determine the Types of Failures - Any equipment condition that does not permit the fresh air louver to meet the performance standard would constitute a failure. A potential failure is an identifiable physical condition which indicates that the failure process has started. For fresh air intake louver, typical potential failures might be:

   - The louver fails to allow adequate fresh air intake.

   - The louver failed to stop snow and rain from entering HVAC system.

   - If the louver is damaged, it destroys the building aesthetically.

   - The louver fails to stop birds, insects, rats and intruders from entering the HVAC system.

A functional failure is the inability to meet the specified performance standard. A fresh air intake louver experiencing the following types of failures would not be able to meet its performance standards and would sustain a functional failure:

A. Blockage by foreign material in the surface of the louver.

B. Blades of the louver damaged.

C. Louver damaged.

D. Louver removed.

Also, we must be aware of hidden failures in which the failure is not apparent until the function is attempted by the operator. However, there is no hidden failure for the fresh air intake louver.

5. Enumerate the Consequences of Failures - What will the result be if a specific failure occurs? Consequences of failure can range from inconvenience to catastrophic. For example, functional failure A is caused by foreign matter blockage in the surface of the louver. This will cause a reduction in air supply to the HVAC system. This causes high static

pressure for the fan and consumes more electrical energy. The functional failure B is caused by physical damage to the louver. This will cause air which is wetter than normal to the fresh air damper. This will cause pre-filter to be saturated with moisture, to sag, and to fail. Also excess wet cold air and snow will cause the freeze protection device to be activated and shut down the system. The function failure C is caused by physical damage or louver falls out of place. The function failure D is caused by physical damage or louver physically removed from its place. This will destroy the building aesthetically. This will provide a path for burglars and jeopardize public safety. The unwanted foreign material can damage filter and fans.

This type of description lends itself to a more systematic table and the above information is put into a table form as shown in Table 3.1.

In the larger context, we must consider that maintenance can affect all phases of the HVAC system operation. Typically, without reliable equipment, quality building environment targets cannot be met.

It follows that without dependable equipment, air quality in terms of temperature, humidity, and fresh air supply are compromised, and building occupancy satisfaction is difficult to attain. Also, unreliable equipment can endanger personnel, create environmental hazards and undermine energy efficiency. For all of these reasons, avoidance of the consequences of failure must be a primary maintenance objective.

Table 3.1 Fresh Air Intake Louver RCM Information Worksheet

RCM Information Worksheet			Component Analyzed: Fresh Air Intake Louver	Fault Tree Analysis Figure 4.2		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To allow adequate fresh air intake	A	The louver fails to allow adequate fresh air intake	1	The louver has been blocked by foreign matter	This will cause a reduction in air supply to the HVAC system. This causes high static pressure for the fan and consumes more electrical energy.
2	To stop snow and rain to the HVAC equipment	B	Failed to stop snow and rain to HVAC equipment	1	Louver has become damaged	This will cause air which is wetter than normal to the fresh air damper.
						This will cause prefilter saturated with moisture, to sag and fail.
						Excess wet cold air and snow will cause freeze protection system to be activated.
3	To provide proper aesthetics	C	Destroyed the building aesthetically	1	Louver has become damaged or removed	This will destroy the building aesthetically.
4	To keep unwanted people or animals from the system	D	Failed to stop birds, insects, rats and burglars from the system	1	Louver has become damaged or removed	This will provide path for burglars and jeopardize public safety. The unwanted foreign material can damage filter and fans.

6. Rank the Consequences of Failures - Because equipment has increased in complexity, the number of ways it can fail have multiplied. Therefore, consequences of failure must be classified to guide us in taking preventive and corrective actions. For example:

- Safety failures endanger personnel as well as equipment

- Operational failures result in product loss (in terms of air quality and poor building environment) plus the cost of repair

- Non-operational failures result only in the cost of repair

In any industry, the most important aspects are the avoidance or reduction of the consequences of safety and operational failures. Therefore, the most competent types of preventive and corrective techniques are applied to the equipment most critical to the safety of individuals and the production process.

7. Apply the Most Effective Condition Monitoring Techniques - To detect potential failures early and accurately distinguish them from normal operating conditions, condition monitoring techniques such

as vibration analysis are used. They are capable of detecting deteriorating equipment conditions with much greater accuracy and reliability than human beings. These techniques also detect hidden failures that human beings would not be able to detect unless they tried a control mechanism and it did not respond. With the availability of more effective and reliable condition monitoring techniques, equipment condition can be more accurately monitored. This allows a unit to remain in service providing that it continues to meet its performance standard rather than replacing the component at the first sign of potential failure. In turn, this approach yields significantly greater life from components and units.

The safe physical location of the louver is of critical importance. This can best be achieved by establishing a monitoring program by video camera over a suitable period of time to ensure that no dangerous fumes from automobile exhaust etc. are in the area. Also suitable gas sensors should be installed in the appropriate locations.

8. Establish an Overall Maintenance Plan - Based on the consequences of failures, a maintenance program featuring condition monitoring techniques is applied to identify potential failures accurately and quickly to preclude their deterioration to

functional failure levels. The most effective maintenance program is built on the preceding implementation steps:

- Critical equipment is identified
- Fresh air intake louver functions are determined
- Performance standards are established for the fresh air intake louver
- Types of failures are identified, component by component
- The consequences of failures are determined for each failure
- Failure consequences are ranked to give priority to preventive actions
- The best, most applicable condition monitoring techniques are identified.

Then, the condition monitoring techniques selected are fitted into existing, competent maintenance programs to protect the fresh air intake louver from functional failures and their consequences.

The failure modes as identified in the RCM information worksheet Table 3.1 are then used as an input to the fault tree analysis as shown in Fault Tree Analysis Figure 4.2 in Chapter 4.

The above approach can be generalized and applied to any system under study. Once the system scope is defined and major components are listed, RCM techniques can be used to identify the intended functions of all components. The causes of failure and the effects of failure are then tabled in the RCM Information worksheet. This approach can be applied to the central HVAC unit with configuration shown in Figure 3.2 with the results shown in RCM information worksheet, Table 3.1, Table A-3.2 to A-3.13. Information concerning relationship between multiple failures is listed in the fault tree analysis Figure B-4.2 to B-4.19.

Since the RCM worksheet is intended to illustrate general application, there is no specified quantity in terms of air flow, static pressure or noise level. In a specific application, the stated variable must be quantified and sensitivity analysis must be addressed. The failure modes obtained from RCM analysis will provide required input into the expert system as discussed in Chapter 6.

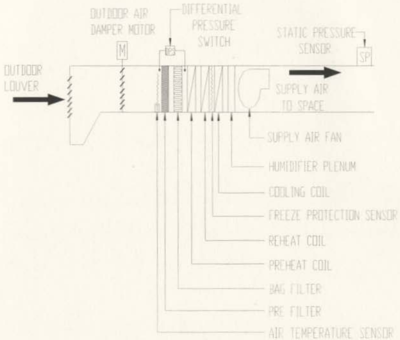


Figure 3.2 **Air Handling System Without Return Air**

Chapter 4 Application of Fault Tree Analysis (FTA)

A fault tree is a graphical representation of causal relations obtained when a system hazard is traced backward to search for its possible causes. The system hazard is then the top event of the fault tree. There are two type of building blocks used to build fault tree, namely gate symbols and event symbols. The application of gate symbols described by Henley and Kumamoto (1992) is listed as follows:

Gate symbols connect events according to their causal relations. The symbols for the gates are listed in Table 4.1. A gate may have one or more input events but only one output event.

The output events of AND gates occur if all input events occur simultaneously. On the other hand, the output events of OR gates happen if any one of the input events occurs. The causal relation expressed by an AND gate or OR gate is deterministic because the occurrence of the output event is completely controlled by the input events. There are causal relations that are not deterministic but probabilistic and represented by a hexagon called inhibit gate. For detail explanations of Priority AND gate, Exclusive OR gate, and m out of n gate see Table 4.1. The structure of a tree is shown in Figure 4.1.

Table 4.1 Gate Symbols

	Gate Symbol	Gate Name	Causal Relation
1		AND gate	Output event occurs if all input events occur simultaneously.
2		OR gate	Output event occurs if any one of the input events occurs.
3		Inhibit gate	Input produces output when conditional event occurs.
4		Priority AND gate	Output event occurs if all input events occur in the order from left to right.

5		Exclusive OR gate	Output event occurs if one, but not both, of the input events occur.
6		*m* out of *n* gate (voting or sample gate)	Output event occurs if m out of n input events occur.

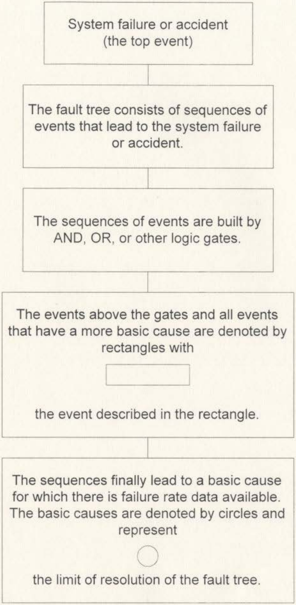


Figure 4.1 **Fundamental structure of a fault tree**

This procedure starts with an initiating event and finds the combination of failures which cause it (backward logic). Using this method and applied to the fresh air intake louver failure as a top event, the fault tree can be constructed as follows:

A. Place fresh air intake louver failure as top event by placing this inside a rectangle, which is represented by a gate.

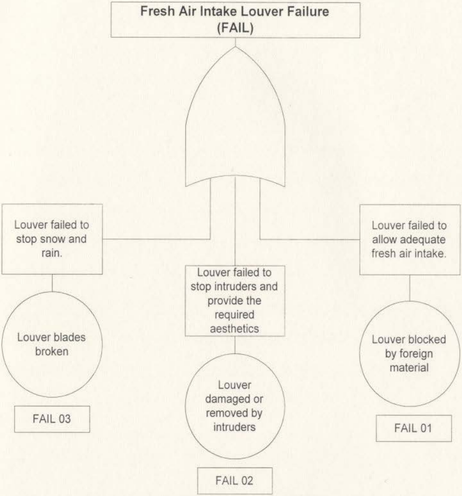
B. The causes of fresh air intake louver failure are either louver being blocked by foreign matter or louver damaged/removed, the input events. Therefore, an OR gate is used to represent "fresh air intake louver failure", an output event occurs if any one of the input events occurs.

This type of analysis lends itself to a graphical procedure into which coded information is put in a figure as shown in Figure 4.2. In the figure, the reliability R(t) for the Fresh Air Intake Louver is modelled as follows:

$$R(t)FAIL = R(t)FAIL01 * R(t)FAIL02 * R(t)FAIL03 \qquad \textbf{(5.5)}$$

where,

R(t) FAIL	=	reliability for the fresh air louver
R(t)FAIL01	=	reliability of louver not blocked by foreign matter
R(t)FAIL02	=	reliability of louver
R(t)FAIL03	=	reliability of louver stay intact



R(t) for Fresh Air Intake Louver = R(t)FAIL01 x R(t)FAIL02 x R(t)FAIL03

Notes: FAIL01 to FAIL03 are information coded using failure modes from RCM worksheet.

Figure 4.2 Fresh Air Intake Louver Failure

This is a well accepted technique and appropriate for finding failure relationships. However, large fault trees are difficult to understand, bear no resemblance to system flow sheet, and are not mathematically unique. This technique as applied to various components of the central HVAC system with configuration in Figure 3.2 is shown in fault tree analysis Figure B-4.2 to B-4.19 in Appendix B.

Latino (1998) explains that in most failures there are actually three layers. Firstly, there is the physical component, secondly there is the human error, and finally the latent root of the problem, which is the management system weakness. In many cases, this is the true cause of the problem. If this is applied to the fresh air intake louver failure and it is found that there is actual blockage by foreign material (physical component), the problem may be traced back to garbage bins located near the fresh air intake louver, an act of human error. This also identifies a management system weakness. The surroundings around the fresh air intake louver must be controlled to ensure no garbage bins, no garbage truck loading, or car exhaust that will pollute the quality of air intake and affect the performance of the louver.

Fault Trees provide a good visual picture for all technical personnel, clearly showing the causes of a particular failure. It provides a clear, concise visual outline of individual failures in a sub-system.

Chapter 5 Mathematical Model and Optimization

This chapter outlines detailed mathematical models required to quantify component and system reliabilities, which are built on the results from the two previous chapters. In Chapter 3, the application of RCM obtains the intended functions, causes of functional failure and the effect of failures. The results of this application show a qualitative model. In Chapter 4, Fault Tree analysis is used to discuss how acquired knowledge from RCM can be analyzed in order to understand the interrelation of functional failures that will result in component failures.

5.1 Network Modelling Concepts

In practice, a system is frequently represented as a network in which the system components are connected together either in series, parallel, or complex, which is a combination of series and parallel. This is well developed by Billinton and Allan (1992).

5.1.1 Series Systems

The components in a set are said to be in series from a reliability point of view if they must all work for system success or only one needs to fail for system failure.

$$R_s = \prod_i^n R_i \qquad \textbf{(5.1)}$$

If there are n components in series, the generalized formulae are:

R_s - is the probability of system success or reliability

R_i - is the individual component reliability

$$Q_s = 1 - \prod_i^n R_i \qquad \textbf{(5.2)}$$

Q_s - the unreliability or probability of system failure

5.1.2 Parallel Systems

The components in a set are said to be in parallel from the reliability point of view if only one needs to be working for system success or all must fail for system failure as shown below.

$$R_p = 1 - \prod_i^n Q_i \quad (5.3)$$

R_p - is the probability of system success or reliability

Q_i - is the unreliability or probability of component failure

$$Q_p = \prod_i^n Q_i \quad (5.4)$$

Q_p - is the unreliability or probability of system failure

5.1.3 Complex Systems

None of the components are connected in a simple series/parallel arrangement. The mathematical model for a complex system is a complicated application of series and parallel modelling based on the physical situation.

5.2 Mathematical Model for Components

Detail mathematical models for reliability R(t) for some key components in the HVAC system can be modeled based on the failure modes as shown in the Fault Tree analysis figures in Appendix B and are discussed as follows:

5.2.1 Model for Fresh Air Intake Louver

The fresh air intake louver failure can be caused by a louver blocked by foreign matter (FAIL01), a broken louver (FAIL02) and a damaged louver or if it is removed (FAIL03)

R(t)FAL = R(t)FAIL01*R(t)FAIL02*R(t)FAIL03 **(5.5)**

where,

R(t) FAL	=	reliability for the fresh air louver
R(t)FAIL01	=	reliability of louver not blocked by foreign matter
R(t)FAIL02	=	reliability of louver
R(t)FAIL03	=	reliability of louver stay intact

5.2.2 Model for Fresh Air Damper Failure

Most of the damper failures are caused by corrosion which is caused by the ocean air chemistry. This effect is directly proportional to the distance from ocean to the damper and inversely proportional to time and rainfall intensity.

R(t) FAD = kD / [n * (AYRF + C)] **(5.6)**

where,

R(t) FAD	=	reliability for the fresh air damper
k	=	constant

D	=	distance from the sea in meter
n	=	time in years
AYRF	=	average yearly rainfall in mm
C	=	constant

5.2.3 Model for Air Filter Failure

The air filter failure mode is a function of intake air velocity, location and type of air intake louver, the rainfall intensity and the direction of the wind. Frequently, architectural considerations dictate the type and style of louver. High-efficiency, low-pressure louvers that effectively limit carryover of rain are available. Cold regions may require a snow baffle to direct fine snow particles to a low-velocity area below the dampers.

$$R(t)\ AF = R(t)\ AFI * R(t)\ AFL * R(t)\ FRAME \qquad \textbf{(5.7)}$$

where,

R(t) AF	=	reliability for air filter
R(t) AFI	=	reliability for air filter based on inlet condition which cause filter to sag
R(t) AFL	=	reliability for air filter based on usage
R(t) FRAME	=	reliability for air filter frame installation

The reliability for the air filter will be lower on windy and rainy days. R(t) AFI will be equal to one on sunny days without snow or rain because the filter will not be saturated with moisture and sagged.

5.2.4 Model for Freeze Protection Failure

The following modes that cause freeze protection failures are identified:

- no power to heating circulating pump;
- direct coupling between motor and pump shaft;
- pump impellor;
- low supply hot water heating temperature;
- draft space between heating coils.

Based on the above findings, the reliability of the freeze protection can be modeled as follows:

R(t) CFP = R(t6)DC * R(t7) PIMP * R(t8) HWHT **(5.8)**

where,

R(t) CFP	=	reliability for coil freeze protection system
R(t6) DC	=	reliability for heating pump direct coupling
R(t7) PIMP	=	reliability for heating pump impeller

R(t8) HWHT	=	reliability for hot water heating temperature

t6, t7 and t8 are time depending upon usage after the component is installed or repaired.

The electrical failure for the pump is being ignored in this study and the draft space between heating coils is a construction problem and can be minimized by design. This failure can only occur when outdoor temperature is below 0°C.

5.2.5 Model for Fan Failure

After six years of monitoring fans for a number of buildings at the Memorial University of Newfoundland, it has been noted the failure of the following components has caused fan failures:

- fan belts;
- fan vortex vane;
- fan bearing;
- fan assembly;
- fan motor.

Of course, there are many other possible failure modes which can exist, such as impeller, coupling, shaft and electrical failure. See Air Movement and

Control Association, Inc. Publication 202-88 Troubleshooting Fan Application Manual for details. However, these failure modes seldom happen and are not included in this study.

Since the fan will fail if any one of the five failure modes exist, these failure modes are independent of each other with the exception that when a bearing failure occurs the fan belt usually fails at the same time. Therefore, fan failure can be modeled as follows:

$$R(t)FAN = R(t1)FB * R(t2)FVV * R(t3)FBG * R(t4)FA * R(t5)FM \quad \textbf{(5.9)}$$

R(t)FAN	=	reliability for fan
R(t1) FB	=	reliability for fan belts
R(t2)FVV	=	reliability for fan vortex vane
R(t3) FBG	=	reliability for fan bearing
R(t4) FA	=	reliability for fan assembly
R(t5) FM	=	reliability for fan motor

t1, t2, t3, t4,and t5 are time depending upon usage after the component is installed or repaired.

For fans without vortex vane system we can reassign R(t2) FVV to the value of one. The reliability of fan belts will be affected by temperature.

especially during shut down and start up conditions. These effects will be minimal if the system is in operation for 24 hours per day.

5.2.6 Model for Computer Control System Failure

Most of the control system failure is caused by the freeze protection subsystem. This again is based on the wind velocity, wind direction, air intake velocity, position of the freezestat and the conditions of the fins in the heating coil. The other failure mode is the failure of the EP (Electric-Pneumatic) relay.

Modeling for R(t)CCS - Reliability for the control system is a very complex process and can be modeled as follows:

R(t)CCS	=	R(t1)CCSF01 * R(t2)CCSF02 * R(t3)CCSF03 * R(t4)CCSF04 * R(t5)CCSF05 * R(t6)CCSF06 * R(t7)CCSF07 * R(t8)CCSF08 * R(t9)CCSF09 **(5.10)**
R(t1)CCSF01	=	reliability for temperature sensor
R(t2)CCSF02	=	reliability for temperature input module
R(t3)CCSF03	=	reliability for temperature output module
R(t4)CCSF04	=	reliability for humidity sensor
R(t5)CCSF05	=	reliability for humidity input module
R(t6)CCSF06	=	reliability for humidity output module
R(t7)CCSF07	=	reliability for static pressure sensor

R(t8)CCSF08 =		reliability for static pressure input module
R(t9)CCSF09 =		reliability for static pressure output module

t1, t2, t3, t4, t5, t6, t7, t8 and t9 are time depending upon usage after the component is installed or repaired.

However, there will be no need for freeze protection if the environment is not below 0°C. The reliability for the control system will decrease if the outdoor temperature is much lower than 0°C.

5.2.7 Model for System Heating System Failed to Heat Supply Air to Required Temperature

$$R(t)\,HSF = R(t)HSF01 * R(t)HSF02 * R(t)HSF03 * R(t)HSF04 * R(t) * HSF05 \quad (5.11)$$

where,

R(t)HSF	=	reliability for heating system
R(t)HSF01	=	reliability for heating water temperature
R(t)HSF02	=	reliability for hot water heating circulating pump
R(t)HSF03	=	reliability for tube and fin
R(t)HSF04	=	reliability for heating coil
R(t)HSF05	=	reliability for heating coil control system

The other failure mode such as outdoor temperature is too cold is not included in the modeling in order to simplify the model. This failure mode is a design problem and cannot be solved by maintenance.

5.2.8 Model for Cooling System Failed to Cool Supply Air to Required Temperature

R(t)CSF = R(t)CSF01*R(t)CSF02*R(t)CSF03*R(t)CSF04*R(t)CSF05*R(t)CSF06 **(5.12)**

where,

R(t)CSF	=	reliability for cooling system
R(t)CSF01	=	reliability for cooling water temperature
R(t)CSF02	=	reliability for cooling water circulating pump
R(t)CSF03	=	reliability for tube- fin
R(t)CSF04	=	reliability for cooling coil
R(t)CSF06	=	reliability for cooling coil control system
R(t)CSF05	=	reliability for outdoor temperature

However. R(t)CSF05 is not included in the model in order to simplify the mathematical model. This failure mode is a design problem and cannot be solved by maintenance.

5.2.9 Model for System Reliability

$$R(t)S = R(t)FAN * R(t)AF * R(t)CCS * R(t)FAD * R(t)CFP * R(t)HSF * R(t)CSF \quad \textbf{(5.13)}$$

where,

R(t)S	=	reliability for the system
R(t)FAN	=	reliability for fan
R(t) AF	=	reliability for air filter
R(t)CCS	=	reliability for the computer control system
R(t)FAD	=	reliability for fresh air damper
R(t)CFP	=	reliability for coil freeze protection system
R(t)HSF	=	reliability for heating system
R(t)CSF	=	reliability for cooling system

5.2.10 Limitations of Reliability Predictions

The reliability predictions based on analysis of the best available data is intended to make reliability prediction as good a tool as possible. However, like any tool, reliability prediction must be used intelligently, with due consideration of its limitations.

The first limitation is that the failure rate models are point estimates which are based on available data. They are valid for the conditions under which the data was obtained and for the components covered. Even when used in similar environments, the differences between system applications can be significant. Failure rates are also impacted by operational scenarios, operator characteristics, maintenance practices and the definition of failure.

5.3 Weibull Analysis

Sinha (1986) states that for items that are likely to fail at any time, it is quite customary to assume that the life of the item is a random variable with a distribution function F(t), which is the probability that the item fails before time t.

There are many distributions such as exponential, normal, log-Normal, Gamma and Weibull used for reliability data analysis. The Weibull distribution is used in this study because it is the distribution widely accepted for failure analysis. Henley and Kumanoto (1992) states that among all the distributions available for reliability calculation, the Weibull distribution is regarded as unique to the field. Detailed information concerning Weibull Analysis can be found in Abernethy (1998).

Equipment Failure

The data for equipment failure is limited because not many equipment suppliers are willing to release this. Despite years of failure data collected by Honeywell Inc., specifically for the buildings under this study, there is still limited meaningful data. A Weibull analysis is used to perform the actual calculation to determine F(t) (the failure distribution) for failure mode because it can be used to provide reasonably accurate failure analysis and failure forecasts with extremely small samples.

Basic formulae for Weibull cumulative distribution function (CDF) has an explicit equation

$$F(t) = 1 - e^{-(t/\eta)^{\beta}} \quad (5.14)$$

$$R(t) = e^{-(t/\eta)^{\beta}} = P(T \geq t) \quad (5.15)$$

where,

$P(T \geq t)$	probability that the item survives for at least time t
F(t)	failure distribution = 1-R(t)
t	time
η	characteristic life or scale parameter in time unit
β	slope or shape parameter
e	2.718281828, the base for natural logarithms
T	a random variable

Estimation of Parameters

There are many methods of estimating the parameters of the Weibull distribution. Methods include maximum likelihood, method of moments, and least squares. Perhaps the easiest to use in this case is the least squares method.

Equation **(5.14)** can be transformed as follows:

$$e^{-(t/\eta)^\beta} = 1 - F(t) \quad \textbf{(5.16)}$$

$$-(t/\eta)^\beta = \ln(1 - F(t)) \quad \textbf{(5.17)}$$

$$(t/\eta)^\beta = \ln(1/(1-F(t))) \quad \textbf{(5.18)}$$

$$\ln\ln\ (1 / 1 - F(t)) = \beta\ln(t) - \beta\ln(\eta) \quad \textbf{(5.19)}$$

This is an equation for a straight line in the form of:

$$y = \beta x + C \quad \textbf{(5.20)}$$

where,

$x = \ln(t)$

$c = -\beta\ln(\eta)$

β = slope of the line

C = y-intercept

$$\ln(\eta) = -C / \beta \quad \textbf{(5.21)}$$

$$\eta = e^{-C/\beta} \quad \textbf{(5.22)}$$

Detailed results obtained from raw data for various component failures for the HVAC system (shown in Appendix C) are discussed as follows:

- For example in Table C-5.11 Rank Table Fan Motor Failure Analysis in Appendix C, raw data (in hours) is obtained from failure record. The equipment ran to an actual failure is recorded as X-value in the table and serves as input to a commercial package, Super SMITH, a leading Weibull analysis software including many options: Weibull, Weibayes, Normal, Log Normal data analysis and plotting with chi-Square, Poisson, Binomial probability calculations, failure forecasting, optimal parts replacement and Monte Carlo confidence bounds.

However, if the equipment did not fail and was suspended, a negative value is placed in front to distinguish the difference. This program will then calculate η and β, the two important parameters for Weibull Analysis. An occurrence CDF graph can then be generated as shown in Figure C-5.6. This graph can be used to predict the relationship of F(t) and the time used in operation. After η and β have been generated, it can then be used to predict F(t) and R(t) at specific hours of operation. This output is shown in Table C-5.12.

For example, a fan failure can be modeled as

$$R(t)\ Fan = R(t1)\ FB \cdot R(t2)\ FVV \cdot R(t3)\ FBG \cdot R(t4)\ FA \cdot R(t5)\ FM \qquad \textbf{(5.23)}$$

where,

R(t1) FB can be obtained from Table C-5.4 and Figure C-5.2

R(t2) FVV can be obtained from Table C-5.6 and Figure C-5.3

R(t3) FBG can be obtained from Table C-5.8 and Figure C-5.4

R(t4) FA can be obtained from Table C-5.10 and Figure C-5.5

R(t5) FM can be obtained from Table C-5.12 and Figure C-5.6

Then R(t) FAN can be calculated. An example using the same time for t1 to t5 is shown in Table C-5.13.

5.4 Optimization - Availability

The basic assumptions are: the planning horizon is infinite, all failure events are independent and in the case of preventive maintenance, failures are removed by replacement or repair. The system under study, when not under maintenance, is assumed to be in one of two states: working or failed. It is assumed that after preventive maintenance or after a repair following a failure, the system returns to "as good as new" condition, i.e., time is reset to zero, when the system returns to service after maintenance or repair.

The availability A(T) (availability) is the percentage of working period of a piece of equipment over a certain period. For example, over a period of 365 days, if a certain piece of equipment is working 330 days; is under maintenance for 20 days and is under emergency repair for 15 days. Then the availability A(T) is

$$^{330}/_{(330+20+15)} = {}^{330}/_{365} \text{ X } 100\%$$

In general, the availability of the system is given by:

$$A(T) = \frac{working\ time}{working\ time + time\ used\ for\ repair + time\ used\ for\ maintenance}$$

Or

$$A(T) = \frac{\int_0^T R(t)dt}{\int_0^T R(t)dt + m_R \cdot F(T) + m_M \cdot R(T)} \quad \textbf{(5.24)}$$

where,

m_R	=	mean time to perform the repair
m_M	=	mean time to perform maintenance
R(t)	=	reliability density
f(t)	=	failure density
R(T)	=	reliability = 1- F(T)
F(T)	=	failure distribution

The mean time to repair includes time to:

- Find the person who can repair the fault.
- Diagnose the fault.
- Repair the fault.
- Revalidate or test the machine.

Equation 5.24 shows that the Availability, A(T), of a system depends on other variables besides the reliability. One expects intuitively that, the steady-state availability will increase as the Reliability, R(t), increases. However as the above equation shows, the relationship between A(T) and R(t) is not linear. The steady state availability also depends on the repair and maintenance times (m_R and m_M) and the failure distribution, F(T). Decreasing either of these will also increase the availability.

This analysis illustrates that no matter how reliable a system is, its availability to perform its function can be influenced dramatically by factors outside its design, and these are the areas of concern for operation and maintenance. The availability will depend on the stability of all these factors.

The unavailabilities due to repair and preventive maintenance respectively are given by:

$$U_R(T)=\frac{m_R \cdot F(T)}{\int_0^T R(t)dt+m_R \cdot F(T)+m_M \cdot R(T)} \qquad \textbf{(5.25)}$$

$$U_M(T) = \frac{m_M * R(T)}{\int_0^T R(t)dt + m_R * F(T) + m_M * R(T)} \quad \textbf{(5.26)}$$

The optimum maintenance interval T=T opt can thus be obtained by equating the derivative of A(T) with respect to T to zero and is given by the solution of the integral equation

$$h(T) \cdot \int_0^T R(t)dt - F(T) = \frac{m_M}{m_R - m_M} \quad \textbf{(5.27)}$$

where,

h(t) is the (hazard function) associated with F(t)

Some properties of the optimal solution for maximizing the availability include:

1. If there is no solution to the equation, T opt = infinity. That is, preventive maintenance is not efficient and no maintenance should be performed.
2. If the hazard rate is constant or decreasing, there is no solution to equation, i.e., T opt = infinite. If the unit is unchanged or improves with time, replacing an unfailed unit with a new unit is not efficient.

3. $(m_R/m_M) > 1$ is a necessary condition for a solution to exist, i.e.. for preventive maintenance to be effective. There is no point in preventive maintenance if it takes longer than a repair, when both the operations bring the unit to the same (as good as new) condition

Other optimum maintenance models with similar solutions

4. Minimizing the cost rate

As shown by Barlow and Hunter(1960), if one wishes to minimize the cost rate, i.e. the cost per unit of operating of time which is given by the solution is the same as the equation with the mean durations m_R and m_M being replaced by the costs C_R and C_M respectively.

$$C(T) = \frac{C_M \cdot R(t) + C_R \cdot F(T)}{\int_0^T R(t)dt} \quad \textbf{(5.28)}$$

where,

C(T)	=	cost per unit of operating of time
C_M	=	cost of maintenance (cost of a planned replacement)
C_R	=	cost of repair (cost of unplanned failure)

Chapter 6 A Knowledge-Based Decision Support System

This chapter describes the methodology and advantages of incorporating RCM and fault tree analysis into the development of a database decision support system for maintenance of system. It also describes how failure data are used to predict the risk of failure for a HVAC system based on Weibull distribution using a data base system as the shell for an expert system.

6.1 Advantages of Incorporating RCM Applications into a Knowledge-Based System Methodology

Conventional expert systems have at least three major shortcomings in fault diagnosis. Firstly, they are incapable of handling unanticipated faults. Secondly, the need of significant time lag between initial construction of a device and the development of a conventional expert system for maintenance. Thirdly, devices commonly go through a series of design modifications, and it is unclear whether a shallow reasoning fault advisor is still correct after such modifications. Once the system is defined and its configuration is put in place, RCM should be used to determine the intended functions, functional failures and effect of failures. Since RCM techniques use fundamental approaches to specify what functions are required, it is robust and generic enough to address the above problems. The operation can be updated to reflect the change in system design for required functions. Once the system is updated, the cause of failures can be traced back to fundamental engineering. In this case, temperature, humidity, pressure, flow rate and vibration are the parameters in the system used to trace the cause of failure.

6.2 How Can This Unification Be Achieved?

Conventional expert systems attempt to capture an expert's opinion. A RCM database support system significantly differs from this approach since it does not depend upon advice. By using RCM, fault tree techniques, and a Weibull analysis, this combination generates of a quantitative model of the system and develops a database system from first principles. This will result in an expert system without an expert in the classic sense. The use of RCM and the fault tree techniques in developing a database system will be illustrated in this chapter using an example. The function, functional failure (loss of function), failure mode (cause of failure) and failure effect (what happens when it fails) for the following major components in the HVAC system are studied in detail as shown in Appendix A. These components are:

I. Fresh air intake louver

II. Fresh air damper

III. Pre-filter

IV. Air filters

V. Heating coils

VI. Freeze protection system

VII. Cooling coils

VIII. Humidifier

IX. Supply fan

X. EP Relays

XI. Control system and sequences of operation

The failure of any component in the system is studied in detail to determine the effect on energy consumption, air pressure balancing and impact on air quality - temperature, humidity and indoor air pollutants; and are measured against American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Standard. Common design problems were discussed which substantiated the hypothesis that some buildings' HVAC systems could be improved by proper design and commission. This study demonstrates the importance of integration of design, construction, commissioning, operation, maintenance and continuous improvement or modification to the system.

6.3 Software Package for the Knowledge-Based System

A commercial database program such as "Microsoft Access" has both the database storage component and the necessary programming integrated to provide all the requirements for a knowledge-based system. The rapid development of general commercial database programs with all the linking and retrieving ability has replaced the need for a specific expert system. The acceptance of any commercial database program in the industry is much higher than a specific expert system. Therefore Microsoft Access is being used as the computing tool.

6.4 Adding RCM Failure Modes and Fault Trees into the Knowledge-Based System

The primary data needed to build the expert system is stored in four database tables. They are:

- problems
- causes
- symptoms
- events

Causes, problems, and symptoms database tables are essentially descriptive and are used to code the descriptions for the operating environment. The fourth database table combines the data from causes, problems, and symptoms and codes the events which take place in the operating environment. The "Events" table is one branch of the fault tree. Related data contained in these tables can be queried resulting in various reports. These tables are described as follows:

6.4.1 Causes

The failure modes, or causes, identified in the RCM table are coded and stored in the database table as shown in Table 6.1.

Table 6.1 Causes Identification

Causes_ID	Cause Description
AFFPF01	Rain or Snow in fresh air
AFFPF02	Pre-filter broken
AFFPF03	Dirty fresh air intake
AFFPF04	Air filter medium broken
CSF01	Cooling water temp. is too high
CSF02	Cooling water circulating pump failed
CSF03	Tube and fins covered by dirt and failed to remove heat
CSF04	Cooling coil ruptured
CSF05	Outdoor temperature is too high
CCSF01	Temperature sensor failed
CCSF02	Temperature input module failed
CCSF03	Temperature output module failed
CCSF04	Humidity sensor failed
CCSF05	Humidity input module failed
CCSF06	Humidity output module failed.
CCSF07	Static pressure sensor failed
CCSF08	Static pressure input module failed
CCSF09	Static pressure output module failed

Causes_ID	Cause Description
EPRF01	Air compressor failed
EPRF02	Air dryer failed
EPRF03	Air line failed
EPRF04	Air filter failed
EPRF05	EP leaking
EPRF06	EP solenoid failed
EPRF07	EP plastic housing failed
FAD01	Fresh air damper motor failed
FAD02	Fresh air damper control system failed
FAD03	Fresh air damper motor linkage or ball joint failed
FAIL01	Fresh air louver blades blocked by foreign matter
FAIL02	Fresh air louver damaged or removed
FAIL03	Fresh air louver broken
FDNO01	Blown Fuse
FDNO02	Broken belts
FDNO03	Loose pulleys
FDNO04	Electricity turned off
FDNO05	Impeller touching housing
FDNO06	Wrong voltage
FDNO07	Motor too small and overload protector has broken circuit
FDNO08	Low voltage excessive line drop or inadequate wire size
FDNO09	Load inertia too large for motor
FDNO10	Seized bearing
FN01	Impeller hitting inlet or housing
FN02	Impeller hitting cutoff
FN03	Drive

Causes_ID	Cause Description
FN04	Coupling
FN05	Bearing
FN06	Shaft seal squeal
FN07	Impeller
FN08	Housing
FN09	Fan motor
FN10	Shaft
FN11	High air velocity
FN12	Obstruction in high velocity gas stream
FN13	Pulsation or surge
FN14	Gas velocity through cracks and holes
FN15	Rattles and/or rumbles
FPS01	Heating water temperature is too low
FPS02	Heating circulating pump motor failed
FPS03	Outdoor temperature is too cold
FPS04	Heating pump impeller failed
FPS05	Heating pump direct coupling failed
HAF01	System
HAF02	Fan
HSF01	Heating water temperature is too low
HSF02	Heating circulating pump failed
HSF03	Tube and fin covered by dirt and failed to transfer heat
HSF04	Heating coil ruptured
HSF05	Heating coil Control system failed
HSF06	Outdoor temperature is too cold
ISAF01	Fan

Causes_ID	Cause Description
ISAF02	Duct system
ISAF03	Filter
ISAF04	Coils
ISAF05	Re-circulation
ISAF06	Obstruction Fan Inlet
ISAF07	No straight duct at fan outlet
ISAF08	Obstruction in high velocity air stream
PCHP01	Fan
PCHP02	System
PCHP03	Gas density
PCHP04	Fan selection
PMP01	Belts
PMP02	Bearing
PMP03	Sheaves
PMP04	Impellers
PMP05	Hub
PMP06	Coupling
PMP07	Shaft
SHL01	Humidifier Control system failed
SHL02	Humidifier failed
SHL03	Humidifier Distribution System failed
SHL04	Fresh air humidity low
SPH01	Duct system
SPH02	Filter
SPH03	Coils
SPL01	Gas density

Causes_ID	Cause Description
SPL02	Duct
SPL03	System
SPL04	Fan

For example, a fresh air intake louver failure can be caused by the louver becoming blocked with foreign matter, louver broken and louver damaged or removed and these failure modes are coded as FAIL01, FAIL02 and FAIL03 respectively as shown in Table 6.1.

6.4.2 Problems

The problems identified by RCM techniques and shown in the respective fault tree diagrams are stored in a table using four fields, which are: problem identification number; problem description, fault tree and RCM Information worksheet, as shown in Table 6.2.

Table 6.2 Problem Identification

Problem_ID	Problem Description	Fault Tree	RCM Information WorkSheet
AFFPF	Air Filter Failure	Figure B- 4.4	Table A- 3.4

Problem_ID	Problem Description	Fault Tree	RCM Information WorkSheet
CSF	Cooling system failed	Figure B- 4.7	Table A- 3.7
CCSF	Computer Control System Failure	Figure B- 4.18	Table A- 3.10
EPRF	EP relay failed	Figure B- 4.19	Table A- 3.11
FAD	Fresh Air Damper Failure	Figure B- 4.3	Table A- 3.2
FAIL	Fresh Air Intake Louver	Figure 4.2	Table 3.1
FDNO	Fan does not operate	Figure B- 4.16	Table A- 3.9F1
FN	Fan Noise	Figure B-4.10	Table A- 3.9A
FPS	Freeze protection system being activated	Figure B- 4.6	Table A- 3.6
HAF	High Air Flow	Figure B- 4.12	Table A- 3.9C1
HSF	Heating System failed	Figure B- 4.5	Table A- 3.5
ISAF	Insufficient Air Flow	Figure B- 4.11	Table A- 3.9B2
PCHP	Power consumption high problem	Figure B- 4.15	Table A- 3.9E
PMP	Premature failure	Figure B- 4.17	Table A- 3.9G1
SHH	Space Humidity High	Figure B- 4.8	Table A- 3.8
SHL	Space Humidity low	Figure B- 4.8	Table A- 3.8
SPH	Static pressure high	Figure B- 4.14	Table A- 3.9D
SPL	Static pressure low	Figure B- 4.13	Table A- 3.9D

For example. Fresh Air Louver Failure is coded FAIL under Problem_ID in one column and is shown as Fresh Air Louver Failure in another column as problem description. The associated Fault Tree Diagram is listed in the third column. The associated RCM Information worksheet is listed in the fourth column.

6.4.3 Symptoms

Similarly all possible symptoms are stored in a data base table with symptom identification as one column and symptoms description in the other column as shown in Table 6.3.

Table 6.3 Symptoms Identification

Symptoms_ID	Symptoms Description
S01	Air Flow too high
S02	Air Flow too low
S03	Air Noise level too high
S04	Dust level too high
S05	Fan does not operate
S06	Humidity level too high
S07	Humidity level too low
S08	Power usage too high
S09	Static Pressure too high
S10	Static Pressure too low
S11	Temperature too high
S12	Temperature too low
S13	No Noise
S14	Premature Failure

For example, foreign matter (FAIL 01) will increase system static pressure and this symptom is coded as S09 under Symptoms_ID in one column and the symptoms description is shown in the other column as shown in Table 6.3. Similarly, louver broken (FAIL 02) and louver damaged or removed (FAIL 03) will decrease system static pressure. This symptom is coded as S10 under Symptoms_ID as shown in Table 6.3.

6.4.4 Events

Possible combinations of problems, symptoms and causes are combined in another table named Event which records the problem identification, symptom identification and cause identification as shown in Table 6.4.

Table 6.4 Events

Problem_ID	Symptoms_ID	Causes_ID
AFFPF	S09	AFFPF01
AFFPF	S04	AFFPF02
AFFPF	S09	AFFPF03
AFFPF	S04	AFFPF04
CCSF	S11	CCSF01
CCSF	S11	CCSF02
CCSF	S11	CCSF03
CCSF	S06	CCSF04

Problem_ID	Symptoms_ID	Causes_ID
CCSF	S06	CCSF05
CCSF	S06	CCSF06
CCSF	S09	CCSF07
CCSF	S09	CCSF08
CCSF	S09	CCSF09
CCSF	S12	CCSF01
CCSF	S12	CCSF02
CCSF	S12	CCSF03
CCSF	S07	CCSF04
CCSF	S07	CCSF05
CCSF	S07	CCSF06
CCSF	S10	CCSF07
CCSF	S10	CCSF08
CCSF	S10	CCSF09
CSF	S11	CSF01
CSF	S11	CSF02
CSF	S11	CSF03
CSF	S11	CSF04
CSF	S11	CSF05
CSF	S11	CSF06
CSF	S12	CSF06
EPRF	S05	EPRF01
EPRF	S05	EPRF02
EPRF	S05	EPRF03
EPRF	S05	EPRF04
EPRF	S05	EPRF05

Problem_ID	Symptoms_ID	Causes_ID
EPRF	S05	EPRF06
EPRF	S05	EPRF07
EPRF	S13	EPRF01
EPRF	S13	EPRF02
EPRF	S13	EPRF03
EPRF	S13	EPRF04
EPRF	S13	EPRF05
EPRF	S13	EPRF06
EPRF	S13	EPRF07
FAD	S02	FAD01
FAD	S02	FAD02
FAD	S02	FAD03
FAD	S09	FAD01
FAD	S09	FAD02
FAD	S09	FAD03
FAIL	S01	FAIL02
FAIL	S01	FAIL03
FAIL	S02	FAIL01
FAIL	S09	FAIL01
FAIL	S10	FAIL02
FAIL	S10	FAIL03
FDNO	S05	FDNO01
FDNO	S05	FDNO02
FDNO	S05	FDNO03
FDNO	S05	FDNO04
FDNO	S05	FDNO05

Problem_ID	Symptoms_ID	Causes_ID
FDNO	S05	FDNO06
FDNO	S05	FDNO07
FDNO	S05	FDNO08
FDNO	S05	FDNO09
FDNO	S05	FDNO10
FDNO	S13	FDNO01
FDNO	S13	FDNO02
FDNO	S13	FDNO03
FDNO	S13	FDNO04
FDNO	S13	FDNO05
FDNO	S13	FDNO06
FDNO	S13	FDNO07
FDNO	S13	FDNO08
FDNO	S13	FDNO09
FDNO	S13	FDNO10
FN	S03	FN01
FN	S03	FN02
FN	S03	FN03
FN	S03	FN04
FN	S03	FN05
FN	S03	FN06
FN	S03	FN07
FN	S03	FN08
FN	S03	FN09
FN	S03	FN10
FN	S03	FN11

Problem_ID	Symptoms_ID	Causes_ID
FN	S03	FN12
FN	S03	FN13
FN	S03	FN14
FN	S03	FN15
FPSF	S13	FPSF01
FPSF	S13	FPSF02
FPSF	S13	FPSF03
FPSF	S13	FPSF04
FPSF	S13	FPSF05
FPSF	S13	FPSF06
HAF	S01	HAF01
HAF	S01	HAF02
HSF	S11	HSF05
HSF	S12	HSF01
HSF	S12	HSF02
HSF	S12	HSF03
HSF	S12	HSF04
HSF	S12	HSF05
HSF	S12	HSF06
ISAF	S02	ISAF01
ISAF	S02	ISAF02
ISAF	S02	ISAF03
ISAF	S02	ISAF04
ISAF	S02	ISAF05
ISAF	S02	ISAF06
ISAF	S02	ISAF07

Problem_ID	Symptoms_ID	Causes_ID
ISAF	S02	ISAF08
PCHP	S08	PCHP01
PCHP	S08	PCHP02
PCHP	S08	PCHP03
PCHP	S08	PCHP04
PMP	S14	PMP01
PMP	S14	PMP02
PMP	S14	PMP03
PMP	S14	PMP04
PMP	S14	PMP05
PMP	S14	PMP06
PMP	S14	PMP07
SHL	S07	SHL01
SHL	S07	SHL02
SHL	S07	SHL03
SHL	S07	SHL04
SHL	S07	SHL05
SHH	S06	CSF01
SHH	S06	CSF02
SHH	S06	CSF03
SHH	S06	CSF04
SHH	S06	CSF05
SPH	S09	SPH01
SPH	S09	SPH02
SPH	S09	SPH03
SPL	S10	SPL01

Problem_ID	Symptoms_ID	Causes_ID
SPL	S10	SPL02

Fault tree analysis, RCM information worksheet and the component failure analysis as discussed in Chapter 3 and 4 can be linked to the output table using the hyperlink capability of the "Microsoft Access" software.

6.5 Adding the Weibull Analysis into the Knowledge-Based System

The combination of RCM and fault tree analysis provide a systematic approach to acquire knowledge and an understanding of system functions. The knowledge acquired can be used for input to a database. This model can be enhanced by using a mathematical model, which is based on the statistical results of the components' failures.

Replacement date and the current date are needed in order to establish the components' ages in hours. The database is modified to include this key element. The Weibull parameters, eta and beta are determined from failure data, then a Weibull analysis is used to determine the probability of failure F(t) for each failure mode. The expert system can then predict and prioritize the modes of failures according to the probability of their occurrence.

For example a HVAC system with the following parameters would illustrate this concept.

Table 6.5 Example for calculation of F(t) based on Weibull Parameters

Component	RD	CD	Duration	HRS/W	t	beta	eta	F(t)
FA damper	4/15/8	6/15/9	4078	88	51266.	3.8533	51996.5	0.612
Fan Belts	5/17/9	6/15/9	1490	88	18731.	2.1467	20464.3	0.562
Vortex	2/15/9	6/15/9	1946	88	24464.	1.6390	68043.0	0.170
Fan Bearing	2/15/9	6/15/9	1946	88	24464.	1.1712	132780.	0.128
Fan Motor	2/15/9	6/15/9	1946	88	24464.	2.4660	62328.4	0.094
Pre-filter	4/15/9	6/15/9	61	88	766.86	1.3982	5997.46	0.054
Fan	2/15/9	6/15/9	1946	88	24464.	2.0350	121417.	0.037
Humidifier	5/15/9	6/15/9	1126	88	14155.	2.9900	57608.5	0.014
Ep relay	2/13/9	6/15/9	852	88	10710.	3.0370	69366.5	0.003

$$F(t) = 1-\exp^{-}({}^{t}/_{\eta})^{\beta} \quad \textbf{(6.1)}$$

RD = last replacement date

CD = current date

duration = in days

HRS/WK = Hours of operation per week

The value for eta and beta will be stored in the knowledge-based system based on appropriate data from similar system. The age of the components (t) in hours can be determined based on last replacement date and the current date and the system weekly operating hours. Detailed construction and application of the knowledge-based system is shown in the next section.

Table 6.5 Example for calculation of F(t) based on Weibull Parameters

Component	RD	CD	Duration	HRS/W	t	beta	eta	F(t)
FA damper	4/15/8	6/15/9	4078	88	51266.	3.8533	51996.5	0.612
Fan Belts	5/17/9	6/15/9	1490	88	18731.	2.1467	20464.3	0.562
Vortex	2/15/9	6/15/9	1946	88	24464.	1.6390	68043.0	0.170
Fan Bearing	2/15/9	6/15/9	1946	88	24464.	1.1712	132780.	0.128
Fan Motor	2/15/9	6/15/9	1946	88	24464.	2.4660	62328.4	0.094
Pre-filter	4/15/9	6/15/9	61	88	766.86	1.3982	5997.46	0.054
Fan	2/15/9	6/15/9	1946	88	24464.	2.0350	121417.	0.037
Humidifier	5/15/9	6/15/9	1126	88	14155.	2.9900	57608.5	0.014
Ep relay	2/13/9	6/15/9	852	88	10710.	3.0370	69366.5	0.003

$$F(t) = 1-\exp^{-}(t/\eta)^{\beta} \quad \textbf{(6.1)}$$

RD = last replacement date

CD = current date

duration = in days

HRS/WK = Hours of operation per week

The value for eta and beta will be stored in the knowledge-based system based on appropriate data from similar system. The age of the components (t) in hours can be determined based on last replacement date and the current date and the system weekly operating hours. Detailed construction and application of the knowledge-based system is shown in the next section.

6.6 Design of the RCM Knowledge-Based Decision Support System

Conventional procedures for building an expert system were discussed in Section 2.3. The design of this proposed RCM database system differs from the conventional procedures by the method used to acquire knowledge and the method of assigning confidence level values. This database system uses RCM techniques to obtain knowledge. The information identified by RCM techniques is stored in four database tables: Events. Causes. Problems and Symptoms. as discussed in Section 6.4. The value for a confidence level is based on the Weibull parameters and the usage time of the component in question as illustrated in Section 6.5.

The four tables Events. Causes. Problems. and Symptoms are linked in Microsoft Access database. The required fields are selected to produce the derived table shown in Figure 6.1. By using this derived table as the starting point for Queries. desired records can be found using the given criteria for known field or fields.

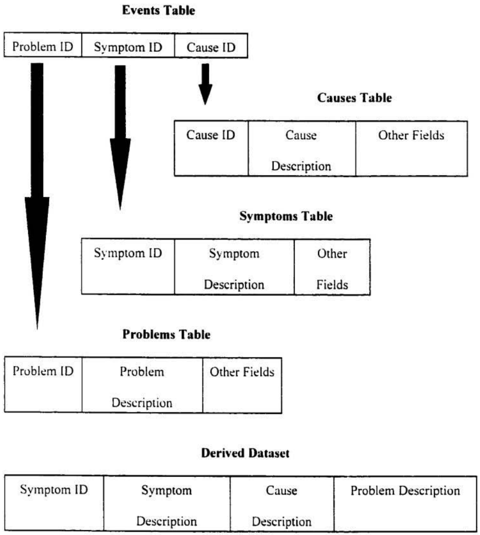


Figure 6.1 Relational Database

For example, the fresh air louver failure is caused by the following:

FAIL01	louver blocked by foreign matter
FAIL02	louver broken
FAIL03	louver damaged or removed

FAIL01 will cause the fresh air louver failure and is linked to Problem_ID FAIL. FAIL01 will cause low air flow and is linked to Symptoms_ID S02. It also will cause high static pressure and linked to Symptoms_ID S09.

FAIL02 will cause the fresh air louver failure and is linked to Problem_ID FAIL. FAIL02 will cause high air flow and is linked to Symptoms_S01. It also will cause low static pressure and link to Symptom_ID S10.

FAIL03 will cause the fresh air louver failure and is linked to Problem_ID FAIL. FAIL03 will cause high air flow and is linked to Symptoms_S01. It also will cause low static pressure and link to Symptom_ID S10.

Causes_ID can be identified either from Problem_ID or Symptoms_ID. In practice, before a system or a component failure, there is usually a symptom that can be identified and from this symptom, the causes can be traced back to the components and from the components to the root causes.

The detailed operational steps which show how the database tables are queried, using either symptoms or problem, are shown in section 6.6.2, with sample outputs shown in Table D-6.13 to Table D-6.26 in Appendix D.

The proposed knowledge-based system must be able to search root causes and also predict the F(t). The information identified by Weibull analysis in order to determine F(t) is stored in a table using ten fields. These are: last replacement date, current date, duration in days, hours of operation per week, the total operating hours, beta, eta, F(t), R(t) and CDF graph. Predictions can be achieved by adding the above field in Table 6.1 in order to force operators and maintenance personnel to record information at the root cause level.

6.6.1 Tables Design

Failure modes identified in the RCM table can be coded as Causes_ID (cause identification), which are the root causes of failure. A table named "Causes Identification" with the following fields is developed and listed as follows:

Table 6.6 Causes Identification

Field Name	Data Type	Description
Causes_ID	Text	Coding for Causes
Cause Description	Text	Cause description

Field Name	Data Type	Description
RD	Date/Time	Last replacement date
CD	Date/Time	Current Date
Duration	Number	Number of days between RD and CD
Hrs/WK	Number	Hours of operation per week
t	Number	Total hours of operation
beta	Number	parameter in Weibull analysis
eta	Number	parameter in Weibull analysis
F(t)	Number	Probability of failure
R(t)	Number	Reliability
CDF Graph	Hyperlink	Identification link to CDF Graph

The problems identified by RCM techniques and shown in related fault tree diagrams are stored in a table named "Problem Identification" and listed as follows:

Table 6.7 Problem Identification

Field Name	Data Type	Description
Problem_ID	Text	Coding for problem
Problem Description	Text	Problem description
Fault Tree	Hyperlink	Link to fault tree Diagram
F(t)	Number	Probability of failure
RCM	Hyperlink	RCM Table

Similarly all possible symptoms can be stored in a table named "Symptom Identification" with symptom identification as one row and the other row with symptom description as list.

Table 6.8 Symptom Identification

Field Name	Data Type	Description
Symptom_ID	Text	Coding for Symptom
Symptoms Description	Text	Symptom Description

Possible combinations of problems, symptoms and causes are combined in another table named "Events" and listed as follows:

Table 6.9 Events

Field Name	Data Type	Description
Problem_ID	Text	Coding for Problem
Symptoms_ID	Text	Coding for Symptoms
Causes_ID	Text	Coding for Causes

6.6.2 Query Design

There are a number of symptoms that exist in the system which can use backward chaining to identify problems and causes that produce certain symptoms and to determine F(t) and R(t) of specific components. This can be performed using Query in the Microsoft Assess and are discussed in the following section.

6.6.2.1 Searching methodology for root causes using Symptoms

The four tables "Events", "Problem", "Symptom" and "Causes" are used to design the query. The Field "Problem_ID" in the "Event" table is linked to "Problem_ID" field in "Problem" table. The "Symptoms_ID" field in "Event" table is linked to "Symptoms_ID" field in "Symptom" table. The "Causes_ID" field in the "Event" table is also linked to the "Causes_ID" in the "Causes" Table.

The query consists of the following fields: Symptoms_ID. Symptoms Description. Problem Description. and Causes Description. These fields are laid out in the above sequence as shown. The criteria under Symptoms_ID is "[LIKE]". This selection criteria allows a user to key in or select the Symptom using a specific code from the keyboard. The code for Symptoms_ID is shown in Table 6.3. With the Symptoms_ID. the root causes can be determined. Detailed design of the query is shown in Table 6.10.

The processing is centered on how to obtain an output that should list all causes that will create a certain symptom and then calculate F(t) and R(t) based on hours of operation. A query named "Query by Symptom" with the following fields is designed as follows:

Table 6.10 Query by Symptom

	Column 1	Column 2	Column 3
Field:	Problem_ID	Symptoms_ID	Symptoms Description
Table:	Events	Events	Symptom
Sort:			
Show:	☑	☑	☑
Criteria:		[LIKE]	
or:			
	Column 4	**Column 5**	**Column 6**
Field:	Problem Description	Fault Tree	RD
Table:	Problem	Problem	Causes
Sort:			
Show:	☑	☑	☑
Criteria:			
or:			
	Column 7	**Column 8**	**Column 9**
Field:	CD	HRS/WK	t:[Duration]*[HRS/Wk]/7
Table:	Causes	Causes	
Sort:			
Show:	☑	☑	☑

Criteria:			
or:			

	Column 10	Column 11	Column 12
Field:	beta	eta	F(t): 1-(Exp(-1*(([t]/[eta])^[beta])))
Table:	Causes	Causes	
Sort:			
Show	☑	☑	☑
Criteria:			
or:			

6.6.2.2 Given the Problem Use Symptom to Determine the Root Causes

Pinpointing the root cause based on the problem_ID identifies additional information supplied from Symptoms_ID, the causes-ID and Description.

The procedure to detect root causes is described as follows:

The four tables "Events", "Problem", Symptom" and "Causes" are used to design the query. The Field "Probelm_ID" in the "Event" table is linked to "Problem_ID" field in "Problem" table. The Symptoms_ID" field in "Event" table is linked to "symptoms_ID" field in "Symptom" table. The "causes_ID" field in the "Event" table is also linked to the "causes_ID" in the "Causes" Table.

The query consists of the following fields:
Problem_ID, Problem Description, Symptoms_ID, Symptoms Description and Causes Description. These fields are laid out in the sequences as shown above. The criteria under Problem_ID is "[LIKE]". This selection criteria allows user to key in the Problem from Key board. The criteria for Symptoms_ID is set as [*]. This allows user to key in the Symptoms_ID from keyboard. With the Problem_ID and the Symptoms_ID, the root causes can be determined. Detailed design of the query by this method is shown in Table 6.11.

The processing is centered on a given problem and using additional information from Symptom to obtain an output that should list all associated causes and then calculate F(t) and R(t) based on hours of operation. A query named "Query by Problem and Symptom " with the following fields is designed as follows:

Table 6.11 Query by Problem and Symptom

	Column 1	Column 2	Column 3
Field:	Problem_ID	Problem Description	Symptoms_ID
Table:	Problem	Problem	Symptom
Sort:			
Show	☑	☑	☑
Criteria:	[Enter Problem ID Code]		[Enter Symptom ID Code]
or:			

	Column 4	Column 5	Column 6
Field:	Symptoms Description	RD	CD
Table:	Symptom	Causes	Causes
Sort:			
Show	☑	☑	☑
Criteria:			
or:			

	Column 7	Column 8	Column 9
Field:	HRS/WK	Duration: DateDiff("d",[RD] ,[CD])	t:[Duration]*[HRS/Wk]/7
Table:	Causes		
Sort:			
Show	☑	☑	☑
Criteria:			
or:			

	Column 10	Column 11	Column 12
Field:	eta	beta	F(t): 1-(Exp(-1*(([t]/[eta])^[beta])))
Table:	Causes	Causes	
Sort:			
Show	☑	☑	☑
Criteria:			
or:			

6.6.3 Output

The output identifies the problems and causes that are associated with each symptom. Tables showing the problems and causes are listed in Table D-6.13 to D-6.26 in Appendix D.

The query does not create a specific report in a form that is clearly illustrated. Therefore, a customized report must be created such as Table 6.12 which leaves no doubt of accuracy in reading the material. Detailed procedures for creating a report can be found in Adamski (1996).

Table 6.12 Report Output for Symptom 03

Problem_ID	Problem Description	Cause Description	HRs/WK	RD	CD	Duration	t	beta	eta	F(t)	R(t)
FN	Fan Noise	Rattles and/or rumbles	88	2/15/96	7/26/99	1257	15802.29	1.1	5000	0.971157	0.028843024
FN	Fan Noise	gas velocity through cracks	88	2/15/96	7/26/99	1257	15802.29	1.1	5000	0.971157	0.028843024
FN	Fan Noise	pulsation or surge	88	2/15/96	7/26/99	1257	15802.29	1.1	5000	0.971157	0.028843024
FN	Fan Noise	High air velocity	88	2/15/96	7/26/99	1257	15802.29	1.1	5000	0.971157	0.028843024
FN	Fan Noise	Obstruction in high velocity	88	2/15/96	7/26/99	1257	15802.29	1.6	25000	0.381221	0.6187788782
FN	Fan Noise	impeller	88	2/15/96	7/26/99	1257	15802.29	1.1	1e+05	0.111589	0.8884112879
FN	Fan Noise	Impeller hitting inlet or	88	2/15/96	7/26/99	1257	15802.29	1.2	1e+05	0.103503	0.8964966985
FN	Fan Noise	shaft	88	2/15/96	7/26/99	1257	15802.29	1.2	1e+05	0.08405	0.915952965
FN	Fan Noise	impeller hitting cutoff	88	2/15/96	7/26/99	1257	15802.29	1.4	2e+05	0.04192	0.9580806677
FN	Fan Noise	Fan motor	88	2/15/96	7/26/99	1257	15802.29	2.466	62328	0.03334	0.9666570817
FN	Fan Noise	Shaft seal squeal	88	2/15/96	7/26/99	1257	15802.29	1.712	1e+05	0.02579	0.9742095453
FN	Fan Noise	bearing	88	2/15/96	7/26/99	1257	15802.29	1.712	1e+05	0.02579	0.9742095453
FN	Fan Noise	Drive	88	2/15/96	7/26/99	1257	15802.29	1.6	2e+05	0.01708	0.9829168639
FN	Fan Noise	coupling	88	2/15/96	7/26/99	1257	15802.29	1.5	3e+05	0.01577	0.984233925
FN	Fan Noise	housing	88	2/15/96	7/26/99	1257	15802.29	2.035	1e+05	0.01565	0.984351535

Chapter 7 MUN HVAC Case Study

7.1 Data Collection

There are many buildings located at the Memorial University of Newfoundland campus. However, most of them were built in the 1960 and 1970's. It is extremely hard to obtain failure data for the older buildings. However, Biotechnology Building started function on April 1992, Arts & Administration Building Extension started functioning on April 1992 and Earth Resource (CERR) Building started functioning on September 1989. These three buildings were selected to be used for data collection because they are relatively new and failure data were available. Each building start date was obtained from the University Works department. Detailed equipment specification and drawings were obtained through Honeywell Inc. Equipment operating schedules were obtained from Honeywell Inc and reconfirmed by University Works in order to establish time in operation before failure occurred. Existing maintenance practice for buildings under study is shown in Appendix H.

Information concerning the selected buildings is described as follows:

Biotechnology Building is located in the south campus and is a three storey building with 2512.7 square metres in area. There are three air handling units located inside the building to serve the building ventilation requirement. Detailed information concerning each air handling unit is shown in Appendix E.

Arts and Administration Extension is located in the south campus and is a 4 storey building with 8414.5 square metres in area. There are three air handling units located inside the building to serve the building ventilation requirement. Detailed information concerning each air handling unit is shown in Appendix F.

Earth Resource (CERR) Building is located in the north campus and is a 6 storey building with 21173.3 square metres in area. There are six air handling units located inside the building to serve the building ventilation requirement. Two units are used for laboratory ventilation, three units are used for make up air requirement, and one unit is used for general ventilation. Detailed information concerning each air handling unit is shown in Appendix G.

7.2 Data Analysis

The building data was collected and stored in data base table by using Access Data program. Each record consists of ten fields and the fields are listed as follows:

- work order #

- date
- time
- building
- room #
- mun (Memorial University of Newfoundland) wo# (work order number)
- requested by
- performed by
- description of the problem
- solution to the problem

However, work order #, MUN work order #, requested by and performed by fields are not related to our problem and are ignored.

The fields in each record were rearranged as follows:

- building
- date
- time
- room#
- description of problem
- solution to the problem

Since each building has a different operating schedule, in order to establish a meaningful study, the unit use for this study will be operating hour.

There are many failure modes and they are listed as follows:

- fan belts broken
- fan motor failure
- system unscheduled shutdown due to freeze protection
- fresh damper motor failure
- air filter failure and cause system failure
- fan bearing failure

The study consists of three elements:

- a detail study of the functions of each component in the system
- a fault tree analysis
- a mathematical model based on Weibull analysis to assess the likelihood of cause of failure, since an expert system cannot handle uncertainty

7.3 Methodology

Data from each building was studied in isolation where possible to determine the parameters of the Weibull failure distribution, eta and beta, using Weilbull Smith

Computer software developed by Fulton Findings TM. Then, data from a number of buildings will be combined to determine overall eta and beta. This data will be used to determine reliability in the mathematical model. Detailed input and output for this methodology is shown in Chapter 6.

Chapter 8 Results and Discussion

This chapter presents the results and discussion of:

1. Application of RCM process to a physical system, in this case a HVAC system, to acquire intended functions, functional failures, failure modes (cause of failure) and failure effects;

2. The failure modes identified by the RCM process are used to develop fault trees and are coded in the databases;

3. Perform failure data analysis using the Weilbull distribution to determine parameters;

4. Using the parallel, series and complex modelling system to develop a mathematical model;

5. Using a commercial database system to build a knowledge-based system based on the RCM, fault tree, Weibull distribution and the developed mathematical model.

8.1 RCM

RCM tables in Appendix A are developed as the result of the RCM process. These tables highlighted the components under analysis, intended functions, functional failures, failure modes (cause of failure) and failure effects of the components. These tables provide a systematic way to acquire and organize knowledge. The knowledge acquired has proved to be fundamentally sound, and can be explained by parameters in engineering equations. For the HVAC system under this study, these parameters are temperature, humidity, pressure, and flow rate.

The knowledge acquired from the RCM process is cross-referenced with knowledge derived from a select panel of professional engineers and designers. This group brings together HVAC consultants, teachers, equipment suppliers, and individuals with experience in operating and maintaining HVAC systems, including staff from Honeywell.

This panel includes:

- David Thompson, P. Eng., an HVAC equipment supplier and former consulting engineer.

- Michael Healey, P. Eng., an HVAC equipment supplier and former college instructor and mechanical contractor.
- Dave Smith, P. Eng., a consulting engineer and former college HVAC instructor.
- Ashok Chowdhury, P. Eng., a college HVAC instructor and former consulting engineer.
- Ray Green, Honeywell Inc., HVAC systems - maintenance
- Paul Walsh, Honeywell Inc., HVAC systems - maintenance

Many participants agree that the systematic approach of acquiring knowledge is much better than the conventional method. This again can be confirmed from Ontario Hydro which hired consultants with RCM experience to revamp their maintenance programs and the Iron Ore Company of Canada which is having its key maintenance personnel trained in the RCM process.

The feedback from three different perspectives are discussed. From the engineers' perspective, RCM process forces them to identify all intended functions that the system must be able to meet. This helps in formulating good design criteria and communicates this information to the operators and owners. This also acts as a check list for the design. From the operators' perspective, the results of the RCM process can help them to understand the system because the causes of functional failures are included in the RCM tables. This helps them in the troubleshooting process and speeds up the setup and adjustment required after each failure. From the maintenance personnel's perspective, they will understand the maintenance requirements. Failure modes can serve as criteria for instrumentation requirement in the design and the construction of system. Areas where effects of functional failures will have safety and environmental effects must be monitored by sensors to predict failures.

RCM provides the proper methodology to acquire knowledge for the development of an expert system. An RCM knowledge-based system that reasons from first principles (i.e., causal reasoning) and requires a specification of the functionality of the device's components to diagnose faults can be developed without the use of a domain expert or "shallow rules".

The following problems usually associated with conventional expert systems can be addressed through RCM techniques:

1. Shallow reasoning is incapable of handling unanticipated faults.
2. Significant lag time exists between initial construction of a device and the development of a conventional expert system for maintenance.
3. Devices commonly go through a series of design modifications, and it is unclear whether a shallow reasoning fault advisor is still correct after such modification.

RCM provides a formal documentation which enables designers to communicate effectively to the operators and maintenance personnel. It also serves as the first step towards total quality improvement. Without such document, it is extremely hard to implement continuous quality improvement. RCM is necessary to gain control of an operation. It is time consuming and expensive up front. RCM's returns are not realized quickly.

RCM can be applied to any physical system, such as an electrical system whose performance can be explained by voltage and current, or a civil related system which can be explained by stress and strength.

8.2 Fault Tree

The fault trees developed in Appendix B are good visual diagrams for operators to understand the interrelation of various failure modes that contribute to component failure. Failure modes can be coded and then used in a database. Failure modes identified are a good reference material for Root Failure Cause Analysis, which is required by the operators and maintenance personnel to operate and service the system efficiently and effectively. Fault Tree is a well accepted technique and appropriate for finding failure relationships. However, large fault trees are difficult to understand, bear no resemblance to system flow sheet.

8.3 Failure Data Analysis

Analysis of failure data will enable the eta and beta parameters in the Weibull distribution to be determined: this Weibull distribution can then be used to provide reasonable failure forecasts with extremely small samples. Mathematical models developed can be used to quantify the probability of failure. This quantitative approach based on operating hours is far more reliable than the confidence level established by experts in conventional expert systems, which in some cases cannot be substantiated. Further, failures can be minimized by comparing failure data between systems. A discussion of failure data for HVAC systems installed in three buildings at the Memorial University of Newfoundland is given in the following sections.

8.3.1 Failure of Fresh Air Intake Louver

Failure of fresh air intake louver is usually due to corrosion but there was no sign of failure during the span of the study. The location of the fresh air intake louver will affect the quality of air. If it is located near the path of car exhausts, it will cause poor air quality in the building. Further, the mounting height from the finish grade and the facing direction of the louver will affect performance of the pre-filter and cause the freeze protect system to be activated. This is discussed in more detail in sub-sections 8.3 and 8.5.

8.3.2 Failure of Linkage in Fresh Air Damper

The linkage usually breaks down on the fresh air damper after a certain length of time because the ball joint becomes worn. The remedial action was to replace the ball joint and adjust or replace the linkage. Failure data are present in Table 8.1 as shown.

Table 8.1 Failure Data for Fresh Air Damper

Building Name	System Name and Type	Failure Data
Arts/Ext *(Arts & Administration Building Extension of MUN)*	AHU#1 VAV *(air handling unit number)* *(variable air volume)*	no failure after 30481 hrs
Arts/Ext	AHU#2 Constant Vol	no failure after 30481 hrs
Biotechnology	AHU#1	one failure after 28944 hrs no failure after 26135 hrs
Biotechnology	AHU#2	no failure after 55080 HRS
CERR	GVU-1 *(general ventilating unit)*	one failure after 27326 hrs no failure after 11028 HRS
CERR	LMU-1 *(laboratory makeup unit)*	no failure after 80544 HRS
CERR	LMU-2	one failure after 34680 hrs no failure after 45864 HRS
CERR	LMU-3	one failure after 49632 hours no failure after 30912 hours
CERR	LVU-1 *(laboratory ventilating unit)*	no failure after 38354 HRS
CERR	LVU-2	no failure after 38354 hrs.

Based on the above failure data,

the eta is determined to equal 51996.59, and

the beta is determined to equal 3.853321.

8.3.3 Failure of Pre-Filters and Filters

The life span of the filters is undetermined and is mainly affected by the operating environment. The pre-filter change policy had changed from once every three months to a full year, and then further revised to once every six months. The air filters were changed once a year or when the static pressure drop through the filter reached 25 mm. Filters can be damaged by snow or undesired dampness in fresh air. The pre-filters were occasionally out of place mainly because the filter medium sagged. The Arts & Administration Building Extension with intake louver located high up on the wall surface at level 5, facing South West and with a low velocity of 1.2 m/s, experienced no filter failure due to rain or snow. The Biotechnology building system tripped out due to freeze protection system in 1996. The intake louver is facing North and at ground level with intake velocity of 1.6152 m/s at the intake louver and 0.6167 m/s in the intake plenum. The intake louver is higher than the intake for the air handling system, and this caused stratification and allowed snow to enter the unit. The CERR building with intake louver facing North and at ground level had experienced system shut down 12 times due to freeze protection system, but no failure due to filter medium sagging in pre-filter. This is mainly because of the long distance between air intake louver and the motorized damper to the HVAC units. Failure data for the pre-filter is presented in Table 8.2 and failure data for the filter is presented in Table 8.3.

Pre-filter:

Table 8.2 Failure Data for Pre-filter

Building Name	System name	Failure data
Arts/EXT	All system	2160 hours 4320 hours 8640 hours
Biotechnology	All system	2160 hours 4320 hours 8640 hours
CERR	All system	2160 hours 4320 hours 8640 hours

Based on the above findings,

eta is determined to equal 5997.463, and

beta is determined to equal 1.398.

Filter

Table 8.3 Failure Data for Air Filter

Building Name	System name	Failure data
Arts/EXT	All system	8640 hours
Biotechnology	All system	8640 hours
CERR	All system	8640 hours

Based on the above findings,

eta is determined to equal 8658 and

beta is determined to equal 221.61

Pre-filter and filter manufacturers recommend maintenance programs. However, most do not consider the "operating context". The present scheduled maintenance program for pre-filter and filter is questionable because it is the same for all buildings with different working environments and different operating conditions. The timing for scheduled maintenance for pre-filter had been changed three times with no sound rationale for Preventive Maintenance (PM) actions. The predictive maintenance strategy for measurement of pressure drop through the filter is a good strategy. However, the setting is set so high that the effectiveness is questionable. Further, there is no monitoring in the pre-filter section where the life span is much shorter than the filter. The current practice should be re-evaluated because conditioning monitoring has the potential for significant payoff when it can be used to tell when it is necessary to perform some maintenance task, thus precluding both unnecessary as well as premature preventive maintenance actions that otherwise would occur.

8.3.4 Failure of Heating Coil

Only one heating coil failure occurred on December 27, 1998 in the CERR Building where the heating coil in LMU-2 was frozen. The cause of failure is still under investigation by University Works. There were human errors in a few instances. For example, the heat pump was turned off in Arts/Ext building and the scheduled water temperature was turned down. There is not enough failure data in this case to predict failure.

Table 8.4 Failure Data for Heating Coil

Building Name	System Name and Type	Failure data	Reason
Arts/Ext	AHU#1 &2	failed on Aug 28/95 after 15727.7 hours	Heat pump off
Arts/Ext	AHU#1 & 2	failed on Jan 30/96 after 17687.35 hours	Scheduled water was turned down

Building Name	System Name and Type	Failure data	Reason
CERR	LMU-2	failed on Dec 28/98 after 81720 hours	heating coil frozen

The reliability of the heating coil not only depends on the heating coil, but also the heating circulating pump, which in turn depends on the pump motor, direct coupling and impellers. The cause of recent heating coil failure should be identified.

8.3.5 Failure of Freeze Protection System

System failures due to freeze protection did not occur in the Arts & Administration Building Extension, mainly because the intake louver is located high up on the wall surface at level 5 and facing South West. The Biotechnology building experienced system trip out due to freezestat in 1996. The intake louver is facing North and at ground level. The intake louver is higher than the intake for the air handling system and this caused stratification and allowed snow to enter the unit.

Table 8.5 Failure Data for Freeze Protection

Building Name	System Name and type	Failure Data
Arts/Ext	AHU#1 VAV	no failure after 30481 hours
Arts/Ext	AHU#2 VAV	no failure after 30481 hours
Biotechnology	AHU#1 VAV	no failure after 17197 hours
Biotechnology	AHU#2 Constant Volume	failure once on 12/02//96
CERR	GVU-1	not known*
CERR	LMU-1	failed on 30/01/97
CERR	LMU-2	not known Coil frozen on Dec 28/98
CERR	LMU-3	failed on 24/11/93
CERR	LVU-1	failed on 28/02/95 failed on 22/01/97
CERR	LVU-2	failed on 14/12/95 failed on 16/01/96 failed on 20/02/96 failed on 17/01/97 failed on 24/01/97

However, there are three more failures in CERR building due to freeze protection in 14/02/94, 13/12/94 and 31/10/95, but the record failed to clearly identify with which units in the building.

Most of the failures occurred in late October to February and only happened to the units with North facing air louver. Therefore, the probability should be conditional probability based on time of the year, and is independent of usage.

In addition to the climatic condition, freeze protection is also a function of the reliability of the heating circulating pump, which depends on the pump motor, direct coupling and impellers.

Discussion with operators and maintenance personnel indicated that they only have time to restore the system back to operation. They are not given enough time to investigate why the equipment failed, and hence, how to correct the deficiency permanently. The result is that the same problem recurs. This repetitive failure problem can only be resolved once the root cause of equipment failure is understood and resources supplied to remove the root cause.

8.3.6 Failure of Cooling Coil

There is no cooling capability in the CERR building. Therefore there are no cooling coils in the heating and ventilating units. There were no cooling failures in the Arts/Ext building. There was only one failure in the control valve after 37320 hours of operation. Unfortunately there were not enough data to perform any meaningful modeling. In Newfoundland, the cooling requirement is very short, and with visual inspection once a year in spring before cooling system start up may be sufficient to ensure the required reliability.

Table 8.6 Failure Data for Cooling Coil

Building Name	System Name and Type	Failure Data
Arts/Ext	AHU#1	no failure after 30481 hours
Arts/Ext	AHU#2	no failure after 30481 hours
Biotechnology	AHU#1	
Biotechnology	AHU#2	Control valve failed after 37320 hours
CERR	no cooling coil exists	

8.3.7 Failure of Humidifiers

There were no proper records on the failure of the humidifiers because Honeywell Inc. was not responsible for the maintenance of the humidifiers. On an October 1998 site visit, the following findings were noted.

The steam distributors for Arts/Ext building were located in the duct work located downstream of the fan section. All humidifiers in the Arts/Ext building were working properly. In the Biotechnology and CERR building, all humidification steam distributors are located upstream of the fan section within the air handling units. There were corrosion problems in the fan sections mainly due to the high humidity level. In the CERR building, all humidifiers failed at the end of 1997 and the system was not working. Although there were two humidification systems in the Biotechnology building , there was only one working. Failure data are presented in Table 8.7.

Table 8.7 Failure Data for Humidifiers

Building Name	System Name	Failure data	Reason
Arts/Ext	AHU#1	no failure after 30481 hours	
Arts/Ext	AHU#2	no failure after 30481 hours	
Biotechnology	AHU#1	System was never in operation	
Biotechnology	AHU#2	Humidification was low after 29856 hours	Breaker was shut off.
CERR	GVU-1	failed after 33737 hours	
CERR	LMU-1	Failed after 70848 hours	
CERR	LMU-2	failed after 70848 hours	
CERR	LMU-3	failed after 70848 hours	
CERR	LVU-1	failed after 33737 hours	
CERR	LVU-2	Failed after 33737 hours	

Based on the above data,

eta was determined to equal 57608.58, and

beta was determined to equal 2.999.

8.3.8 Fan Failure

8.3.8.1 Fan Belts

Most hot water heating or steam heating systems are required to have the heating coil on when the systems shut down. This is a protection procedure to prevent the coil from freezing. This procedure may create temperatures as high as 50 degree C within the unit. This causes fan belts to deteriorate and leads to premature belt failure. Fan belts located in the return system or heat recovery system had life spans 2 to 3 times longer than those in the supply system. This is mainly due to the fact that the fan belts were exposed to constant room temperature and not subject to the high heat situation of the supply system.

Also the arrangement of the fan motor will affect the life span of the belts. If the fan motor and the belts are located outside the unit at a constant ambient temperature, the belts usually last longer because they are not subjected to high temperature.

8.3.8.2 Remedial Action

The above failures can be rectified by new control methods. For a recirculating system, when the unit is running, the heating coil will be controlled by the supply air temperature sensor. When the unit is shut down, the coil will be controlled from a mixed air sensor to prevent overheating while still protecting the heating coil. In 100% fresh air units, an extra sensor located upstream of the coil will be added to control the coil when the unit is shut down.

Since fan belts seem to be the weakest link in the fan, it is highly recommended that the following information should be checked:

- motor horse power
- motor driver rpm
- driven (fan) rpm
- center distance between motor shaft and fan shaft
- the diameter of the motor shaft and the diameter of the fan shaft

Computer analysis should be employed to ensure proper selection of fan belts.

Table 8.8 Failure Data for Fan Belts

Building Name	System Name and Type	Failure Data
Arts/Ext	AHU#1 VAV	with only one set of belts failure after 6385 hours
Arts/Ext	AHU#2 VAV	with only one set of belts failure after 11505 hours
Arts/Ext	AHU#3 Constant Volume	no failure after 17197 hours
Biotechnology	AHU#1 VAV	failed after 18766.0 hours
Biotechnology	AHU#2 Constant Volume	failed after 14789.29 hours
Biotechnology	AHU#3 Heat Reclaim	with only one belt failure after 46704 hours
CERR	LMU#1	
CERR	LMU#2	
CERR	LMU#3	
CERR	LVU#1	
CERR	LVU#2	
CERR	GVU#1	

Based on the above findings,

eta has been determined to equal 20464.3, and

beta has been determined to equal 2.1467.

8.3.8.3 Vortex Vanes

Table 8.9 Failure Data for Vortex Vanes

Building Name	System Name and Type	Failure Data
Arts/Ext	AHU #1 VAV	no failure after 28990 hours
Arts/Ext	AHU #2 VAV	no failure after 28990 hours
Arts/Ext	AHU #3 Constant Volume	no failure after 17200 hours
Biotechnology	AHU#1 VAV	failure after 20079.97 hours
Biotechnology	AHU#2 Constant Volume	N/A
Biotechnology	AHU#3 Heat Reclaim	N/A
CERR	LMU#1	with only one failure after 59232 hours
CERR	LMU#2	with only one failure after 74856 hours
CERR	LMU#3	N/A
CERR	LVU#1	no failure after 37977 hours
CERR	LVU#2	no failure after 37977 hours
CERR	GVU#1	no failure after 37977 hours

Based on the above findings,

eta has been determined to equal 68043.08, and

beta has been determined to equal 1.639.

8.3.8.4 Fan Bearing

During the unoccupied period, due to the freeze protection, the grease will dry up much faster and cause the bearing to fail.

Table 8.10 Failure Data for Fan Bearing

Building Name	System Name and type	Failure Data
Arts/Ext	AHU #1 VAV	no failure after 28900 hours
Arts/Ext	AHU #2 VAV	no failure after 28900 hours
Arts/Ext	AHU #3 Constant Volume	no failure after 17200 hours
Biotechnology	AHU#1 VAV	no failure after 55176 hours
Biotechnology	AHU#2 Constant Volume	with only one failure after 31272 hours
Biotechnology	AHU#3 Heat Reclaim	no failure after 55176 hours
CERR	LMU#1VAV	no failure after 79752 hours
CERR	LMU#2 VAV	failure after 75528 hours
CERR	LMU#3 Variable Speed	no failure after 79752 hours
CERR	LVU#1 VAV	no failure after 37977 hours
CERR	LVU#2 VAV	no failure after 37977 hours
CERR	GVU#1 VAV	no failure after 37977 hours

Based on the above findings,

eta has been determined to equal 132780.2, and

beta has been determined to equal 1.712307

8.3.8.5 Fan Assembly

Table 8.11 Failure Data for Fan Assembly

Building Name	System Name and type	Failure Data
Arts/Ext	AHU #1 VAV	no failure after 28900 hours
Arts/Ext	AHU #2 VAV	no failure after 28900 hours
Arts/Ext	AHU #3 Constant Volume	no failure after 17200 hours
Biotechnology	AHU #1 VAV	no failure after 55176 hours
Biotechnology	AHU #2 Constant Volume	no failure after 55176 hours
Biotechnology	AHU #3 Heat Reclaim	no failure after 55176 hours
CERR	LMU#1	no failure after 79752 hours
CERR	LMU#2	failure after 75528 hours
CERR	LMU#3	no failure after 79752 hours
CERR	LVU#1	failure after 35965 hours
CERR	LVU#2	no failure after 37977 hours
CERR	GVU#1	no failure after 37977 hours

Based on the above findings.

eta has been determined to equal 121417.4. and

beta has been determined to equal 2.035.

8.3.8.6 Fan Motor

Fan motors used in a variable volume system will have a shorter lifespan than motors working in a constant volume system. In older designs, the motor for the air handling unit was located outside the air stream. The motor was not influenced by the air flow. However, in the new design, the motor is located within the unit and influenced by the air temperature and the humidity level of the air. High humidity will cause a motor which is not totally enclosed to corrode and burn out. High temperature will cause the motor to fail because most of the motors in this type of application are not designed to operate in high temperature environment. Failure data is presented in Table 8.12.

Table 8.12 Failure Data for Fan Motor

Building Name	System Name and type	Failure Data
Arts/Ext	AHU#1 VAV	no failure after 28990 hours
Arts/Ext	AHU#2 VAV	no failure after 28990 hours
Arts/Ext	AHU#3 Constant Volume	no failure after 17200 hours
Biotechnology	AHU#1 VAV	motor failed after 22800 hours
Biotechnology	AHU#2 Constant Volume	no failure after 55176 hours
Biotechnology	AHU#3 Heat Reclaim	no failure after 55176 hours

Building Name	System Name and type	Failure Data
CERR	LMU#1	no failure after 79752 hours
CERR	LMU#2	no failure after 79752 hours
CERR	LMU#3	one failure after 48984 hours and one failure after 21528 hours
CERR	LVU#1	failure after 35965 hours
CERR	LVU#2	no failure after 37977 hours
CERR	GVU#1	no failure after 37977 hours

Based on the above findings,

eta has been determined to equal 62328.46, and

beta has been determined to equal 2.466.

8.3.9 Failure of Electric/Pneumatic (EP) Relay

Three common modes of failures for the EP relay are leakage of compressed air, solenoid failure and the cracking of the plastic housing. Since solenoid failure and the cracking of the plastic housing do not occur and are ignored in this study, the reliability of this device is determined solely by the quality of compressed air in terms of moisture and oil. The quality of compressed air also depends on air filter, air dryer, PRV station compressor and air line. There is only enough failure data to model for EP leaking failure mode.

Table 8.13 Failure Data for EP Relays

Building Name	System Name and Type	Failure Data
Arts/Ext	AHU#1 VAV	no failure after 28900 hours
Arts/Ext	AHU# 2 VAV	no failure after 28900 hours
Arts/Ext	AHU#3 Constant Volume	no failure after 17200 hours
Biotechnology	AHU#1 VAV	no failure after 55176 hours
Biotechnology	AHU#2 Constant Volume	no failure after 23688 hours
Biotechnology	AHU# 3 Heat Reclaim	no failure after 55176 hours
CERR	LMU#1	no failure after 79752 hours
CERR	LMU#2	failure after 46320 hours
CERR	LMU#3	failure after 70512 hours
CERR	LVU#1	no failure after 37977 hours
CERR	LVU#2	no failure after 37977 hours
CERR	GVU#1	no failure after 37977 hours
CERR	Main compressed air supply	two failures both at 56088 hours

Based on the above findings,

eta has been determined to equal 69366.52, and

beta has been determined to equal 3.037.

No failure occurred for compressed air system in Biotechnology and Arts/Ext. However, in CERR building the services required for:

1. Compressors after 51552 hours
2. Air filter after 69192 hours

3. Air dryer after 70632 hours

Failure data analysis will enable maintenance personnel to identify the weakest links in the system This is reflected by failure mode with a low value of eta. The system reliability can be increased if there are means to increase the value of eta. As this failure data analysis apply to the HVAC system for three buildings at MUN, eta for fan belts can be increased if the humidifies are installed away from the fan. The maintenance personnel should use the mathematical model for maintenance activities to ensure the components and the systems are maintained to their established reliability requirements based on previously supplied scientific data.

8.4 Mathematical Model

The mathematical model for various components is discussed in detail in Chapter 5. Even though there are many failure modes which can happen to a fan, only fan belts, vortex vanes, fan bearing, fan assembly, and fan motor failure had occurred during this study. Basically all the system and subsystem reliability can be modeled by parallel system, series system, and the complex system. The model for reliability for the HVAC system R(t)S is as shown in equation 5.11.

$$R(t)S = R(t)FAN * R(t)AF * R(t)CCS * R(t)FAD * R(t)CFP * R(t)HSF * R(t)CSF \qquad \textbf{(5.11)}$$

where,

R(t)S	=	Reliability for the system
R(t)Fan	=	Reliability for the fan
R(t) AF	=	Reliability for air filter
R(t)CCS	=	Reliability for the computer control system
R(t)FAD	=	Reliability for fresh air damper
R(t)CFP	=	Reliability for coil freeze protection system
R(t)HSF	=	Reliability for Heating System
R(t)CSF	=	Reliability for Cooling System

where,

$0 < R(t)S < 1$

There are many methods which may be used to optimize reliability. H.L. Resnikoff (1978) recommends partitioning the system into many subsystems. In the case of HVAC systems. the subsystems consist of fan. air filter. computer control system. fresh air damper. coil freeze protection system. heating system. and cooling system with corresponding equations shown in Chapter 5. If the failure modes associated with each subsystem can be minimized. then the subsystem reliability will be increased. This will in turn increase the reliability of the system and increase the availability of the system since total reliability in this case is the product of all the subsystem reliabilities. This mathematical model methodology can be applied to any physical system. If there are no previous failure data available for a specific system, then eta and beta from a similar system with similar operating conditions can be used. Failure data can then be generated using Monte Carlo method. Simulation software (e.g. SuperSmith) provides this capability. This model is based on Weibull distribution but models based on normal distribution, log normal distribution and maximum likelihood can be used, and again are options with the simulation software. If the cost of unplanned failure from a wear out failure mode is greater than the cost of a planned replacement, there will be an optimal interval. This is another option with simulation software.

For example, if the failure data for fan belts as listed in Table C-5.3 were used as input to the WinSmith program of the SuperSmith Software and a distribution analysis performed, the result of the analysis will be as follows:

Table 8.14 **Distribution Analysis (Regression) for Fan Belts using 2 Parameter Weibull, 3 Parameter Weibull, logNormal, and Normal Distribution**

Weibull [t0 = None ... 2 Parameter] Correlation(r)=.9792855 r^2=.959 ccc^2=.8704 r^2-ccc^2= .0886 (Okay) Characteristic Value=20464 Weibull Slope=2.147 Method=rr
Weibull [t0 = 1035.717 ... 3 Parameter] [Scale Not As Recorded] Correlation(r)=.9797959 r^2=.960 ccc^2=.9364 r^2-ccc^2= .0236 (Okay) Characteristic Value=19681 Weibull Slope=1.911 Method=rr/t0^
LogNorm [t0 = None ... 2 Parameter] Correlation(r)=.9751922 r^2=.951 ccc^2=.8857 r^2-ccc^2= .0653 (Okay) Log-Mean Antilog=17124 Std. Dev. Factor=1.992 Method=rr
Normal+ [t0 = None ... 2 Parameter] Correlation(r)=.9848858 r^2=.970 ccc^2=.8857 r^2-ccc^2= .0843 (Okay) Mean=17431 Std. Deviation=7890 Method=rr
Optimum Distribution: Weibull [t0 = None ... 2 Parameter]

where,

CCC^2 = Square of Critical Correlation Coefficient

The best distribution is the one with the largest positive difference, r^2 - CCC^2.

This analysis indicated the Weibull Distribution with two parameter is the optimum distribution for failure data for fan belts. However, in some other case, log-normal or normal distribution will be the optimum distribution.

If the same failure data for fan belts are used with the following conditions:

A. Analysis parameter Eta = 20464.3, Beta = 2.1467

B. Block Replacement = No

C. View Length units = 20,000 Hrs.

D. Cost Each Planned Replacement ($) = 150

E. Cost Each Not Planned Replacement ($) = 500

Then the optimum replacement interval can be determined as follows:

Table 8.15 Weibull Optimum Replacement Interval for Fan Belts

RESULTS Date: M11-D12-YR1999

Eta = 20464.3 Beta = 2.1467

Cost / Item [$] Planned = 150 Cost / Item [$] Not Planned = 500

At Optimum (13333.33) Steady-State: Replacement Rate [/Unit-Units] =

5.034206E-05

Failure-Rate (FR) [/Unit-Units] = 2.465794E-05 MTBF(1/FR) = 40554.89

Cost/Time [$/Units]:

Units.........Cost		Units.........Cost		Units.........Cost		Units.........Cost	
333.3	.4502	5333	.0323	10333	.02316	15333	.02272
666.7	.2254	5667	.03094	10667	.023	15667	.02278
1000	.1507	6000	.02976	11000	.02287	16000	.02285
1333	.1134	6333	.02874	11333	.02276	16333	.02292
1667	.09114	6667	.02786	11667	.02268	16667	.023
2000	.07639	7000	.02708	12000	.02261	17000	.02309
2333	.06594	7333	.02641	12333	.02257	17333	.02317
2667	.05817	7667	.02582	12667	.02254	17667	.02326
3000	.05219	8000	.0253	13000	.02252	18000	.02336
3333	.04747	8333	.02485	13333*	.02252	18333	.02345
3667	.04365	8667	.02446	13667	.02253	18667	.02355
4000	.04053	9000	.02411	14000	.02255	19000	.02365
4333	.03793	9333	.02382	14333	.02258	19333	.02375
4667	.03574	9667	.02356	14667	.02262	19667	.02385
5000	.03389	10000	.02334	15000	.02267	20000	.02395

Another example, if the failure data for fan Vortex Vanes as listed in Table C-5.5 were used as input to the WinSmith program of the SuperSmith Software and a distribution analysis performed, the result of the analysis will be as follows:

Table 8.16 **Distribution Analysis (Regression) For Vortex Vanes using 2 Parameter Weibull, 3 Parameter Weibull, logNormal, and Normal Distribution**

Weibull [t0 = None ... 2 Parameter] Correlation(r)=.9884331 r^2=.977 ccc^2=.8021 r^2-ccc^2= .1749 (Okay) Characteristic Value=68043 Weibull Slope=1.639 Method=rr
Weibull [t0 = 4155.506 ... 3 Parameter] [Scale Not As Recorded] Correlation(r)=.9889388 r^2=.978 ccc^2=.899 r^2-ccc^2= .079 (Okay) Characteristic Value=64514 Weibull Slope=1.387 Method=rr/t0^
LogNorm [t0 = None ... 2 Parameter] Correlation(r)=.9767292 r^2=.954 ccc^2=.8117 r^2-ccc^2= .1423 (Okay) Log-Mean Antilog=50925 Std. Dev. Factor=2.326 Method=rr
Normal+ [t0 = None ... 2 Parameter] Correlation(r)=.9848858 r^2=.970 ccc^2=.8117 r^2-ccc^2= .1583 (Okay) Mean=57341 Std. Deviation=30403 Method=rr
Optimum Distribution: Weibull [t0 = None ... 2 Parameter]

where,

r = Correlation coefficient. used to measure the strength of a linear

relationship between two variable

CCC^2 = Square of 90% Critical Correlation Coefficient

The best distribution is the one with the largest positive difference. r^2 - CCC^2.

In this case, two parameter Weibull is the optimum distribution.

If the same failure data for fan belts are used with the following conditions:

A. Analysis parameter Eta = 68043, Beta = 1.639

B. Block Replacement = No

C. View Length units = 60,000 Hrs.

D. Cost Each Planned Replacement ($) = 250

E. Cost Each Not Planned Replacement ($) = 1000

Then the optimum replacement interval can be determined as follows:

Table 8.17 Weibull Optimum Replacement Interval for Vortex Vanes

RESULTS Date: M11-D12-YR1999

Eta = 68043.08 Beta = 1.638581

Cost / Item [$] Planned = 250 Cost / Item [$] Not Planned = 1000

At Optimum (48000) Steady-State: Replacement Rate [/Unit-Units] = 1.184643E-05

Failure-Rate (FR) [/Unit-Units] = 8.9869E-06 MTBF(1/FR) = 111273.1

Cost/Time [$/Units]:

Units........	Cost	Units........	Cost	Units........	Cost	Units........	Cost
1000	.251	16000	.02057	31000	.01544	46000	.01468
2000	.1264	17000	.01983	32000	.01533	47000	.01468
3000	.08512	18000	.0192	33000	.01523	48000*	.01467
4000	.06461	19000	.01865	34000	.01514	49000	.01467
5000	.05242	20000	.01817	35000	.01506	50000	.01468
6000	.04437	21000	.01774	36000	.015	51000	.01468
7000	.03868	22000	.01737	37000	.01494	52000	.01469
8000	.03447	23000	.01704	38000	.01488	53000	.0147
9000	.03124	24000	.01675	39000	.01484	54000	.01471
10000	.0287	25000	.01649	40000	.0148	55000	.01472
11000	.02665	26000	.01626	41000	.01477	56000	.01474
12000	.02497	27000	.01605	42000	.01474	57000	.01475
13000	.02358	28000	.01587	43000	.01472	58000	.01477
14000	.02241	29000	.01571	44000	.01471	59000	.01479
15000	.02141	30000	.01557	45000	.01469	60000	.01481

The required R(t)S various substantially based on the type of occupancy and the intended use of the space served by the HVAC system. For example, the R(t)S for HVAC system used in for operating room in hospital will be very high and will be low in normal office building. Further, the reliability of the total system cannot be higher than the value of the reliability of any subsystem. The reliability of the subsystem cannot be higher than the reliability of the failure modes within the subsystem. The optimum replacement interval for individual failure mode is a function of planned replacement cost and unplanned replacement cost. The reliability of the system also can be influenced by the geographical location where the systems are installed. In Newfoundland, the requirement for heating is long and the cooling requirement is low. This also has an impact on maintenance strategy.

8.5 Knowledge-Based System

The knowledge-based system developed using information obtained by the RCM method can address most of the faults encountered and is described in detail in Chapter 6. The information obtained can be explained by fundamental engineering theory. In this case, temperature, humidity, pressure, flow rate, and vibration are the parameters in the expert system used to trace the cause of failure. Based on the symptoms of these parameters, trouble shooting can be performed. The outputs of this knowledge-based system for troubleshooting are listed in Table D- 6.13 to Table D-6.26 in Appendix D. The database system can be easily modified by adding additional records if additional failure mode encounters. It is easy to use and link the RCM worksheets and fault tree figures by the built-in hypertext capability of the database system. The failure data obtained from this study can be used to predict the risk of failure for the components of the HVAC system based on the Weibull distribution. The developed knowledge-based system proves that an expert system that reasons from first principles (i.e., causal reasoning) and requires specification of functionality of the components to diagnose faults can be developed without the use of a domain expert or "shallow rules". This database system can be used for troubleshooting and used to predict failure based on Weibull distribution. This thesis uses HVAC system as a work example. However, such methodology can be applied to any physical system. The main advantages are that it can be used for training operators and maintenance personnel. It quantifies the prediction of failure based on sound engineering approach instead of arbitrary assigned value from domain expert. This developed expert system provides an integrated approach to response to failure.

8.6 RCFA

Root cause failure analysis can be applied to the fresh air intake louver, pre-filter, and fan belts to determine the root causes which are discussed in Section 8.2. However, the failure of freeze protection, humidifier, heating system, and cooling system cannot be determined because the failure data does not indicate which physical components failed in each case. A training program for the maintenance and operating personnel must be in place to have the personnel trained to record information properly before RCFA can be performed.

RCFA is in real time. It deals with today's problems and eliminates them from being tomorrow's problems. Bottom-line results can be immediate if recommendations are acted on quickly. RCFA can be proactive when accepted chronic failures that comprise the maintenance budget are eliminated from recurring. RCM coupled with RCFA covers all the bases in moving towards total failure avoidance.

Chapter 9 Conclusions, Contributions and Findings

9.1 Conclusion

This thesis has presented a new. enhanced methodology for a knowledge-based system development which integrates qualitative and quantitative tools. This improved system bridges previous gaps in predicting components failure within a system. as well as trouble shooting when failures occur. Previous methods relied upon input from experts. which cannot be integrated with qualitative and quantitative tools as described in this thesis. The model used here predicts component failures within a typical HVAC system. but it can also be applied generically to other systems.

The improved database decision support system developed in this thesis integrates the following qualitative and quantitative tools:

* Qualitative Tools: Reliability Centred Maintenance was combined with a Fault Tree analysis to formulate a model for the system. This model is based on the actual physics of the system. not on the experience and knowledge of experts as in classical expert systems. The reliability model

is used as the basis for the mathematical model which has been developed to predict failures. The failure modes associated with each component failure are used as inputs for the database system.

* Quantitative Tools: Based on actual failure data analyse, parameters for the Weibull distribution can be estimated. The Weibull distribution model is then incorporated into the database system to estimate probabilities of failure.

By using this improved database decision support system, a ranking of failure probabilities can be derived for each of the failure modes within any system. To implement this system, maintenance personnel must input data pertaining to failure modes into the mathematical model. This is required to estimate the parameters for a Weibull Distribution, namely last replacement dates for each component, weekly hours of operation, and the current date. By using this information, the mathematical model, with parameters established from previous failure data, will provide a list of probabilities for the root causes when a failure occurs, based on the symptoms entered into the computer. This helps narrow-down the causes of failure, shortens downtime, and thereby increases system availability. However, the estimation of parameters for the Weibull distribution is a basic problem that faces all new maintenance programs. Data specific to the system at hand have to be completed before the program can be effective. This difficulty can be circumvented by using similar data from similar situation elsewhere.

Using Microsoft Access as a shell for the database decision support system, new failure information can readily be added to the database. This allows for integrating new information into the expert system, without the need for extensive computer programming. The advantages of using Microsoft Access are that it is a flexible, high-quality program which has widespread use.

9.2 Contributions

The developed database system is superior to classical expert systems for the following reasons:

1. The RCM Tables A-3.2 to A-3.11 developed in the database system can be used as a decision tool for the optimized operations and maintenance because it states the function, functional failure, failure mode (cause of failure) and failure effects. This will help maintenance personnel to focus on the impact of each failure mode and to determine a priority in maintenance strategy.

2. Fault Tree figures B-4.3 to B-4.19 developed during the development of the database system provide a good visual picture for all technical personnel, clearly showing the causes of a particular failure. It provides a clear, concise visual outline of individual failures in a sub-system.

3. The acquired parameters for the Weibull distribution, based on the failure data from three buildings located at the Memorial University of Newfoundland, can be used to predict component reliability and failure. These parameters are shown in Table C-5.1 to Table C-5.13. These parameters can be used to model similar buildings in similar geographical location.

It has been shown that the two parameter Weibull distribution model used in the developing the database system is better than the three parameter, log-normal or normal distribution, see Table 8.14 and Table 8.16.

This quantitative approach, based on operating hours, is more scientific than the confidence level established by experts in conventional expert systems and it provides a more reliable quantitative feedback to the operators of the most likely causes of failure. Maintenance strategies can then be developed to meet the established reliability requirement for the intended usage.

4. The database portion of the knowledge-based system enables us to retrieve information easily and the built-in hyperlink capability enables us to link to RCM Tables and Fault Tree figures without any programming

requirements. This built in function also enables us to rank failure probabilities without extensive programming requirements. Most maintenance departments in industry have the required Access program or a similar database program installed, and can therefore use the database system developed in this way . The developed database system can link failure modes at the root cause level based on certain symptoms as shown in Table D-6.13 to Table D-6.25. It provides a suitable tool for the operator and/or the maintenance personnel to record the failure data at the root cause level.

9.3 Findings derived from the MUN HVAC case study

1. Problems repeated themselves without the root cause initially being identified.

   These included:

   - premature failure of fan belts in the Earth Science Building
   - failure of the pre-filter in the Biotechnology Building
   - failure of the freeze protection components in the HVAC systems in the Earth Science Building

These problems persisted because the operators did not address the root causes of the failures, but instead merely replaced failed components.

2. A subsequent analysis of the failures determined the root causes to be as follows: In the case of premature failure of the fans, both humidifiers were located too close to the fan. This is reflected in the Earth Resource Building when the humidifiers in the HVAC systems failed, which had the effect of increasing the life span of fan belts substantially. New system designs have the humidifiers moved further from the fan.

In the case of the pre-filter failures, one root cause was determined to be the location of the air intake louvers. In this case, snow entered through the louver and damaged the pre-filters. Further investigation of the air intake louvers showed their location is not in accordance with good engineering practice. In this study, the importance of the inlet location and its relationship with pre-filter failures and the freeze protection system have been identified.

In the case of the failure of the freeze protection components in the HVAC systems, the root causes were not determined. This is mainly due to the fact that the failure data only recorded failure of freeze protection instead of the failure modes that cause the failure. The probable causes are: heating water temperature being too low; pump motor failure; pump impeller failure; pump direct coupling failure; or extremely low outdoor air temperature. Since the data failed to record at this level, the true cause was not determined. There is a need to establish how failure data should be recorded.

3. Modification of a system may be required if managers are to determine the root causes of failure and address these causes. Modification, with specific attention to these components, will improve the system reliability. It was clearly demonstrated that if the humidifier was relocated to other sections of the system and away from the fan, then this would definitely increase life expectancy of fan belts and improve system reliability.

4. Maintenance personnel were aware of many ongoing maintenance requirements with the HVAC systems, and responded by implementing a regular replacement schedule for the particular components based on Original Equipment Manufacture (OEM) recommendations. For pre-filters, the original replacement schedule was once every three months based on OEM recommendations. However, this was changed to once a year, and since has been changed to once every six months, see Appendix H.

These policy changes were made with sketchy rationale for preventive maintenance action. In addition, no systematic analysis of the failures was conducted, which may have provided sound rationale for establishing a replacement schedule. This resulted in unnecessary and conservative preventive maintenance (PM), as related to pre-filter replacement. Not all HVAC units need to be replaced according to the fixed intervals recommended in OME guidelines. Instead, conditional maintenance should be used, whereby the timing of changes to components is determined using real-life data.

5. In this study, it was determined that the perimeter surrounding fresh air intake louvers must be controlled to ensure no activities like garbage truck loading or car exhaust will pollute quality of air intake. Snow must be controlled to ensure that snow will not get into the HVAC equipment.

This example highlights not only pre-filter failure, but also weakness in the management system. In this study, it was determined the pre-filter had become clogged due to truck and car exhaust entering the air intake louvers, which resulted in a clogging of the pre-filters. The developed expert system, as presented here, would have compelled operators to look for the root cause of the pre-filter failures because they would have rationale data at hand indicating the problem occurred not because of a failure of this component, but elsewhere outside the boundaries of the HVAC system. Similarly, failure of the freeze protection system occurred when snow around air intake louvers was not removed in a timely fashion. This snow would pile up around the air intake louvers, get sucked into the HVAC system, and cause damage.

6. HVAC systems for this study are located in mechanical rooms and remotely controlled by computers. The total productive maintenance (TPM) model can hardly apply because there is no operator on site.

If the above integrated approach is applied to the practice of maintenance, failure will be reduced resulting in increased system reliability and availability.

Chapter 10 Recommendations

This chapter presents the recommendations of this study with respect to the application of Reliability Centered Maintenance, Fault Tree Analysis, Mathematical Modeling, and Database Management Systems to the development of a database decision support system.

The recommendations for additional areas of study are:

1. The Effect of Group Dynamics and Team Approaches on the Maintenance Process

   This area has received much attention from the plant operation perspective. However, it has not experienced the same acceptance or importance from the engineering design/maintenance perspective. More formalized methods for the use of team approaches in design/maintenance processes need to be developed.

   In order to maximize the benefits of the RCM, this process shall be performed by a group of system design engineers, system operators and maintenance personnel. This process is expensive and time consuming and must have full support from top management before it can proceed. The team members for the RCM process must be properly trained before joining the team.

2. The Data Gathering Process

Standardized data gathering processes need to be developed. This includes psychological data (organizational culture, etc.) as well as technical failure data. Failure data collected should include parts (failed components), position (where were things at the time of failure), documentation (operating conditions such as temperatures, pressures, levels, etc. prior to, during, and after the incident), people (who were there, where were they, and what did they see, hear, feel, or smell prior to, during, and after the incident?), and paradigms (what are the cultural norms of the organization, what do people accept as a way of doing business, such as communication between units or shifts, what repetitive remarks were made during the interview that indicate beliefs, values or deep-seated convictions?) as per Broussard (1994).

3. The Feedback Process

The feedback loop in the Engineering Design/Maintenance is weak as viewed from an operating plant's perspective. This was very evident from the system under study for this thesis, considering that design modification was never considered for failures encountered during the period under study. Processes which improve and ensure feedback need to be developed. Failure data analysis must be studied in detail by designers as a means of feedback for future design and system modifications. In the case of HVAC systems, if the location of fresh air louvers and inlet conditions are studied further and the system modified to correct the causes, this will minimize air filter failure, system shut down due to the activation of the freeze protection system, and improve indoor air quality. The current practice that the fan section contains the motor and the humidifier, definitely decreases life expectancy and lowers system reliability. It is recommended that in future designs, the humidifier shall be located down stream of the supply fan instead of up stream. The failure data for the heating coil and the cooling coil is based on the central system with good maintenance personnel. Heating and cooling with an individualized system should be studied and compared with the central system. Electric humidifier failure data for Biotechnology building are not accurate and new data should be obtained from new buildings.

4. Condition Based Maintenance

Condition Based Maintenance should be used in monitoring system components such as filters in the HVAC system. The condition shall be logged to establish the potential failure point and the inspection interval. The present scheduled maintenance method for pre-air filter and air filters must be modified. New failure data for pre-air filters and air filters must be obtained in order to achieve meaningful parameters for the Weibull distribution. The present practice of letting pressure drop through the filters to 25 mm before replacement shall be re-evaluated to ensure good quality air supply.

5. New Parameters and Longitudinal Studies

The data collected for this study was very specific to a given site. and for a set time period. The effect of the variability of other parameters. such as location. designers, manufacturers and available technology can be studied with a larger database covering a longer time period. Failure data for the HVAC system located within CERR. Biotechnology and Arts/Extension should be collected and analyzed for the next ten years in order to obtain the additional life cycle data of the HVAC system. Further. additional failure modes encountered should be used to update the fault trees, the RCM worksheet, the mathematical models, and the expert system. This study is based on the assumption that there is no difference between designers, equipment manufacturers or the technology at the time. However, if failure data for buildings with the same designer is available then data should be analyzed to see whether there is a difference between designers. Also, failure data from the same equipment manufacturer should be analyzed to identify whether there is a difference between equipment from different manufacturers. During different periods in history, designers using different technologies. Failure data should therefore be grouped based on the time of construction to identify that there is a difference in the parameters obtained for the Weibull analysis.

6. Mathematical Models

Systematic method must be established to determine cost for planned maintenance and unplanned maintenance. This can be achieved by using the work design and material handling approaches that are presently used by the industrial engineers. There are many distribution functions that can be used in modeling for system failure. Weibull distribution is used in this case. However, failure data for each failure mode must be analyzed to determine which distribution is the most appropriate function and the associated parameters for that particular failure mode. At present, the mathematical models do not include weather conditions which can be included in the models. The present models are based on the users having the weather conditions before using the expert system.

7. Database Systems

There are many macro functions in the database system which can be used to enhance the reporting requirement for users. The queries and reports should be modified to the required format for the end users. Further development work can take place on the use of commercial, low cost, database systems for knowledge-based system development. A generic shell, similar to how MS Project is based on MS Access for project management, can be developed for maintenance operations.

8. Scope of Study Area (RCFA)

Root Cause Failure Analysis must be used to deal with each failure mode. In the HVAC system, a lot of causes of failure can be minimized if the maintenance scope is extended outside the air intake louver, which is the conventional starting point for HVAC system operators and maintenance personnel. By controlling the intake conditions, the system reliability can be increased.

In order to complete the expert system for the HVAC system, the scope of study should be expanded to the source of the cooling system and source of heating system. In the case for MUN, this will be a study for the cooling tower and high temperature heating plants located in the Utility Annex.

Failure data for non-electric humidifiers should be collected and compared with failure data for electric humidifiers.

9. Training

The recommendations for alternative approaches to the research are listed as follows: the data presented by Honeywell Inc. is at the problem identification level. In order to optimize the mathematical model, more data should be recorded at the root cause level, a level lower than the problem level. This confirms that more education and training is required for operation and maintenance personnel.

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Appendices

Appendix A: RCM Information Worksheets

Table A - 3.2 Fresh Air Damper RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fresh Air Damper		Fault Tree Analysis Figure B - 4.3		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To allow adequate fresh air intake to the HVAC unit when system is in operation	A	The fresh air damper failed to allow fresh air intake during system operation	1	The damper motor failed to open and let fresh air to the system	This will cause a reduction of air supply to the system. This causes high static pressure for the fan to operate and consume high electrical energy. In extreme cases can cause ductwork in the suction side of the fan to collapse if the damper is completely closed.
				2	The control air system failed to provide control air to operate the damper motor	
				3	Linkage loose and ball joints failed	
2	To shut off fresh air to the HVAC equipment	A	The fresh air damper failed to stop fresh air to HVAC equipment during system shut-down	1	The damper motor failed to return damper to normal close position	This will cause a danger of freezing the coils in the HVAC system.
				2	The control air system failed to provide control air to operate the damper motor	
				3	Linkage loose and ball joints failed	

Table A - 3.3 Pre-Filter RCM Information Worksheet

RCM Information Worksheet			Component Analyzed: Pre-filter	Fault Tree Analysis Figure B - 4.4		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To remove entrained coarse contaminants	A	The pre-filter fails to remove entrained solid particles from the air	1	The pre-filter element has become saturated with dirt	This will cause a reduction in the air flow supplied to the HVAC system
				2	The pre-filter element has become torn	This will cause dirt to be carried prematurely downstream. This will cause downstream filter failure

Table A - 3.4 Filter RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Final Air Filter		Fault Tree Analysis Figure B - 4.4		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To remove entrained fine contaminants	A	The filter fails to remove entrained fine contaminants	1	The filter element has become saturated with fine dirt	This will cause a reduction in the air flow supplied to the HVAC system.
				2	The filter element has become torn or ripped	This will allow fine contaminants to be distributed throughout the space.

Table A - 3.5 Heating Coil RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Hot Water Heating Coil		Fault Tree Analysis Figure B - 4.5		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To heat the fresh supply air to the desired temperature	A	The heating coil fails to provide adequate heating capacity to heat fresh supply air to the desired temperature	1	The hot water heating supply temperature is too low	This will cause space to become uncomfortable for humans. This will activate freeze protection device and shut down the system.
				2	The hot water heating circulating pump failed due to either pump motor, coupling or impeller failure	This will cause heating coil freeze up in cold weather and activate freeze protection device and shut down the system.
				3	Heating coil ruptured	This will cause water damage within the unit and inadequate or no heat supply to the space.
		B	The heating coil provides too much heat to the supply air	1	Three way mixing valve failed	This will cause high temperature in the heating coil surface and provide too much heat transfer to the supply air.

Table A - 3.6 Freeze Protection System RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Freeze Protection Device		Fault Tree Analysis Figure B - 4.6		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To protect heating coil from freezing	A	Freeze protection sensor failed to operate when the supply air temperature is too low	1	Freeze protection sensor failed	This will cause system to shut down unnecessarily if outdoor temperature is low.
				2	Heating pump impeller failed	
				3	Heating pump direct coupling failed	
				4	Heating pump motor failed	
				5	Hot water heating supply temperature too low	

Table A - 3.7 Cooling Coil RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Cooling Coil		Fault Tree Analysis Figure B - 4.7		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To cool supply air to the desired temperature	A	The cooling coil fails to provide adequate cooling capacity to cool supply air to the desired temperature	1	Cooling coil ruptured	This will cause water damage within the unit and inadequate or no cooling of supply air to space.
				2	The cooling water temperature is too high	Inability to cool supply air due to lack of temperature difference between air and cooling surface.
				3	The cooling water circulating pump failed due to either pump motor direct coupling or impeller failure	Inadequate supply of cooling water and little or no temperature difference between air and cooling surface.
		B	The cooling coil provides too much cooling to the supply air	1	Three way mixing valve failed	This will cause low temperature in the cooling coil surface and provide too much cooling to the supply air.

Table A - 3.8 Humidifier RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Humidifier		Fault Tree Analysis Figure B - 4.8		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To provide moisture to the supply air	A	The humidifier failed to provide adequate moisture to the fresh air	1	The humidifier failed	This will cause low humidity in supply air.
				2	The control system (including humidity operating sensor) for humidifier failed	This will give out too much steam and cause discomfort in space. If the supply fan is shut down excessive humidity will cause fan belt failure prematurely. If the supply fan is shut down, excess humidity can cause corrosion of electrical equipment in supply fan section.
				3	Distributor failed	Steam will not be evenly distributed.
		B	The humidifier provided too much humidity to the supply air	1	Humidity high limit failed to operate	This will cause discomfort in space.

Table A - 3.9A1 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figures B - 4.9 & B - 4.10		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition of the occupancy	A	The supply air noise level is too high	1	Fan impeller hitting inlet or housing • impeller not centered in inlet or housing • inlet or housing damage • bent or damaged impeller • Shaft loose in bearings • Impeller loose on shaft • Bearing loose in bearing support • Bent shaft • Misaligned shaft and bearings	This will cause noise problem and possible physical damage to fan impeller and housing.
				2	Fan impeller hitting cutoff: • Cutoff not secure in housing • Cutoff damaged • Cutoff improperly positioned	This will cause noise problem and possible catastrophic failure
				3	Drive (Fan Belt) • Sheave not tight on shaft (motor or fan) • Belts hitting belt guard • belts too loose. Adjust for belt stretching after 48 hours operating	This will cause noise problem

Table A - 3.9A2 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figures B - 4.9 & B - 4.10	
Function		Functional Failure		Failure Mode (Cause of Failure)	Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition of the occupancy	A	The supply air noise level is too high	• Belts too tight • Belts wrong cross-section • Belts not "matched" in length on multi-belt drive • Variable pitch sheaves not adjusted so each groove has same pitch diameter (multi-belt drive) • misaligned sheaves • Belts worn • Motor, motor base or fan not securely anchored • Belts oily or dirty • Improper drive selection • Loose key on shaft	This will cause noise problem

Table A - 3.9A3 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figures B - 4.9 & B - 4.10		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition of the occupancy	A	The supply air noise level is too high	4	Coupling • Coupling unbalanced, misaligned, loose or may need lubricant • Loose key on shaft	This will cause noise problem
				5	Bearing • Defective bearing • Needs lubrication • Loose on bearing shaft • Loose on shaft • Bearings misaligned • Foreign material inside bearing • Worn bearing • Fretting corrosion between inner race and shaft • Bearing not sitting on flat surface	This will cause noise problem
				6	Shaft Seal Squeal • Needs lubrication • Misaligned • Bent Shaft • Bearing loose on support	This will cause noise problem

Table A - 3.9A4 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4.9 & B - 4.10		
Function		Functional Failure			Failure Mode (Cause of Failure)	Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition of the occupancy	A	The supply air noise level is too high	7	Impeller • Loose on shaft • Defective impeller. Do not run fan. Contact the manufacturer • Unbalanced • Coating loose • Worn as a result of abrasive or corrosive material moving through flow passages • Blades rotating close to structural member • Blades coinciding with an equal number of structural members	This will cause noise problem
				8	Housing • Foreign material in housing • Cutoff or other parts loose (rattling during operation)	This will cause noise problem

Table A - 3.9A5 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4.9 & B - 4.10		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition of the occupancy	A	The supply air noise level is too high	9	Motor • Power cable not secure • AC hum in motor or relay • Starting relay chatter • Noisy motor bearings • single phasing a 3 phase motor • Low voltage • Cooling fan striking shroud	This will cause noise problem
				10	Shaft • Bent • Undersized. May cause noise at impeller, bearings or sheave	This will cause noise problem
				11	High Air Velocity • ductwork too small for application • Fan selection too high for application • Registers or grilles too small for application • Heating or cooling coil with insufficient face area for application	This will cause noise problem

Table A - 3.9A6 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4.9 & B - 4.10		
Function		Functional Failure			Failure Mode (Cause of Failure)	Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition of the occupancy	A	The supply air noise level is too high	12	Obstruction in high velocity air stream may cause rattle, or pure tone whistle • Dampers • Registers • Grilles • Sharp elbows • Sudden expansion in ductwork • Sudden contraction in ductwork • Turning vanes	This will cause noise problem
				13	Pulsation or Surge • Restricted system causes fan to operate at poor point of rating • Fan too large for application • Ducts vibrate at same frequency as fan pulsations (resonance) • Rotating stall • Inlet vortex surge • Distorted inlet flow	This will cause noise problem

				14	Velocity Through Cracks, Holes or Past Obstructions • Leaks air handling unit • Fins on coils • Registers or grilles	This will cause noise problem

Table A - 3.9A7 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4.9 & B - 4.10		
Function		Functional Failure			Failure Mode (Cause of Failure)	Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition of the occupancy	A	The supply air noise level is too high	15	Rattles and/or Rumbles • Vibrating ductwork • Vibrating cabinet parts • Vibrating parts not isolated from building	This will cause noise problem

Table A - 3.9B1 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4. 11		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition of the occupancy	B	Insufficient Air Flow	1	Fan • Impeller Installed backwards • Impeller running backwards • Improper blade angle setting • Cutoff missing or improperly installed • Impeller not centered with inlet collar(s) • Fan speed too slow • Impeller/inlet dirty or clogged • Improper running clearance • Improper inlet cone to wheel fit • Improperly set inlet vane or damper	It cannot supply the required air flow to the space

Table A - 3.9B2 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4.11	
Function		Functional Failure	Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition of the occupancy	Insufficient Air Flow	2	Duct System • Actual system is more restrictive (more resistance to flow) than expected • Dampers closed • Registers closed • Leaks in supply ducts • Insulating duct liner loose	It cannot supply the required air flow to the space
			3	Filters • Dirty or clogged • Replacement filter with greater than specified pressure drop	It cannot supply the required air flow to the space
			4	Coils • Dirty or clogged • Incorrect fin spacing	It cannot supply the required air flow to the space
			5	Recirculation • Internal cabinet leaks in bulkhead separating fan outlet (pressure zone) from fan inlets (suction zone) • Leaks around fan outlet at connection through cabinet bulkhead	It cannot supply the required air flow to the space

Table A - 3.9B3 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4.11		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition	B	Insufficient Air Flow	6	Obstructed Fan Inlets • Elbows, cabinet walls or other obstructions restricting air flow. Inlet obstructions cause restricted air flow but may cause increased negative pressure readings near the fan inlet(s). Fan speed may be increased to counteract the effect of restricted fan inlet(s).	Cannot supply the required air flow to the space.
	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition		Insufficient Air Flow	7	Insufficient straight duct at Fan Outlet • Fans which are normally used in duct system are tested with a length of straight duct at the fan outlet. If there is no straight duct at the fan outlet, decreased performance may result. If it is not practical to install a straight section of duct at the fan outlet, the fan speed may be increased to overcome this pressure loss.	Cannot supply the required air flow to the space

Table A - 3.9B4 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4.11		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition	B	Insufficient Air Flow	8	Obstructions in High Velocity Air Stream • Obstruction near fan outlet or inlet • Sharp elbows near fan outlet or inlet • Improperly designed turning vanes • Projections, dampers or other obstruction in a part of the system where air velocity is high	It cannot supply the required air flow to the space

Table A - 3.9C1 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis B - 4. 12		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition	C	CFM High - Too much Air Flow	1	System Failure • Oversized ductwork • Access door open • Registers or grilles not installed • Dampers set to by-pass coils • Filter(s) not in place • system resistance low	It supplies too much air to the system
				2	Fan • Fan speed too fast • Improper blade angle setting	It supplies too much air to the system

Table A - 3.9D1 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4.13		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition	D	Static Pressure Wrong	1	System, Fan or Interpretation of Measurements	
				2	Air Density Pressures will be less with high temperature air or at high altitudes	
				3	System System has less resistance to flow than expected. This is a common occurrence. Fan speed may be reduced to obtain desired flow rate . This will reduce power (operating cost)	It supplies too much air
				4	System • Fan inlet and/or outlet conditions not the same as conditions when fan was tested and certified	It cannot deliver the required air flow

Table A - 3.9D2 Fan RCM Information Worksheet

RCM Information Worksheet			Component Analyzed: Fan	Fault Tree Analysis Figure B - 4.13		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition	D	Static Pressure Wrong	5	Fan • Impeller installed backwards • impeller running backwards • Improper blade angle setting • Cutoff missing or improperly installed • Impeller not centered with inlet collar(s) • Fan speed incorrect • Impeller/inlet dirty or clogged • Improper running clearance • Improper inlet cone to wheel fit • Improperly set inlet vane or damper	
				6	Duct System • Actual system is more restrictive (more resistance to flow) than designed • Dampers closed • Registers closed • Insulating duct liner loose	

Table A - 3.9D3 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4.14		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition of the occupancy	D	Static Pressure Wrong	7	Filters • Dirty or clogged • Replacement filter with greater than specified pressure drop	It increases system static and reduces air flow
				8	Coils • Dirty or clogged • Fin spacing too close •	It reduces air flow and fails to cool or heat the air

Table A - 3.9E1 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4. 15		
Function		Functional Failure			Failure Mode (Cause of Failure)	Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition of the occupancy	E	Amperage High	1	Fan • Backward inclined impeller installed backwards • Fan speed too high • Forward curve or radical blade fan operating below design pressures • blade angle not set properly	- High energy consumption - Motor operates in overload condition - Premature motor failure
				2	System • Oversized ductwork • face and by-pass dampers oriented so coil dampers are open at same time by-pass dampers are open • Filter(s) left out • Access door open	
				3	Air Density • Calculated horsepower requirements based on conditions other than actual running conditions e.g. very high or low temperature	

Table A - 3.9E2 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4.15		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition of the occupancy	E	Power High	4	Fan Selection • Fan not selected at efficient point of rating	

Table A - 3.9F1 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4.16		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition	F	Fan Does Not Operate	1	Electrical or Mechanical • Blown fuses • Broken belts • Loose pulleys • Electricity turned off • Impeller jammed • Wrong voltage • Motor too small and overload protector has broken circuit • Low voltage, excessive line drop or inadequate wire size • Load inertia too large for motor • Seized bearing	This will cause fan failure with no air flow to the system.

Table A - 3.9G1 Fan RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Fan		Fault Tree Analysis Figure B - 4.17		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To supply the required amount of conditioned air at acceptable noise level to meet the inside condition	G	Premature Failure	1	Belts, Bearings, Sheaves, Impellers, Hubs, etc.	This will cause noise and air flow problem. The will cause fan failure prematurely.
				2	Couplings (a) coupling unbalanced, misaligned, loose or may need lubricant (a) Loose key on shaft	This will cause noise and air flow problem. The will cause fan failure prematurely.
				3	Shaft (a) Bent (a) Undersized	This will cause noise and air flow problem. The will cause fan failure prematurely.

Table A - 3.10 Control System RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: Control System		Fault Tree Analysis Figure B - 4.18		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To provide status of supply and air return air temperature, humidity and static pressure	A	The temperature monitoring system failed to provide the status of supply and return air temperature	1	Temperature sensors failed	This will cause the control system to fail to provide information concerning operating temperature conditions.
				2	Computer temperature input module failed	
		B	The humidity monitoring system failed to provide the status of humidity	1	Humidity sensors failed	This will cause the control system to fail to provide information concerning operating humidity conditions.
				2	Computer humidity input module failed	
		C	The static pressure monitoring system failed to provide the status of status pressure information	1	Static pressure sensors failed	This will cause the control system to fail to provide information concerning operating status pressure.
				2	Computer static pressure input module failed	

Table A - 3.10 (Cont'd)

RCM Information Worksheet		Component Analyzed: Control System		Fault Tree Analysis Figure B - 4.18		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
2	To control the supply air temperature, humidity and static pressure	A	The control system failed to control supply air temperature	1	Temperature sensors failed	This will cause the system to fail to provide proper supply air temperature.
				2	Computer temperature input module failed	
				3	Computer temperature output control module failed	
				4	The computer failed	
				5	Low air flow in the system	
				6	Heating system failed	
				7	Cooling system control failed	

Table A - 3.10 (Cont'd)

RCM Information Worksheet		Component Analyzed: Control System		Fault Tree Analysis Figure B - 4.18		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
2	To control the supply air temperature, humidity and static pressure	B	The control system failed to control supply air humidity	1	Humidity sensors failed	This will cause the system to fail to provide proper humidity in supply air.
				2	Control humidity input module failed	
				3	Control system output module failed	
				4	The computer control system failed	
				5	Humidifier failed	

Table A - 3.10 (Cont'd)

RCM Information Worksheet		Component Analyzed: Control System		Fault Tree Analysis Figure B - 4.18		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
2	To control the supply air temperature, humidity and static pressure	C	The control system failed to control fan operating static pressure	1	Static pressure sensors failed	This will cause the system to deliver too much or too little air flow.
				2	Control system static pressure input module failed	
				3	Control system static pressure output module failed	
				4	The computer control system failed	
				5	Fan failed	

Table A - 3.11 EP Relays RCM Information Worksheet

RCM Information Worksheet		Component Analyzed: EP Relays		Fault Tree Analysis Figure B - 4. 19		
Function		Functional Failure		Failure Mode (Cause of Failure)		Failure Effect (What Happens when it Fails)
1	To provide control air to the system	A	Failed to provide control air to operate the system	1	Air compressor failed	No control air to HVAC system and system cannot function.
				2	Air dryer failed	Moisture in control air causes control equipment failure.
				3	Air filter failure	Dirt in control air causes equipment malfunction.
				4	Air line leakage	Cannot provide adequate control air system pressure.
				5	EP leakage	Low control air pressure.
				6	EP plastic housing failure	Low control air pressure.
		B	Failed to energize the electrical system	1	EP solonoid failure	No control air to the system.

Appendix B: Fault Tree Analysis

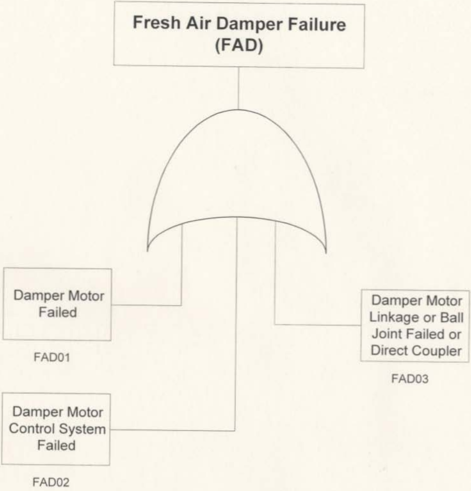

Figure B - 4.3 Fresh Air Damper Failure

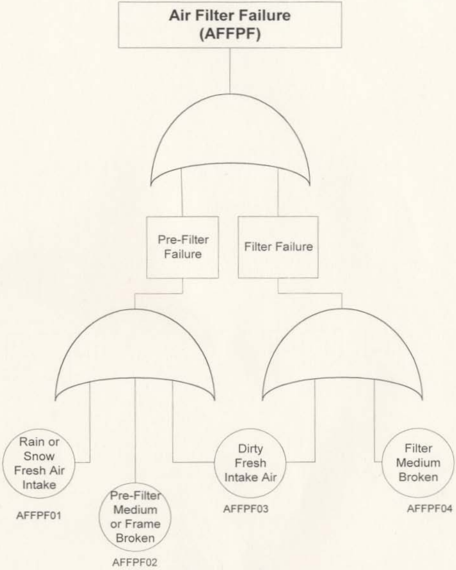

Figure B - 4.4 Air Filter Failure

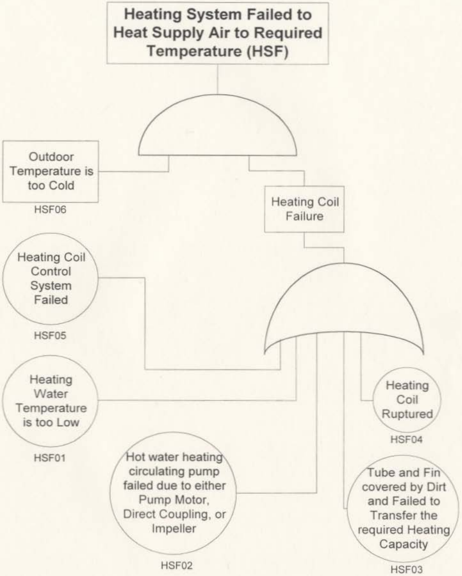

Figure B - 4.5 **Heating System Failed to Heat Supply Air to Required Temperature**

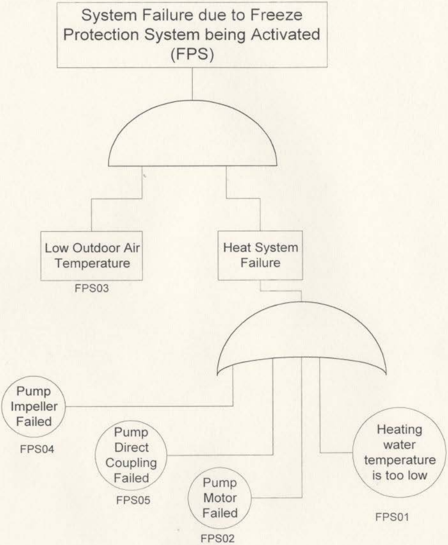

Figure B - 4.6 **System Failure due to Freeze Protection System being Activated**

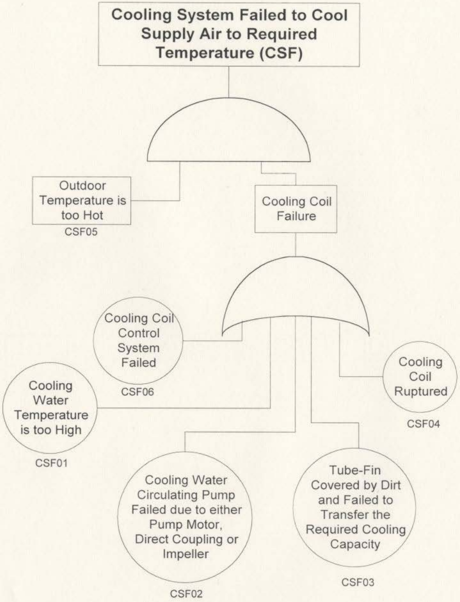

Figure B - 4.7 **Cooling System Failed to Cool Supply Air to Required Temperature**

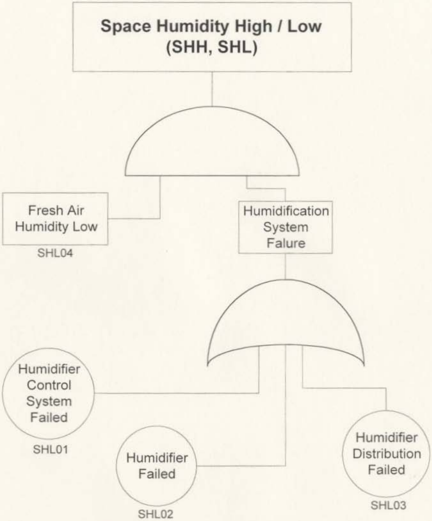

Figure B - 4.8 **Space Humidity High / Low**

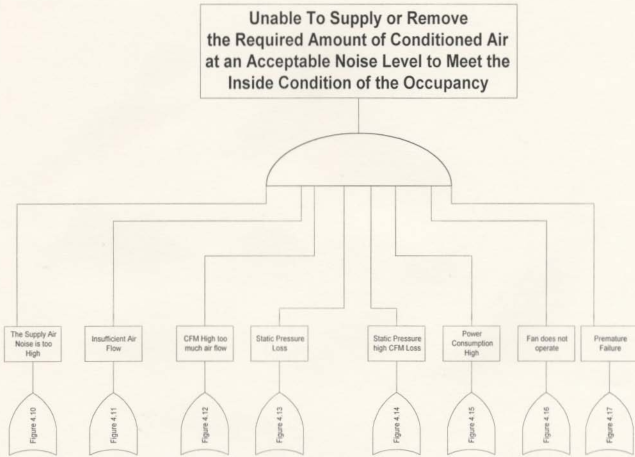

Figure B - 4.9 **Unable to Supply or Remove the Required Amount of Conditioned Air at an Acceptable Noise Level to Meet the Inside Condition of the Occupancy**

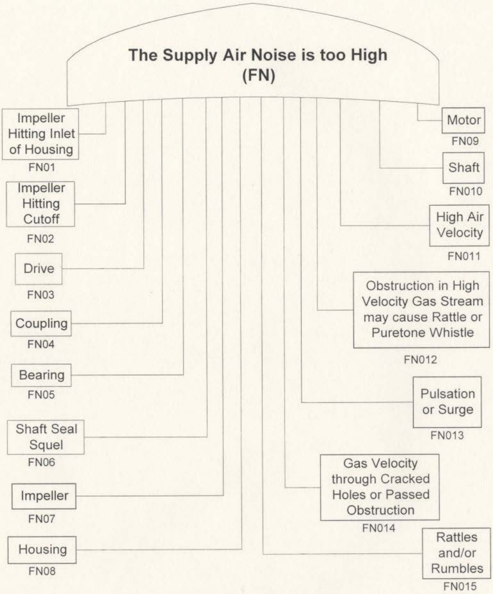

Figure B - 4.10 The Supply Air Noise is too High

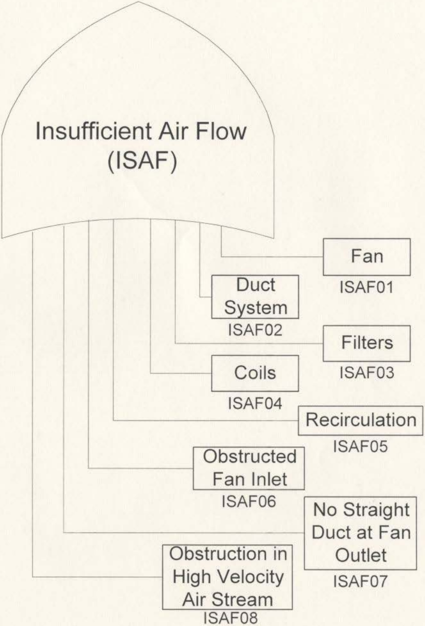

Figure B - 4.11 Insufficient Air Flow

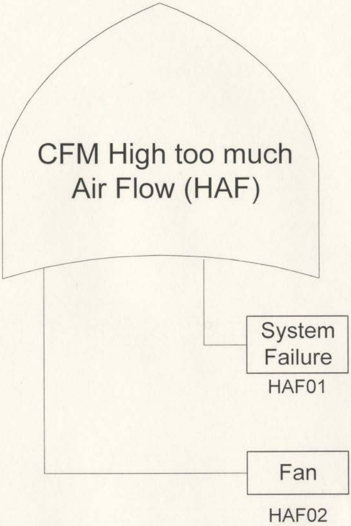

Figure B - 4.12 CFM High too much Air Flow

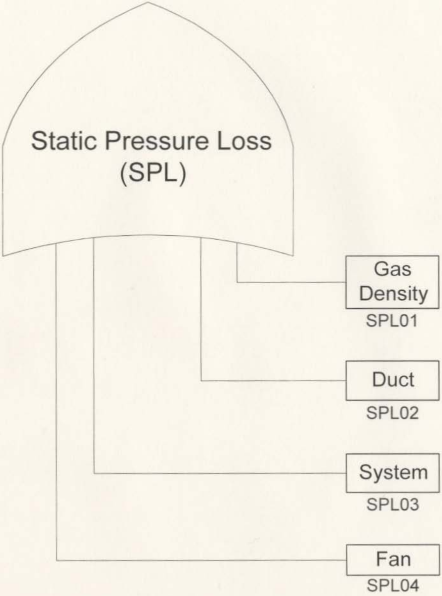

Figure B - 4.13 **Static Pressure Loss**

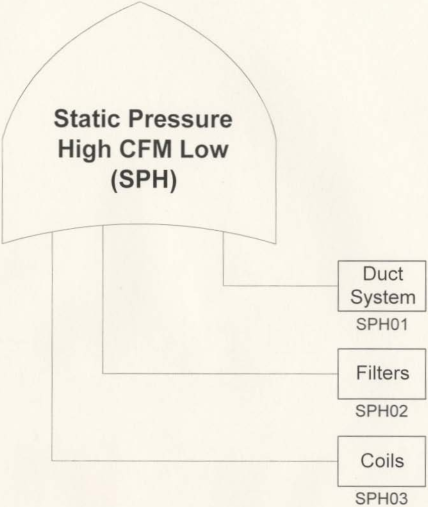

Figure B - 4.14 **Static Pressure High CFM Low**

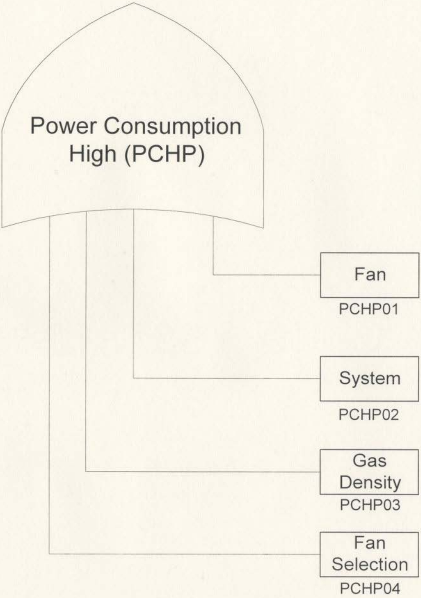

Figure B - 4.15 Power Consumption High

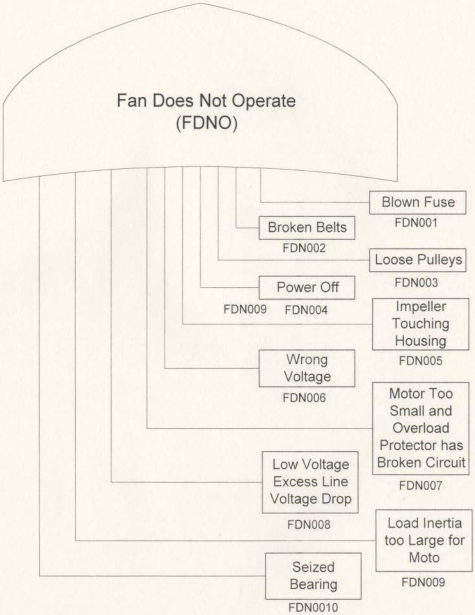

Figure B - 4.16 Fan Does Not Operate

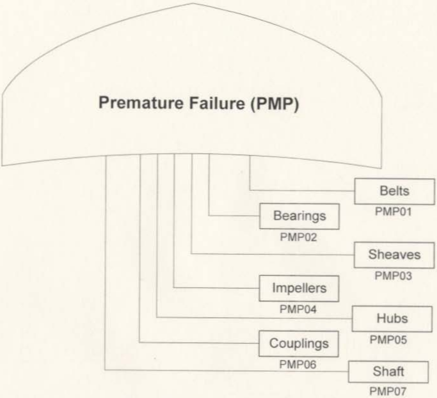

Figure B - 4.17 Premature Failure

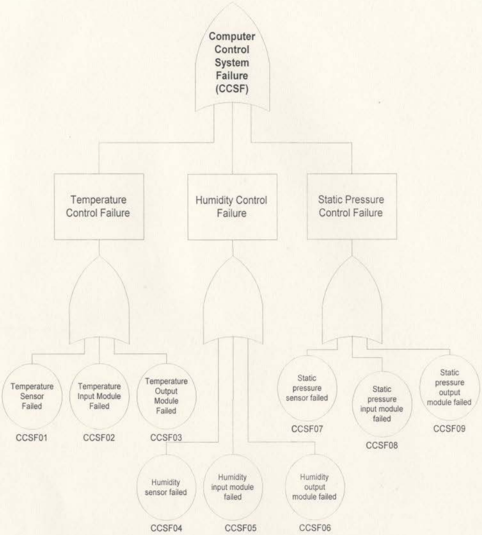

Figure B - 4.18 Computer Control System Failure

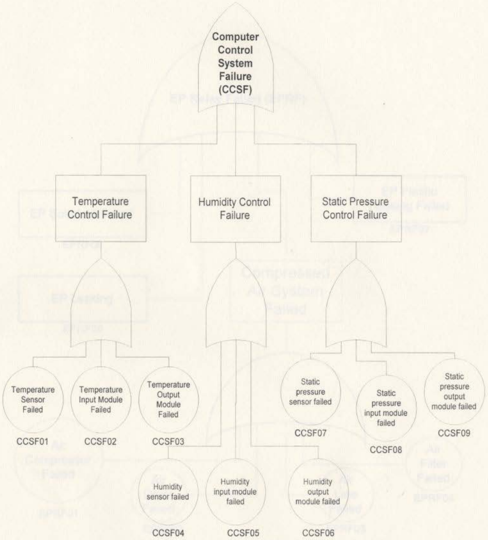

Figure B - 4.18 Computer Control System Failure

Appendix C: Weibull Analysis for Components

Table C - 5.1 Rank Table - Fresh Air Damper - Failure Analysis

TITLE: Fresh Air Damper - Failure Analysis

BUILDING NAMES: Biotechnology, CERR and Arts/Ext.

Rank Table:

Point	x-value	Order	Median Rank
1	-11028	suspension	
2	-26135	suspension	
3	27326	1.153846	0.05929487
4	28944	2.307692	0.1394231
5	-30481	suspension	
6	-30481	suspension	
7	-30912	suspension	
8	34680	3.894231	0.2495994
9	-38354	suspension	
10	-38354	suspension	
11	-45864	suspension	
12	49632	6.670673	0.4424079
13	-55080	suspension	
14	-80544	suspension	

c.l.: Weibull eta = 51996.59

shape factor: beta = 3.853321

14 pts. total 10 susps. W/rr (Weibull analysis using least square method)

correlation (r) = .9263473, ccc = .8923981 (OK), r*r=.8581192

Figure C - 5.1 CDF Graph for Fresh Air Damper Failure Analysis

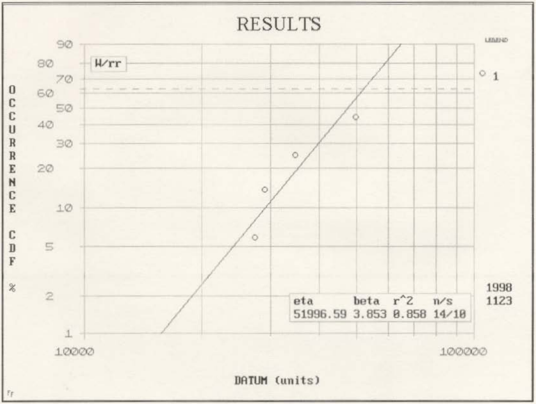

Table C - 5.2 F(t) and R(t) Prediction Table - Fresh Air Damper

TITLE: Fresh Air Damper - Failure Analysis

BUILDING NAMES: Biotechnology, CERR and Arts/Ext.

Prediction for beta = 3.853321, eta = 51996.59

[Confidence = 50.0000%]

Hours of Operation	F(t) in %	R(t) in %100%
1000	0.00002	99.99998
1500	0.00012	99.99988
2000	0.00035	99.99965
2500	0.00083	99.99917
3000	0.00168	99.99832
4000	0.0051	99.9949
5000	0.01205	99.98795
6000	0.02433	99.97567
7000	0.04407	99.95593
8000	0.07371	99.92629
9000	0.11602	99.88398
10000	0.17408	99.82592
11000	0.25123	99.74877
12000	0.35113	99.64887
13000	0.47768	99.52232
14000	0.63501	99.36494
15000	0.82766	99.17234
20000	2.48672	99.51328
25000	5.77635	94.22365

Hours of Operation	F(t) in %	R(t) in %100%
30000	11.31873	88.68127
35000	19.55242	80.44758
40000	30.50786	69.49214
45000	43.617	56.383
50000	57.68181	42.31819

Table C - 5.3 Rank Table - Fan Belts Failure Analysis

TITLE: Fan Belts Failure Analysis

BUILDING NAMES: Biotechnology, Arts/Ext. and CERR.

Rank Table:

Point	x-value	Order	Median Rank
1	-4834	suspension	
2	4896	1.045455	0.03327922
3	5703	2.090909	0.07995129
4	6385	3.136364	0.1266234
5	-8472	suspension	
6	9864	4.239899	0.1758883
7	-10583	suspension	
8	11505	5.412405	0.2282324
9	-12342	suspension	
10	-12744	suspension	
11	-13032	suspension	
12	13416	6.878038	0.2936624
13	-13872	suspension	
14	15552	8.490234	0.3656355
15	15792	10.10243	0.4376085
16	17197	11.71463	0.5095815
17	-17395	suspension	
18	18960	13.59552	0.5935501
19	-20880	suspension	
2	-22605	suspension	
21	23328	16.73035	0.7334977
22	-33144	suspension	

c1.: Weibull	eta = 20464.3	22 pts. total 11 susps. W/rr
shape factor:	beta = 2.1467	correlation (r) = .9797708, ccc = .9323768
		(O.K).r*r=.9599508

Figure C - 5.2 CDF Graph for Fan Belts Failure Analysis

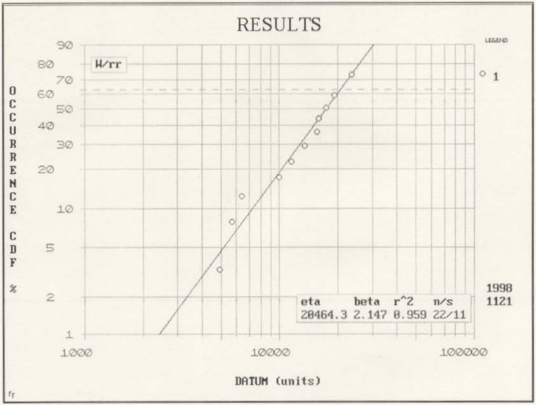

Table C - 5.4 F(t) and R(t) Prediction - Fan Belt

TITLE: Fan Belts Failure Analysis

BUILDING NAMES: Biotechnology, Arts/Ext. and CERR.

Prediction for beta = 2.1467, eta = 20464.3

[Confidence = 50.0000%]

Hours of Operation	F(t) FB in %	R(t) FB in % (100 - F(t))
1000	0.15	99.85
1500	0.37	99.63
2000	0.68	99.32
2500	1.09	98.91
3000	1.61	98.39
4000	2.96	97.04
5000	4.74	95.26
6000	6.93	93.07
7000	9.51	90.49
8000	12.47	87.53
9000	15.76	84.24
10000	19.34	80.66
11000	23.19	76.81
12000	27.24	72.76
13000	31.45	68.55
14000	35.77	64.23
15000	40.15	59.85
20000	61.4	38.6
25000	78.5	21.5

Hours of Operation	F(t) FB in %	R(t) FB in % (100 - F(t))
30000	89.7	10.3
35000	95.78	4.22
40000	98.52	1.48
45000	99.56	0.44
50000	98.89	0.11
55000	99.98	0.02

Table C - 5.5 Rank Table - Vortex Vanes - Failure Analysis

TITLE: Vortex Vanes - Failure Analysis

BUILDING NAMES: Biotechnology, CERR and Arts/Ext.

Rank Table:

Point	x-value	Order	Median Rank
1	12936	1	0.0614035
2	-20352	suspension	
3	-20520	suspension	
4	21888	2.222222	0.168616
5	-28990	suspension	
6	-28990	suspension	
7	-37977	suspension	
8	-37977	suspension	
9	-37977	suspension	
10	59232	5481482	0.4545159
11	74856	8.740741	0.7404159

c.l.: Weibull eta = 68043.08

shape factor: beta = 1.638581

11 pts. total 7 susps. W/rr

correlation (r) = .9886051, ccc = .8923981 (OK), r*r=.97734

Figure C - 5.3 CDF Graph for Vortex Vanes Failure Analysis

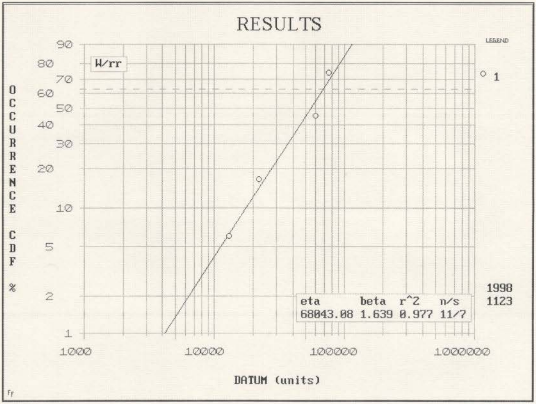

Table C - 5.6 F(t) and R(t) Prediction Table - Vortex Vanes

TITLE: Vortex Vanes - Failure Analysis

BUILDING NAMES: Biotechnology, CERR and Arts/ Ext.

Prediction for beta = 1.638581, eta = 68043.08

[Confidence = 50.0000%]

Hours of Operation	F(t) FVV in %	R(t) FVV in % (100 - F(t))
1000	0.01	99.9
1500	0.19	99.81
2000	0.31	99.69
2500	0.44	99.56
3000	0.6	99.4
4000	0.96	99.04
5000	1.38	98.62
6000	1.85	98.15
7000	2.38	97.62
8000	2.95	97.05
9000	3.57	96.43
10000	4.23	95.77
11000	4.92	95.08
12000	5.66	94.34
13000	6.42	93.58
14000	7.22	92.78
15 ,000	8.05	91.95
20000	12.58	87.42
25000	17.62	82.38

Hours of Operation	F(t) FVV in %	R(t) FVV in % (100 - F(t))
30000	23	77
35000	28.56	71.44
40000	34.21	65.79
45000	39.82	60.18
50000	45.31	54.69
55000	50.62	49.38

Table C - 5.7 Rank Table - Fan Bearing - Failure Analysis

TITLE: Fan Bearing - Failure Analysis

BUILDING NAMES: Biotechnology, CERR and Arts/Ext.

Rank Table:

Point	x-value	Order	Median Rank
1	-17200	suspension	
2	-28900	suspension	
3	-28900	suspension	
4	31272	1.3	0.0806452
5	-37977	suspension	
6	-37977	suspension	
7	-37977	suspension	
8	-55176	suspension	
9	-55176	suspension	
10	75528	4.225	0.3165323
11	-79752	suspension	
12	-79752	suspension	

c.l.: Weibull eta = 132780.2
shape factor: beta = 1.712307
12 pts. total 10 susps. W/rr
correlation (r) = 1, ccc = .99999 (OK), r*r=1

Figure C - 5.4 CDF Graph for Fan Bearing Failure Analysis

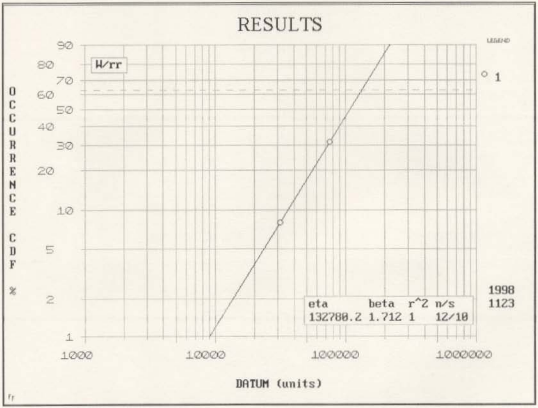

Table C - 5.8 F(t) and R(t) Prediction - Fan Bearing

TITLE: Fan Bearing - Failure Analysis

BUILDING NAMES: Biotechnology. Arts/Ext. and CERR.

Prediction for beta = 1.712307. eta = 132,780.2

[Confidence = 50.0000%]

Hours of Operation	F(t) FBG in %	R(t) FBG in % (100 - F(t))
1000	0.02	99.85
1500	0.05	99.95
2000	0.08	99.92
2500	0.11	99.89
3000	1.15	99.85
4000	0.25	99.75
5000	0.36	99.64
6000	0.5	99.5
7000	0.65	99.35
8000	0.81	99.19
9000	0.99	99.01
10000	1.19	98.81
11000	1.4	98.6
12000	1.62	98.38
13000	1.85	98.15
14000	2.1	97.9
15000	2.36	97.64
20000	3.84	96.16
25000	5.57	94.43

Hours of Operation	F(t) FBG in %	R(t) FBG in % (100 - F(t))
30000	7.53	92.47
35000	9.69	90.31
40000	12.03	87.97
45000	14.51	85.49
50000	17.12	82.88
55000	19.84	80.16

Table C - 5.9 Rank Table - Fan Assembly Failure Analysis

TITLE: Fan Assembly - Failure Analysis

BUILDING NAMES: Biotechnology, CERR and Arts/Ext.

Rank Table:

Point	x-value	Order	Median Rank
1	-17200	suspension	
2	-28900	suspension	
3	-28900	suspension	
4	35965	1.3	0.0806452
5	-37977	suspension	
6	-37977	suspension	
7	-55176	suspension	
8	-55176	suspension	
9	-55176	suspension	
10	75528	4.225	0.3165323
11	-79752	suspension	
12	-79752	suspension	

c1.: Weibull eta = 121417.4

shape factor: beta = 2.03499

12 pts. total 10 susps. W/rr

correlation (r) = .1. ccc = .99999 (O.K) r*r = 1

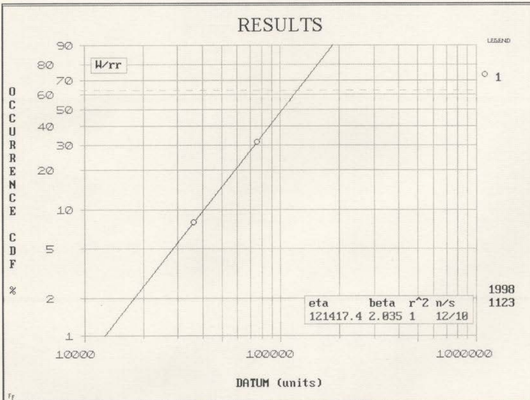

Figure C - 5.5 CDF Graph for Fan Assembly Failure Analysis

Table C - 5.10 F(t) and R(t) Prediction - Fan Assembly

TITLE: Fan Assembly - Failure Analysis

BUILDING NAMES: Biotechnology, CERR and Arts/Ext.

Prediction for beta = 2.035, eta = 121417.4

[Confidence = 50%]

Hours of Operation	F(t) FA in %	R(t) FA in % 100%
1000	0.01	99.99
1500	0.01	99.99
2000	0.02	99.98
2500	0.04	99.96
3000	0.05	99.95
4000	0.1	99.9
5000	0.15	99.85
6000	0.22	99.78
7000	0.3	99.7
8000	0.4	99.6
9000	0.5	99.5
10000	0.62	99.38
11000	0.75	99.25
12000	0.9	99.1
13000	1.05	98.95
14000	1.22	98.78
15000	1.41	98.59
20000	2.52	97.48
25000	3.93	96.07

Hours of Operation	F(t) FA in %	R(t) FA in % 100%
30000	5.65	94.35
35000	7.65	92.35
40000	9.91	90.09
45000	12.42	87.58
50000	15.16	84.84
55000	18.09	81.91
60000	21.2	78.8

Table C - 5.11 Rank Table - Fan Motor Failure Analysis

TITLE: Fan Motor Failure Analysis

BUILDING NAMES: Biotechnology. CERR and Arts/Ext.

Rank Table:

Point	x-value	Order	Median Rank
1	-17200	suspension	
2	21528	1.071429	0.05357143
3	22800	2.142857	0.1279762
4	-28990	suspension	
5	-28990	suspension	
6	-32376	suspension	
7	35965	3.571429	0.2271825
8	-37977	suspension	
9	-37977	suspension	
10	48984	5.476191	0.3594577
11	-55176	suspension	
12	-55176	suspension	
13	-79752	suspension	
14	-79752	suspension	

c.l.: Weibull eta = 62328.46

shape factor: beta = 2.466204

14 pts. total 10 susps. W/rr

correlation (r) = .9320917. ccc = .8923981 (OK). r*r=.8687949

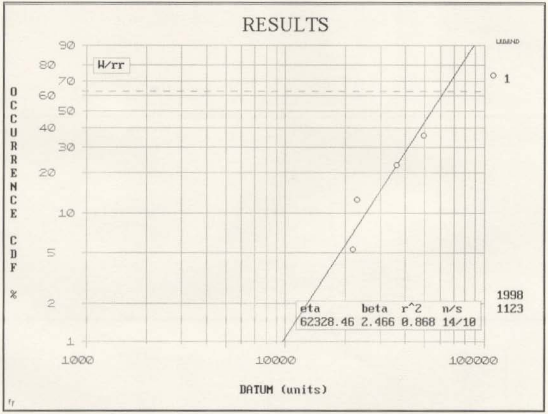

Figure C - 5.6 CDF Graph for Fan Motor Failure Analysis

Table C - 5.12 F(t) and R(t) Prediction

TITLE: Fan Motor - Failure Analysis

BUILDING NAMES: Biotechnology, CERR and Arts/Ext.

Prediction for beta = 2.466204. eta = 62328.46

[Confidence = 50.0000%]

Hours of Operation	F (t) FM in %	R(t) FM in % (100 - F(t))
1000	0.01	99.99
1500	0.01	99.99
2000	0.02	99.98
2500	0.04	99.96
3000	0.06	99.94
4000	0.11	99.89
5000	0.2	99.8
6000	0.31	99.69
7000	0.46	99.54
8000	0.63	99.37
9000	0.84	99.16
10000	1.09	98.91
11000	1.38	98.62
12000	1.7	98.3
13000	2.07	97.93
14000	2.48	97.52
15000	.2.94	97.06
20000	5.88	94.12

Hours of Operation	F (t) FM in %	R(t) FM in % (100 - F(t))
25000	9.98	90.02
30000	15.19	84.81
35000	21.41	78.59
40000	28.46	71.54
45000	36.09	63.91
50000	44.05	55.95
60000	59.76	40.24

Table C - 5.13 R(t) Prediction Table - Fan Reliability

Prediction for beta = 2.1467, eta = 20464.3 for fan belts

Prediction for beta = 1.63858, eta = 68043.08 for Fan Vortex Vanes

Prediction for beta =2.466204, eta =62328.46 for Fan motor

Prediction for beta =2.035, eta =121417.4 for Fan assembly

Prediction for beta =1.712307, eta =132780.2 for Fan Bearing

[Confidence = 50.0000%]

Hours of Operation	R(t) FB	R(t) FVV	R(t) FM	R(t) FA	R(t) FBG	R(t) FAN
1000	0.9985	0.999	0.9999	0.9999	0.9998	0.99710254927
1500	0.9963	0.998	0.9999	0.9999	0.9995	0.99361149419
2000	0.9932	0.997	0.9998	0.9996	0.9992	0.9888346459
2500	0.9891	0.996	0.9996	0.9996	0.9989	0.98327285154
3000	0.9839	0.994	0.999	0.9995	0.9985	0.97545571549
4000	0.9704	0.9904	0.999	0.999	0.9975	0.95676504538
5000	0.9526	0.9862	0.998	0.9985	0.9964	0.93279864109
6000	0.9307	0.9815	0.997	0.9978	0.995	0.90419428246
7000	0.9049	0.9762	0.995	0.997	0.9935	0.87061371021
8000	0.8753	0.9705	0.994	0.9961	0.9919	0.83427587078
9000	0.8424	0.9643	0.992	0.995	0.9901	0.79386076504
10000	0.8066	0.9577	0.989	0.9938	0.9881	0.75021179577
11000	0.7681	0.9508	0.986	0.9925	0.986	0.70467892555
12000	0.7276	0.9434	0.983	0.991	0.9838	0.65784344692
13000	0.6855	0.9358	0.979	0.9895	0.9815	0.60992901576

Hours of Operation	R(t) FB	R(t) FVV	R(t) FM	R(t) FA	R(t) FBG	R(t) FAN
14000	0.6423	0.9278	0.975	0.9877	0.979	0.56182964552
15000	0.5985	0.9195	0.971	0.9859	0.9764	0.51439383577
20000	0.386	0.8742	0.941	0.9748	0.9616	0.29764439277
25000	0.215	0.8238	0.9	0.9607	0.9443	0.1446107363
30000	0.129	0.77	0.848	0.9435	0.9247	0.0734884436
35000	0.0045	0.7144	0.786	0.9235	0.9031	0.002107411
40000	0.0016	0.6579	0.7154	0.9009	0.8797	0.00059682
45000	0.0006	0.6018	0.639	0.8758	0.8549	0.00017275
50000	0.0002	0.5469	0.56	0.8484	0.8288	0.0000431
55000	0.0000	0.4938	0.4797	0.8191	0.8016	0

Table C - 5.14 Rank Table - EP Relay - Failure Analysis

TITLE: EP Relay Failure Analysis

BUILDING NAMES: Biotechnology. CERR and Arts/Ext.

Rank Table:

Point	x-value	Order	Median Rank
1	-17200	suspension	
2	23688	1.066667	0.04978355
3	-28900	suspension	
4	-28900	suspension	
5	-34488	suspension	
6	-37977	suspension	
7	-37977	suspension	
8	-37977	suspension	
9	46320	2.933333	0.1709957
10	-55176	suspension	
11	-55176	suspension	
12	56088	5.546667	0.3406926
13	56088	8.16	0.5103896
14	70512	10.77333	0.6800866
15	-79752	suspension	

c.l.: Weibull eta = 69366.52

shape factor: beta = 3.036842

15 pts. total 10 susps. W/rr

correlation (r) = .965255, ccc = .9021535 (OK), r*r=.9317172

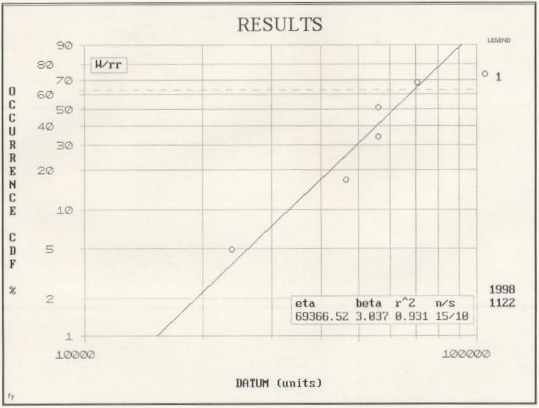

Figure C - 5.7 CDF Graph for EP Relay Failure Analysis

Table C - 5.15 F(t) and R(t) Prediction Table - EP Relay

TITLE: EP Relay - Failure Analysis

BUILDING NAMES: Biotechnology, CERR and Arts/Ext.

Prediction for beta = 3.037, eta = 69366.52

[Confidence = 50.0000%]

Hours of Operation	F(t) in %	R(t) in % 100%
1000	0.0003	99.9997
1500	0.0009	99.9991
2000	0.0021	99.9979
2500	0.0042	99.9958
3000	0.0072	99.9928
4000	0.0173	99.9827
5000	0.034	99.966
6000	0.0591	99.9409
7000	0.0944	99.9056
8000	0.1416	99.8584
9000	0.2024	99.7976
10000	0.2786	99.7214
11000	0.3719	99.6281
12000	0.4841	99.5159
13000	0.6169	99.3831
14000	0.7721	99.2279
15000	0.9511	99.0489
20000	2.2635	97.7365

Hours of Operation	F(t) in %	R(t) in % 100%
25000	4.4085	95.5915
30000	7.5437	92.4563
35000	11.7732	88.2268
40000	17.1301	82.8699
45000	23.5626	76.4374
50000	30.9278	69.0722
55000	38.9957	61.0043

Appendix D: Knowledge-Based System

Table D - 6.13 Symptom S01 - Air Flow too High

Symptoms_ID	Symptom Description	Problem Description	Cause Description	Fault Tree	RCM Information
S01	Air Flow too high	High Air flow	System	D:\FT\Figure 4.12	D:\RCM\Table 3.9C1
S01	Air Flow too high	High Air flow	Fan	D:\FT\Figure 4.12	D:\RCM\Table 3.9C1
S01	Air Flow too high	Fresh Air Louver Failure	Fresh air Louver broken	D:\FT\Figure 4.2	D:\RCM\Table 3.1
S01	Air Flow too high	Fresh Air Louver Failure	Fresh Air louver damaged or	D:\FT\Figure 4.2	D:\RCM\Table 3.1
S01	Air Flow too high	Air Filter Failure	Pre-Filter Medium or Frame	D:\FT\Figure 4.4	D:\RCM\Table 3.4
S01	Air Flow too high	Air Filter Failure	Filter Medium Broken	D:\FT\Figure 4.4	D:\RCM\Table 3.4

Table D - 6.14 Symptom S02- Air Flow Too Low

Symptoms_ID	Symptoms Description	Problem Description	Cause Description	Fault Tree	RCM Information
S02	Air Flow too low	Insufficient Air Flow	Fan	D:\FT\Figure 4.11	D:\RCM\Table 3.9B2
S02	Air Flow too low	Insufficient Air Flow	Duct system	D:\FT\Figure 4.11	D:\RCM\Table 3.9B2
S02	Air Flow too low	Insufficient Air Flow	Filter	D:\FT\Figure 4.11	D:\RCM\Table 3.9B2
S02	Air Flow too low	Insufficient Air Flow	Coils	D:\FT\Figure 4.11	D:\RCM\Table 3.9B2
S02	Air Flow too low	Insufficient Air Flow	Recirculation	D:\FT\Figure 4.11	D:\RCM\Table 3.9B2
S02	Air Flow too low	Insufficient Air Flow	Obstruction Fan Inlet	D:\FT\Figure 4.11	D:\RCM\Table 3.9B2
S02	Air Flow too low	Insufficient Air Flow	No straight duct at fan	D:\FT\Figure 4.11	D:\RCM\Table 3.9B2
S02	Air Flow too low	Insufficient Air Flow	Obstruction in high	D:\FT\Figure 4.11	D:\RCM\Table 3.9B2
S02	Air Flow too low	Fresh Air Damper Failure	Fresh Air Damper Motor	D:\FT\Figure 4.3	D:\RCM\Table 3.2
S02	Air Flow too low	Fresh Air Damper Failure	Fresh Air Damper Control	D:\FT\Figure 4.3	D:\RCM\Table 3.2
S02	Air Flow too low	Fresh Air Damper Failure	Fresh Air Damper Motor	D:\FT\Figure 4.3	D:\RCM\Table 3.2
S02	Air Flow too low	Fresh Air Louver Failure	Fresh air Louver blades	D:\FT\Figure 4.2	D:\RCM\Table 3.1
S02	Air Flow too low	Air Filter Failure	Dirty Fresh Intake Air	D:\FT\Figure 4.4	D:\RCM\Table 3.4

Table D - 6.15 Symptom S03 - Air Noise Level too High

Symptoms_ID	Symptoms Description	Problem Description	Cause Description	Fault Tree	RCM Information
S03	Air Noise Level too high	Fan Noise	Impeller hitting inlet or	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	impeller hitting cutoff	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	Drive	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	coupling	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	bearing	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	Shaft seal squeal	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	impeller	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	housing	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	Fan motor	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	shaft	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	High air velocity	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	Obstruction in high	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	pulsation or surge	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	gas velocity through	D:\FT\Figure 4.10	D:\RCM\Table 3.9A
S03	Air Noise Level too high	Fan Noise	Rattles and/or rumbles	D:\FT\Figure 4.10	D:\RCM\Table 3.9A

Table D - 6.16 Symptom S04 - Dust Level too High

Symptoms_ID	Symptoms	Problem Description	Cause Description	Fault Tree	RCM Information
S04	Dust Level too high	Air Filter Failure	Pre-Filter Medium or	D:\FT\Figure 4.4	D:\RCM\Table 3.4
S04	Dust Level too high	Air Filter Failure	Filter Medium Broken	D:\FT\Figure 4.4	D:\RCM\Table 3.4

Table D - 6.17 Symptom S05 - Fan does not operate

Symptoms_ID	Symptoms Description	Problem Description	Cause Description	Fault Tree	RCM Information
S05	Fan does not operate	EP relay failed	air compressor failed	D:\FT\Figure 4.19	D:\RCM\Table 3.11
S05	Fan does not operate	EP relay failed	air dryer failed	D:\FT\Figure 4.19	D:\RCM\Table 3.11
S05	Fan does not operate	EP relay failed	air line failed	D:\FT\Figure 4.19	D:\RCM\Table 3.11
S05	Fan does not operate	EP relay failed	air filter failed	D:\FT\Figure 4.19	D:\RCM\Table 3.11
S05	Fan does not operate	EP relay failed	EP leaking	D:\FT\Figure 4.19	D:\RCM\Table 3.11
S05	Fan does not operate	EP relay failed	EP solenoid failed	D:\FT\Figure 4.19	D:\RCM\Table 3.11
S05	Fan does not operate	EP relay failed	EP plastic housing failed	D:\FT\Figure 4.19	D:\RCM\Table 3.11
S05	Fan does not operate	Fan does not operate	Blown fuse	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S05	Fan does not operate	Fan does not operate	Broken belts	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S05	Fan does not operate	Fan does not operate	Loose pulleys	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S05	Fan does not operate	Fan does not operate	Electricity turned off	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S05	Fan does not operate	Fan does not operate	impeller touching housing	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S05	Fan does not operate	Fan does not operate	wrong voltage	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S05	Fan does not operate	Fan does not operate	Motor too small and	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S05	Fan does not operate	Fan does not operate	low voltage, excessive line	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S05	Fan does not operate	Fan does not operate	Load inertia too large for	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S05	Fan does not operate	Fan does not operate	Seized bearing	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1

Table D - 6.18 Symptom S06 - Space Humidity High

Symptoms_ID	Symptoms Description	Problem Description	Cause Description	Fault Tree	RCM Information
S06	Humidity Level too high	Space Humidity high	Cooling water temp. is too	D:\FT\Figure 4.8	D:\RCM\Table 3.8
S06	Humidity Level too high	Space Humidity high	Cooling water circulating	D:\FT\Figure 4.8	D:\RCM\Table 3.8
S06	Humidity Level too high	Space Humidity high	Tube and fin covered by	D:\FT\Figure 4.8	D:\RCM\Table 3.8
S06	Humidity Level too high	Space Humidity high	Cooling coil ruptured	D:\FT\Figure 4.8	D:\RCM\Table 3.8
S06	Humidity Level too high	Space Humidity high	Outdoor temperature is	D:\FT\Figure 4.8	D:\RCM\Table 3.8
S06	Humidity Level too high	Computer Control System	Humidity Sensor failed	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S06	Humidity Level too high	Computer Control System	Humidity input module	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S06	Humidity Level too high	Computer Control System	Humidity Output Module	D:\FT\Figure 4.18	D:\RCM\Table 3.10

Table D - 6.19 Symptom S07 - Space Humidity Low

Symptoms_ID	Symptoms Description	Problem Description	Cause Description	Fault Tree	RCM Information
S07	Humidity Level too low	Space Humidity low	Humidifier Control system	D:\FT\Figure 4.8	D:\RCM\Table 3.8
S07	Humidity Level too low	Space Humidity low	Humidifier failed	D:\FT\Figure 4.8	D:\RCM\Table 3.8
S07	Humidity Level too low	Space Humidity low	Humidifier Distribution	D:\FT\Figure 4.8	D:\RCM\Table 3.8
S07	Humidity Level too low	Space Humidity low	Fresh air humidity low	D:\FT\Figure 4.8	D:\RCM\Table 3.8
S07	Humidity Level too low	Computer Control System	Humidity Sensor failed	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S07	Humidity Level too low	Computer Control System	Humidity input module	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S07	Humidity Level too low	Computer Control System	Humidity Output Module	D:\FT\Figure 4.18	D:\RCM\Table 3.10

Table D - 6.20 Symptom S08 - Power usage too high

Symptoms_ID	Symptoms Description	Problem Description	Cause Description	Fault Tree	RCM Information
S08	Power usage too high	Power consumption high	Fan	D:\FT\Figure 4.15	D:\RCM\Table 3.9E
S08	Power usage too high	Power consumption high	system	D:\FT\Figure 4.15	D:\RCM\Table 3.9E
S08	Power usage too high	Power consumption high	gas density	D:\FT\Figure 4.15	D:\RCM\Table 3.9E
S08	Power usage too high	Power consumption high	fan selection	D:\FT\Figure 4.15	D:\RCM\Table 3.9E

Table D - 6.21 Symptom S09 - Static pressure too high

Symptoms_ID	Symptoms Description	Problem Description	Cause Description	Fault Tree	RCM Information
S09	Static Pressure too high	Static pressure high	Duct system	D:\FT\Figure 4.14	D:\RCM\Table 3.9D
S09	Static Pressure too high	Static pressure high	Filter	D:\FT\Figure 4.14	D:\RCM\Table 3.9D
S09	Static Pressure too high	Static pressure high	Coils	D:\FT\Figure 4.14	D:\RCM\Table 3.9D
S09	Static Pressure too high	Air Filter Failure	Rain or snow Fresh Air	D:\FT\Figure 4.4	D:\RCM\Table 3.4
S09	Static Pressure too high	Air Filter Failure	Dirty Fresh Intake Air	D:\FT\Figure 4.4	D:\RCM\Table 3.4
S09	Static Pressure too high	Computer Control System	Static Pressure Sensor	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S09	Static Pressure too high	Computer Control System	Static pressure input	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S09	Static Pressure too high	Computer Control System	Static pressure output	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S09	Static Pressure too high	Fresh Air Damper Failure	Fresh Air Damper Motor	D:\FT\Figure 4.3	D:\RCM\Table 3.2
S09	Static Pressure too high	Fresh Air Damper Failure	Fresh Air Damper Control	D:\FT\Figure 4.3	D:\RCM\Table 3.2
S09	Static Pressure too high	Fresh Air Damper Failure	Fresh Air Damper Motor	D:\FT\Figure 4.3	D:\RCM\Table 3.2
S09	Static Pressure too high	Fresh Air Louver Failure	Fresh air Louver blades	D:\FT\Figure 4.2	D:\RCM\Table 3.1

Table D - 6.22 Symptom S10 - Static Pressure Too Low

Symptoms_ID	Symptoms Description	Problem Description	Cause Description	Fault Tree	RCM Information
S10	Static Pressure too low	Static pressure loss	Gas density	D:\FT\Figure 4.13	D:\RCM\Table 3.9D
S10	Static Pressure too low	Static pressure loss	Duct	D:\FT\Figure 4.13	D:\RCM\Table 3.9D
S10	Static Pressure too low	Computer Control System	Static Pressure Sensor	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S10	Static Pressure too low	Computer Control System	Static pressure input	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S10	Static Pressure too low	Computer Control System	Static pressure output	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S10	Static Pressure too low	Fresh Air Louver Failure	Fresh air Louver broken	D:\FT\Figure 4.2	D:\RCM\Table 3.1
S10	Static Pressure too low	Fresh Air Louver Failure	Fresh Air louver damaged	D:\FT\Figure 4.2	D:\RCM\Table 3.1
S10	Static Pressure too low	Air Filter Failure	Pre-Filter Medium or	D:\FT\Figure 4.4	D:\RCM\Table 3.4
S10	Static Pressure too low	Air Filter Failure	Filter Medium Broken	D:\FT\Figure 4.4	D:\RCM\Table 3.4

Table D - 6.23 Symptom S11 - Temperature too high

Symptoms_ID	Symptoms Description	Problem Description	Cause Description	Fault Tree	RCM Information
S11	Temperature too high	Cooling system failed	Cooling water temp. is too	D:\FT\Figure 4.7	D:\RCM\Table 3.7
S11	Temperature too high	Cooling system failed	Cooling water circulating	D:\FT\Figure 4.7	D:\RCM\Table 3.7
S11	Temperature too high	Cooling system failed	Tube and fin covered by	D:\FT\Figure 4.7	D:\RCM\Table 3.7
S11	Temperature too high	Cooling system failed	Cooling coil ruptured	D:\FT\Figure 4.7	D:\RCM\Table 3.7
S11	Temperature too high	Heating System failed	Heating coil Control	D:\FT\Figure 4.5	D:\RCM\Table 3.5
S11	Temperature too high	Cooling system failed	Cooling Coil Control	D:\FT\Figure 4.7	D:\RCM\Table 3.7
S11	Temperature too high	Computer Control System	Temperature Sensor failed	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S11	Temperature too high	Computer Control System	Temperature Input	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S11	Temperature too high	Computer Control System	Temperature Output	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S11	Temperature too high	Heating System failed	Heating coil Control	D:\FT\Figure 4.5	D:\RCM\Table 3.5

Table D - 6.24 Symptom S12 - Temperature too low

Symptoms_ID	Symptoms Description	Problem Description	Cause Description	Fault Tree	RCM Information
S12	Temperature too low	freeze protection system	Heating water temp. is too	D:\FT\Figure 4.6	D:\RCM\Table 3.6
S12	Temperature too low	freeze protection system	Heating circulating pump	D:\FT\Figure 4.6	D:\RCM\Table 3.6
S12	Temperature too low	freeze protection system	Outdoor temp. is too cold	D:\FT\Figure 4.6	D:\RCM\Table 3.6
S12	Temperature too low	freeze protection system	Heating pump impeller	D:\FT\Figure 4.6	D:\RCM\Table 3.6
S12	Temperature too low	freeze protection system	Heating pump direct	D:\FT\Figure 4.6	D:\RCM\Table 3.6
S12	Temperature too low	Heating System failed	Heating water temp. is too	D:\FT\Figure 4.5	D:\RCM\Table 3.5
S12	Temperature too low	Heating System failed	Heating circulating pump	D:\FT\Figure 4.5	D:\RCM\Table 3.5
S12	Temperature too low	Heating System failed	Tube and fin covered by	D:\FT\Figure 4.5	D:\RCM\Table 3.5
S12	Temperature too low	Heating System failed	Heating coil ruptured	D:\FT\Figure 4.5	D:\RCM\Table 3.5
S12	Temperature too low	Heating System failed	Heating coil Control	D:\FT\Figure 4.5	D:\RCM\Table 3.5
S12	Temperature too low	Heating System failed	Outdoor temp. is too cold	D:\FT\Figure 4.5	D:\RCM\Table 3.5
S12	Temperature too low	Computer Control System	Temperature Sensor failed	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S12	Temperature too low	Computer Control System	Temperature Input	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S12	Temperature too low	Computer Control System	Temperature Output	D:\FT\Figure 4.18	D:\RCM\Table 3.10
S12	Temperature too low	Cooling system failed	Cooling Coil Control	D:\FT\Figure 4.7	D:\RCM\Table 3.7

Table D - 6.25 Symptom S13 - No Noise

Symptoms_ID	Symptoms Description	Problem Description	Cause Description	Fault Tree	RCM Information
S13	No Noise	Fan does not operate	Blown fuse	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S13	No Noise	Fan does not operate	Broken belts	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S13	No Noise	Fan does not operate	Loose pulleys	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S13	No Noise	Fan does not operate	Electricity turned off	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S13	No Noise	Fan does not operate	impeller touching housing	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S13	No Noise	Fan does not operate	wrong voltage	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S13	No Noise	Fan does not operate	Motor too small and	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S13	No Noise	Fan does not operate	low voltage, excessive line	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S13	No Noise	Fan does not operate	Load inertia too large for	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S13	No Noise	Fan does not operate	Seized bearing	D:\FT\Figure 4.16	D:\RCM\Table 3.9F1
S13	No Noise	EP relay failed	air compressor failed	D:\FT\Figure 4.19	D:\RCM\Table 3.11
S13	No Noise	EP relay failed	air dryer failed	D:\FT\Figure 4.19	D:\RCM\Table 3.11
S13	No Noise	EP relay failed	air line failed	D:\FT\Figure 4.19	D:\RCM\Table 3.11
S13	No Noise	EP relay failed	air filter failed	D:\FT\Figure 4.19	D:\RCM\Table 3.11
S13	No Noise	EP relay failed	EP leaking	D:\FT\Figure 4.19	D:\RCM\Table 3.11
S13	No Noise	EP relay failed	EP solenoid failed	D:\FT\Figure 4.19	D:\RCM\Table 3.11
S13	No Noise	EP relay failed	EP plastic housing failed	D:\FT\Figure 4.19	D:\RCM\Table 3.11

Table D - 6.26 Symptom S14 - Premature Failure

Symptoms_ID	Symptoms Description	Problem Description	Cause Description	Fault Tree	RCM Information
S14	Premature Failure	Premature failure	Belts	D:\FT\Figure 4.17	D:\RCM\Table 3.9G1
S14	Premature Failure	Premature failure	bearing	D:\FT\Figure 4.17	D:\RCM\Table 3.9G1
S14	Premature Failure	Premature failure	sheaves	D:\FT\Figure 4.17	D:\RCM\Table 3.9G1
S14	Premature Failure	Premature failure	impellers	D:\FT\Figure 4.17	D:\RCM\Table 3.9G1
S14	Premature Failure	Premature failure	hub	D:\FT\Figure 4.17	D:\RCM\Table 3.9G1
S14	Premature Failure	Premature failure	coupling	D:\FT\Figure 4.17	D:\RCM\Table 3.9G1
S14	Premature Failure	Premature failure	shaft	D:\FT\Figure 4.17	D:\RCM\Table 3.9G1

Using the Microsoft Access program under a new table design:

(a) enter "*component name*" in Field Name, select "Text" in Data Type, and enter "component failure mode" in the Description.

(b) enter "RD"in the Field Name, select Data/Time in Data Type, and enter "*last replacement date*" in the Description.

(c) enter "CD" in the Field Name, select Data/Time in Data Type, and enter "current date" in Description.

(d) enter "Duration" in the Field Name, select "Number" in the Data Type, and enter "the duration in days between RD and CD." in the Description. Using DateDiff["d",[RD],[CD]] as "Duration"

(e) enter "HRS' in the field Name, select "Number" in Data Type, and enter "Hours of operation per week" in the Description.

(f) enter "t" in the Field Name, select "Number" in Data Type, and enter "time in hours of operation" in the Description. "Duration"/7*"HRS"

(g) enter "beta" in the Field Name, select "Number" in Data Type, and enter "beta" in the Description. To format the beta column, right click on the column *(in the design view)*, click on properties, click in the format field and choose "fixed". Also change the Decimal places to 5.

(h) enter "eta" in the Field Name, select "Number" in Data Type, and enter "eta" in the Description. To format the eta column, right click on the column *(in the design view)*, click on properties, click in the format field and choose "fixed". Also change the Decimal places to 5.

(i) enter"F(t)" in the Field Name. select "Number" in the Data Type. and enter "r" probability of failure in the Description. To format the F(t) column, right click on the column *(in the design view)*. click on properties, click in the format field and choose "fixed". Also change the Decimal places to 5.

Using Microsoft program access under a new query design:

(j) Since "t" is equal to [Duration]*[HRS/WK]/7. then the expression ":[Duration]*[HRS/WK]/7" is added in the field after "t".

(k) Since "F(t)" is equal to $1\text{-exp}^{(-1)} \cdot (^{t}/_{\eta})^{\beta}$

Therefore. in the field after "F(t)" add ":" to start expression. Type " 1-(exp(-1*(([t]/[eta])^[beta])))". This can be achieved many ways. We can type in the expression or use expression Builder. Under Function click Built-in Functions and select "EXP" then Click "Paste" to add the functions. After the complete expression is completed then we can run the program. Under the F(t) column, right click and select "descending". the output is a list of probability of failure mode in descending order to highlight the results.

Appendix E: Biotechnology Building Information

Biotechnology Building started functioning on April 1992

Equipment: The building is served by three air handling units and are listed as follows:

AHU#1 Variable Volume System

The pre-filter section consists of 15 24x24x2 and 12 12x24x2 pleated filter.

The filter section consists of 15 24x24x4 and three 12x24x4 pleated filter.

Supply fan motor size is 75HP with four 5V900 type of belt size with running speed at ?? Rpm.

AHU#2 Constant Volume Terminal Reheat System

The pre-filter section consists of three 24x24x2 and four 12x24x2 pleated filter.

The filter section consists of three 24x24x4 and four 12x24x4 pleated filter.

Supply fan motor size is 20 hp with six BX38 type belt size with running speed at ?? rpm

.

AHU#3 Heat Reclaim System

The pre-filter section consists of 28 16x25x2 M47 type filter.

The exhaust fan motor size is 30HP with six 3V500 belt size with running speed at ? rpm.

Interlocked with Exhausted fan #14 & 15.

Operating conditioning: After the building was built. it was under warranty for one year and the maintenance will cut in after the warranty period. The systems are in operation 24 hours a day.

Appendix F: Arts and Administration Extension Building Information

Arts & Administration Building Extension started functioning on April 1992

Equipment: This building is served by three air handling units and are listed as follows:

AHU#1 100% Fresh Air Variable Volume System with No Return Air

The pre-filter section consists of 9- 24x24x2 M47 filter.

The filter section consists of 9 24x24 x2 pleated Dry-Pack type filter.

Supply fan motor is 25 hp with 2-B112 type of belt running at 30 rps.

Return fan motor is 15 hp with 2-BX108 type of belt and running at 30 rps.

AHU#2 Mixed Air Variable Volume System

The pre-filter section consists of 6- 24x24x2 Pleated filter.

The filter section consists of 6 24x24 x2 pleated Dry-Pack type filter.

Supply fan motor is 15 hp with 2-B85 type of belt running at 30 rps.

Return fan motor is 5 hp with 1-BA75 type of belt and running at 30 rps.

AHU#3 100% Constant Volume to Serve the Cafeteria Area

The pre-filter section consists of 4- 24x24x2 Pleated filter.

The filter section consists of 6 24x24 x2 pleated Dry-Pack type filter.

Supply fan motor is 7.5 hp with 1-B79 type of belt running at ?? rpm.

Operating schedule for AHU#1 and AHU#2 is 88.5 hours per week

Schedule

Day	Perm Start	Perm Stop
Sunday	99:99	99:99
Monday	07:00	23:00
Tuesday	07:00	23:00
Wednesday	07:00	23:00
Thursday	07:00	23:00
Friday	07:00	23:00
Saturday	08:30	17:00
Holiday	99:99	99:99

Operating schedule for AHU#3 is 52.5 hours per week.

Schedule

Day	Perm Start	Perm Stop
Sunday	99:99	99:99
Monday	07:30	18:00
Tuesday	07:30	18:00
Wednesday	07:30	18:00
Thursday	07:30	18:00
Friday	07:30	18:00
Saturday	99:99	99:99
Holiday	99:99	99:99

Notes:

99:99 means shut down

Appendix G: Earth Resource (CERR) Building Information

Earth Resource (CERR) Building started functioning on September 1989

Equipment: This building is served by six air handling units Lab Ventilation units LVU1. LVU2. Lab Make up units LMU1. LMU2,LMU3 and a General Ventilation unit

LMU#1 Laboratory Make Up Air Handling Unit

The pre-filter section consists of 10- 24x24x2 and 5- 12x24x2 M47 filter.

The filter section consists of 10- 24x24x18 Bag Dry-Pack type filter.

Supply fan motor is 40 hp with 5-B98 type of belt.

LMU#2 Laboratory Make Up Air Handling Unit

The pre-filter section consists of 10- 24x24x2 and 5- 12x24x2 M47 filter.

The filter section consists of 10- 24x24x18 and 5- 12x24x18 Bag Dry-Pack Type filter.

Supply fan motor is 40 hp with 5-B98 type of belt.

LMU #3 Laboratory Make Up Air Handling Unit

The pre-filter section consists of 12- 20x25x2 M47 filter.

The supply fan is 7.5 hp with 1-B60 type of belt.

LVU#1 Laboratory Ventilation Unit

The pre-filter section consists of 10- 24x24x2 and 5- 12x24x2 M47 filter.

The filter section consists of 10- 24x24x18 and 5- 12x24x18 Bag Dry-Pack type filter.

Supply fan motor is 50 hp with 3-5V950 type of belt.

LVU#2 Laboratory Ventilation Unit

The pre-filter section consists of 10- 24x24x2 and 5- 12x24x2 M47 filter.

The filter section consists of 10- 24x24x18 and 5- 12x24x18 Bag Dry-Pack type filter.

Supply fan motor is 50 hp with 3-5V950 type of belt.

GVU#1 General Ventilation Unit

The supply fan motor is 50 hp with 3-5V950 type of belt.

Units LMU1, LMU2 and LMU3 are running 24 hours a day.

Operating schedule for Units GVU1 and LVU1 and LVU2. i.e.80 hours per week

Schedule

Day	Perm Start	Perm Stop
Sunday	99:99	99:99
Monday	07:00	23:00
Tuesday	07:00	23:00
Wednesday	07:00	23:00
Thursday	07:00	23:00
Friday	07:00	23:00
Saturday	99:99	99:99
Holiday	99:99	99:99

Notes:

99:99 means shut down.

Appendix H: Existing Practice for the Arts/Ext, Biotechnology and CERR Buildings

Equipment List	Maintenance Schedule	Method
Fresh air intake louver	No maintenance	
Fresh air damper motor	lubricated every 3 month	Scheduled
Pre-filter	It was once every 3 month then it was changed to once every year. Current practice is change once every six months.	Scheduled
Filter	once a year	It was set up as on-condition method of maintenance because the pressure drop through the filter was monitored. But the setting was set at 25 mm. a setting that was too high and will not exist within one year.
Heating Coil	vacuum once every 3 month	Scheduled
Freeze protection system	once a year for inspection and testing	Scheduled
Cooling coil	Visual inspection once a year usually in spring before cooling system start up	Scheduled
Humidifier	Pneumatic actuator and diaphragm once a year and	scheduled
Fan	.1 Lubricated once every 3 months .2 belts. bearing and motor are based on breakdown only .3 Inlet vanes are inspected once every 3 months	scheduled Breakdown Scheduled
Control system	once a year	Scheduled
EP relays	Once a year	Scheduled

CERR Building

Air compressors will be maintenance check once every 6 months. This included change the oil. test the safety valve, pressure switch . and running the compressor in and out.

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