12-2003

A Simulation Based Approach for Determining Maintenance Strategies

Vasanth Murthi
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Vasanth Murthi entitled "A Simulation Based Approach for Determining Maintenance Strategies." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

Dr. Rupy Sawhney, Major Professor

We have read this thesis and recommend its acceptance:

Dr. Denise Jackson, Dr. Thomas Shannon

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Vasanth Murthi entitled "A Simulation Based Approach for Determining Maintenance Strategies". I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for degree of Master of Science, with a major in Industrial Engineering.

Dr. Rupy Sawhney

____

Major Professor

We have read this dissertation
and recommend its acceptance:

Dr. Denise Jackson

____

Dr. Thomas Shannon

____

Accepted for the Council
Anne Mayhew

____

Vice Provost and
Dean of Graduate Studies

(Original signatures are on file with official student records.)

A Simulation Based Approach

for

Determining

Maintenance Strategies

A thesis

presented for the

Master of Science Degree

The University of Tennessee, Knoxville

Vasanth Murthi

December 2003

Acknowledgements

I thank Dr. Rupy Sahwney for his continuous guidance, inspiration and enthusiasm. He manages to strike the perfect balance between providing direction and encouraging independence. He has certainly been my biggest inspiration at the University of Tennessee, Knoxville and I thank him for providing me adequate exposure to practical IE applications. I would also like to thank my thesis committee Dr. Denise Jackson and Dr. Thomas Shannon for helping me complete this thesis through all my hardships.
I am grateful to many people in the Department of Industrial Engineering who have assisted me in the course of this work and have been particularly helpful and generous with their time and expertise.

Few people in chaos will understand a word of this thesis, yet it would not exist without the club. In particular, Panogiotis Martinis, Ammar Aamer, Abhishek Padiyar, Naim Hossine, Anshuman Mehrotra, Carlos Noriega, Shankar Damodar, Danny Paulose and the gang have filled my past two years with unforgettable memories. I extend a very special thanks to Kannnan Kase for simplifying my life. I would also like to thank Rohan, Faezeh and Paulo for their support.

My parents have always encouraged me and guided me through everything, never tying to limit my aspirations. I am grateful to them and amazed at their generosity. Most importantly I thank Archana Niranjan, who has shown untiring patience and support, reminding me of my priorities and keeping things in perspective.

Abstract

Manufacturing organizations are continuously in the mode of identifying and implementing mechanisms to achieve a competitive edge. To this point manufacturers have recognized the critical role of equipment in the productivity of manufacturing operations. With the current trend of manufacturers attempting to lean out their production processes, primary and auxiliary equipment have become even more important to manufacturers as measured by productivity, quality, delivery, and cost metrics. As a result of the focus on lean manufacturing, maintenance management has found a new vigor and purpose to increase equipment capacity and capability. However, the most proactive maintenance strategy is not always the most effective utilization of resources. It is typical for manufacturers to integrate both reactive and proactive maintenance to define a cost effective maintenance strategy. A simulation-based approach is presented that allows an end user to develop such a maintenance strategy.

Table of Contents

Chapter 3

Approach

Chapter 4

Case Studies

Chapter 5

Conclusion

List of Tables

List of Figures

Chapter I

Introduction

1.1 Introduction

Lean manufacturing has resulted in the reduction of inventory, direct labor, indirect labor, space requirements, of quality costs and material cost (Moore, Ron). However, if one probes beneath the surface, the picture concerning lean changes significantly. It is common knowledge among actual lean implementers that there are more failures in implementing lean than there are successes (Liker, Jeffrey). There are many reasons for these failures including lack of commitment, lack of resources, lack of planning, and lack of training. One primary reason for the failure in implementing lean in industry is the lack of an appropriate maintenance program to support the redesigned production system (Larry, Madelyn, Shirley).

One example involves the design of a manufacturing cell. A cell is comprised of a set of equipment placed in an order dictated by the process sequence and in proximity to allow an efficient one-piece flow of a family group of products. These cells are characterized by increased complexity of equipment and unavailability of backup or redundant equipment. The cells can be extremely efficient, yet at the same time vulnerable. The reason for this vulnerability is increased cell dependency on the equipment. Therefore logically cell performance is dependent upon the resources allocated to maintenance including adequate number and skill level of personnel performing maintenance, availability and condition of testing equipment, and availability

of spare parts. Historically, the lack of maintenance support has resulted in the underachievement of manufacturing cells (Peter Willmott).

Appropriate and effective maintenance has traditionally not been provided because it is not perceived as a mechanism for developing a competitive edge but rather as a necessary cost of "doing business". However, reported cost of maintenance may provide most management with a shock and an incentive to re-evaluate their paradigm for maintenance. Examples of reported costs include the following; maintenance cost represent up to 15% of the total value-added costs (Campbell, Dixon), and that maintenance costs are 3%-6% of the replacement cost of a plant (Moore, Ron). These cost estimates reveal the need for a maintenance strategy that balances the cost of downtime due to maintenance with the cost of resources allocated to maintenance.

1.2 Background

The first thoughts that come to our minds when the word "maintenance" is brought up are the high cost involved, under utilization of maintenance resources and maintenance being considered as a non value-added attribute in the system.

But today's complex systems demand higher quality, cost effectiveness and greater integration and maintenance becomes one of the essential components if all the above points need to be satisfied. Maintenance has taken on the role of being a non-value added – essential component in the manufacturing system. Figure 1.1 sheds more light on the changing trends in the importance given to maintenance.

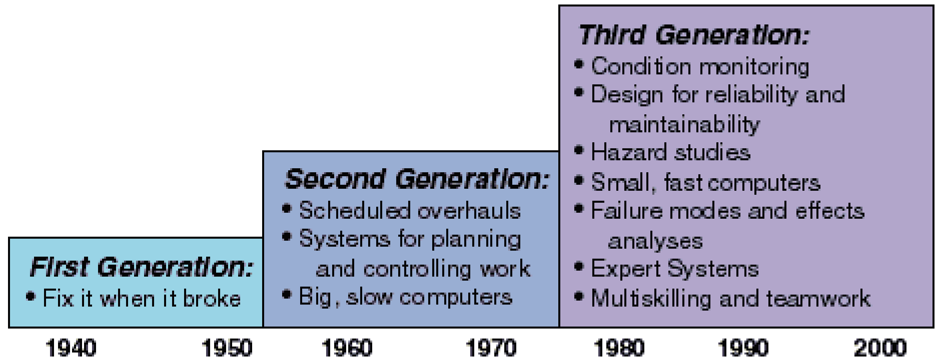


Figure 1.1: Changing Trends in Maintenance (Moubray)

Uptime, a measure of operational excellence, is negatively correlated with high reactive maintenance levels (Campbell, Dixon). The maintenance community has presented many arguments in favor of a move from a reactive maintenance strategy to a more proactive one but with careful consideration of the fundamentals (Mulvilill, Robert, Gulati). One such argument takes into consideration the excessive time and cost associated with unplanned maintenance activities as compared to planned maintenance activities especially in a lean production environment. Given the stated benefits, it would seem logical that manufacturers would be implementing proactive maintenance throughout their facilities, but over the past decade few manufacturers have truly taken advantage of increasing their uptime via a valid maintenance strategy. Two possible reasons are listed below:

1. Executive managers typically do not view maintenance as a strategic issue that will translate to a significant contribution to the company's bottom line. Such a paradigm can result in lack of maintenance resources and a narrow scope of work.

2. Maintenance manager and other industry managers are not able to sell maintenance based on short-term economic justifications. Maintenance costs actually increase during the initial phase of transitioning to a more proactive maintenance strategy. This is typically true if the proposal is to have proactive maintenance throughout the facility. Most maintenance managers are not able to quantify and communicate the longer-term benefits given both the initial investment and the temporarily increased cost of maintenance (Campbell, Dixon).

1.3 Problem Statement

By definition, reliability is the probability that a plant or component will not fail to perform within specified limits in a given time while working in a stated environment. The focus of reliability is to reduce the effect of failure of components in the system. Downtime affects every aspect of a manufacturing system. It affects the productive capability of physical assets by reducing output, increasing operating costs and interfering with customer service (Moubray). Uptime is an essential component of system reliability.

As depicted in Figure 1.1 there has been a major change in the importance given to maximizing uptime with new developments such as decision support tools, hazard studies, failure modes and effects analyses conditional monitoring, expert systems etc.

If the goal is to derive all the benefits of maximizing uptime, management would definitely choose the best possible maintenance strategy. But having the best maintenance strategy assigned to all pieces of equipment in a manufacturing system might not be the most economically feasible approach.

At present there are a few tools that analyze reliability using reliability based diagrams and Monte-Carlo simulation. These tools address specific issues related to reliability and do not analyze the manufacturing system from an enterprise level. There is a need for a tool that analyzes how different maintenance strategies affect the targets of the manufacturing system and aid in maintenance resource allocation. To address this concern, the research work illustrated in this thesis proposes to do the following

- Develop a model that estimates the best maintenance strategies that are both feasible and economically justifiable for a complex manufacturing system.
- Provide a feasible and exhaustive means of testing different parameters on this model and analyzing the results.

1.4 General Approach

There is currently a need for a user-friendly mechanism that allows practitioners to effectively develop and experiment with maintenance strategies. It is proposed that a computer-based model be developed that is able to fulfill the following requirements:

1. User-friendly.
2. Flexibility to allow end-user to experiment.
3. Provide a robust and fundamentally sound structure to develop strategies based on end-user requirements.
4. Ability to analyze the maintenance strategies in financial and operational terms.
5. Provide a mechanism for enhancing communication with others.

The proposed approach suggests that the basic process is modeled in a simulation model and all possible maintenance parameters/ strategies are experimented on the

model. A full factorial design of experiments model automates the simulation model to run the experiment in a structured way. A cost model analyzes the data from all these experiments and suggests the best strategy to be used that would balance both operational metrics and financial constraints.

1.5 Organization of Thesis

This thesis comprises of five chapters including this introductory chapter. Chapter 2, “Literature Review”, introduces the basic elements of industrial maintenance and reliability, provides a comprehensive review of the tools and techniques available in the market that are used to address the issue and the work that has been done in developing simulation based methodologies. Chapter 3, “Research Methodology”, gives a general description of the model approach applied in this thesis. This chapter emphasizes on the components of the model and how the model deals with the challenges posed by this approach. Chapter 4, “Case Studies”, contains a case study that illustrates the use of the proposed approach. The case study deals with approaching the problem using key performance indices to analyze data from the computer model and also uses a cost model that incorporates the computer model’s output to better address the issue of maintenance resource allocation. Chapter 5 “Conclusion”, summarizes the major conclusions of this document. It sheds light on some of the applications of this tool in looking at other avenues related to continuous improvement and the scope for future research in this area.

Chapter 2

Literature Review

Chapter 2 provides a detailed review of techniques, methodologies used in maintenance resource allocation. The chapter also outlines some of the academic work done in the area of modeling maintenance, especially with the use of simulation models. Section 2.6 looks at few of the software that address similar issues related to managing maintenance resources.

2.1 Trends in Maintenance

Figure 2.1 (Wireman) shows the different trends in maintaining equipment over the past 75 years. There is a significant difference in terms of the importance given to maintenance in the recent years.

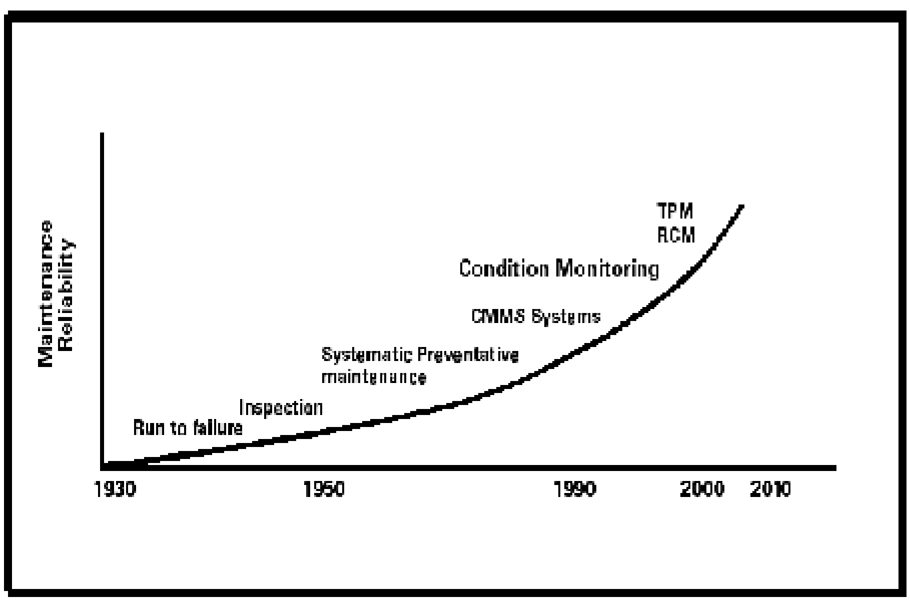


Figure 2.1: Trends in Maintenance

During the Pre-World War II era, industry was not very highly mechanized; therefore the impact of down time was not very significant [Moubray]. Also equipment was simpler, which made it easy to fix, and companies performed mainly Corrective Maintenance (CM). During the Post-World War II until the mid 1970's era, increased mechanization led to more numerous and complex equipment. Companies were beginning to rely heavily on this equipment. This dependence led to the concept of Preventive Maintenance (PM). In the 1960's, PM consisted mainly of equipment overhauls done at fixed intervals. Also, the increased costs of this equipment led management to start finding ways to increase the life of these assets. The latest era began with the aircraft industry in the early to mid 1970's. The huge costs of new highly-mechanized equipment resulted in companies wanting to ensure that equipment lasted and operated correctly for as long as possible.

2.2 Maintenance Strategies

In general, maintenance is either planned or unplanned as shown in Figure 2.2. Corrective maintenance is a reactive strategy, which is unplanned and is carried out after failure has occurred. The intention is to restore an item to a state that can perform its required function.

Unplanned maintenance may be the appropriate strategy in some cases, when one of the following holds true (Daya, Duffuaa, Raouf)

- Hazard rate is constant
- Failure has no serious cost or safety consequence
- It is low on the priority list of equipment that constraints production

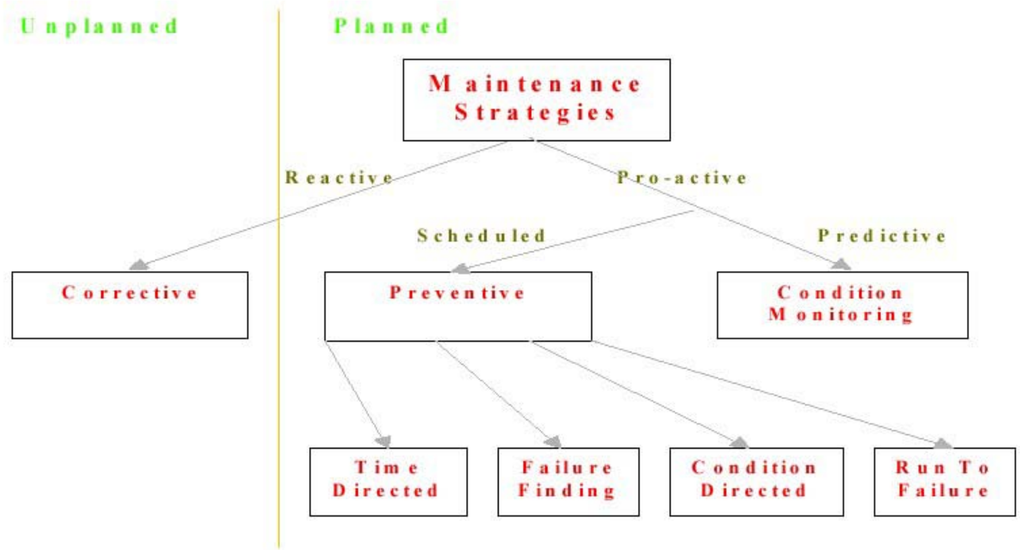


Figure 2.2: Major Subdivisions in Maintenance

Planned maintenance strategies are proactive in nature and can be divided into two groups: Preventive and Condition Monitoring. Preventive maintenance, which is sometimes called scheduled, is a maintenance carried out at regular intervals.

There are four basic tasks that can be selected under this category:

- Time Directed task involves number of operations, operating hours, or seasonal change.
- Failure Finding is for identifying equipment failure that are not evident to the operating crew (hidden failures). Usually used for protective equipment.
- Condition Directed applies to the situation when the condition of equipment reaches a limit, or when continued satisfactory operation cannot be ensured.
- Run to Failure is an option that is selected only in the event that a technically correct and cost effective task cannot be identified.

Predictive Maintenance (PdM) is carried out when it is deemed necessary, based on periodic inspections, diagnostic tests or other means of condition monitoring. Condition Monitoring is the monitoring or diagnostic activity that is used to predict equipment failure. Though conditional monitoring is the best maintenance alternative in most cases, it is also expensive and difficult to implement.

2.3 Reliability Engineering

Reliability is of fundamental importance to engineering. Whether failure occurs or not and its time to occurrence, can seldom be predicted accurately. Reliability is therefore an aspect of engineering uncertainty, which is best expressed in terms of probability. Usually, engineering education is traditionally concerned with teaching how manufactured products work and perform. The ways in which products fail, the effects of failure and aspects of design, manufacture, maintenance and use, which affect the likelihood of failure, are not usually taught, mainly because it is necessary to understand how a product works before considering ways in which it might fail. The task of an engineer is to design and maintain the product so that the failed state is deferred. It is precisely for these reasons that an understanding of reliability engineering principles and methods is now an essential ingredient of modern engineering. (O'Connor, Newton Bromley, Stolarski)

Reliability engineering is the function of analyzing the expected or actual reliability of a product, process or service, and identifying actions to reduce failures or mitigate their effect. Engineers analyzing reliability typically carry out reliability predictions, FMEA or FMECA, design testing programs, monitor and analyze field

failures, and suggest design or manufacturing changes. The overall goal of reliability engineering is to make your product more reliable in order to reduce repairs, lower costs, and to maintain your company's reputation. To best meet this goal, reliability engineering should be done at all levels of design and production, with all engineers involved.

A formal definition suggests that Reliability engineering provides the theoretical and practical tools whereby the probability and capability of parts, components, equipment, products, and systems to perform their required functions for desired periods of time without failure, in specified environments, and with a desired confidence can be specified, designed in, predicted, tested and demonstrated.

2.3.1 Key Reasons for Reliability Engineering

- For a company to succeed in today's highly competitive and technologically complex environment, it is essential that it knows the reliability of its product and is able to control it so it can produce products at an optimum reliability level. The optimum reliability level yields the minimum life cycle cost for the user, as well as minimizes the manufacturer's costs of such a product without compromising the product's reliability and quality.
- Our growing total dependence on technology requires that the products that make up our daily lives work successfully for the desired or designed-in period of time. It is insufficient for a product to work for time shorter than its mission duration. At the same time, there is no need to design a product to operate much past its intended life, since it would only impose additional costs to the manufacturer. In today's complex living almost everything is done with automated equipment, we

are totally dependent on the successful operation of these equipment (their reliability) and on their quick restoration to function (their maintainability) if they fail.

- Product failures range from failures that cause minor nuisances, such as a television's remote control, to catastrophic failures, such as an aircraft accident. Reliability engineering was born out of the necessity to avoid such catastrophic events. It is not surprising that Boeing was one of the first commercial companies to embrace and implement reliability engineering, the success of which can be seen in the safety of today's commercial air travel.
- Today, reliability engineering can and should be applied to all products. The previous example of the failed remote control does not have any major life and death consequences to the consumer. However, it can pose a life and death risk to a non-biological entity: the company that produced it. Today's consumer is more intelligent and product-aware than the consumer of years past. This consumer will no longer tolerate products that do not perform in a reliable fashion, or as promised and advertised. Customer dissatisfaction with products reliability can have disastrous financial consequences to the manufacturer. Statistics show that when a customer is satisfied with a product they might tell 8 other people; however, a dissatisfied customer will tell 22 people, on average.
- The critical applications with which many modern products are entrusted make their reliability a factor of paramount importance. For example, the failure of a computer component will have more negative consequences today than it did twenty years ago. This is because twenty years ago the technology was relatively

new and not very widespread, and one most likely had backup paper copies somewhere. Now, as computers are often the sole medium in which many clerical and computational functions are performed, the failure of a computer component will have a much greater effect.

2.3.2 Advantages of Reliability Engineering

The following list presents useful information that can be obtained with the implementation of a sound reliability program:

- Optimum burn-in time or breaking-in period.
- Optimum preventive replacement time for components in a repairable system.
- Spare parts requirements and production rate, resulting in improved inventory control through correct prediction of spare parts requirements.
- Better information about the types of failures experienced by parts and systems that aid design, research, and development efforts to minimize these failures.
- Establishment of which failures occur at what time in the life of a product, and better preparation to cope with them.
- Studies of the effects of age, mission duration, and application and operation stress levels on reliability.
- A basis for comparing two or more designs and choosing the best design from the reliability point of view.
- Evaluation of the amount of redundancy present in the design.

- Estimations of the required redundancy to achieve the specified reliability.
- Guidance regarding corrective action decisions to minimize failures and reduce maintenance and repair times, which will eliminate over-design as well as under-design.
- Help providing guidelines for quality control practices.
- Optimization of the reliability goal that should be designed into products and systems for minimum total cost to own, operate, and maintain for their lifetime.
- The ability to conduct trade-off studies among parameters such as reliability, maintainability, availability, cost, weight, volume, operability, serviceability, and safety to obtain the optimum design.
- Establishment of guidelines for evaluating suppliers from their product reliability point of view.
- Increase of customer satisfaction, and an increase of sales as a result of customer satisfaction.
- Increase of profits, or for the same profit, provision of even more reliable products and systems.

2.4 Tools for Analyzing System Reliability

The following are a few tools that are used to analyze reliability of the system and can be directly applied to address the issue of maintenance resource allocation.

2.4.1 Reliability Block Diagram (RBD)

A Reliability Block Diagram (RBD) is a tool for analyzing more complex systems and configurations. When performing a Reliability Prediction analysis, failure rates for components, assemblies, and systems are calculated. The RBD is the most popular modeling technique that describes how pieces of a product act and interact to determine the reliability of the product. It is characterized by blocks representing parts, subassemblies, subsystems etc. Each block is defined by a probability of success or a probability of success or a probability distribution function and values the associated parameters (Criscimagna). Based on the pdf and parameter values, the reliability of each block can be calculated for a given time. Then, by mathematically combining the reliabilities the system reliability is assessed and the necessary resource allocation is made to compensate for the lack of reliability in the blocks represented in the RBD.

2.4.2 Monte Carlo Simulation

In applications of resource allocation modeling, RBDs and Monte Carlo Simulations are used hand in hand in many application tools. Using Monte Carlo technique the RBD is performed over time and provides various measures of performance, depending on the type of input data that were used. Some of the parameters can be calculated are Uptime, Mean Repair Time, Mean Time Between Maintenance, Number of maintenance tasks, Spares Cost, Availability (steady state, minimum and maximum) etc (Criscimagna).

2.4.3 Weibull Analysis

Weibull analysis is the process of discovering the trends in product or system failure data, and using them to predict future failures in similar situations. By learning these trends, one can attempt to correct or compensate for them, thereby improving product reliability. Weibull analysis can be used to study a variety of fields, practices, and disciplines. It can employ several different failure distributions, depending upon the specific situation. For example, the Weibull distribution is one of the most widely used distributions for failure data analysis. It is useful for mechanical, chemical, electrical, electronic, materials, and human failure analysis. The Weibull distribution can analyze the data from burn-in (infant mortality), useful life, and wear-out periods - meaning that it is effective in increasing, constant, and decreasing failure rate situations.

Some of the questions that Weibull analysis can answer include:

- What type of failure mechanism is the root cause?
- How many failures are expected?
- How reliable is the existing part compared to a possible new design?
- When should I replace an existing part with a new one to minimize maintenance costs?

Weibull analyses study the relationship between product reliability and product lifespan. They provide insight into the decrease in reliability as the usage of a product or system increases. The primary advantage of Weibull analysis is that it can provide reasonably accurate failure analyses and failure forecasts with extremely small data samples. This facilitates cost-effective and efficient component testing.

2.4.4 FMEA/FMECA

A Failure Mode and Effects Analysis (also referred to as a FMEA or FMECA) is a bottoms up approach to analyzing system design and performance. To begin a FMEA or FMECA, the lowest levels of the system are outlined. This can be the individual components (referred to as a *piece part FMEA*) or the lowest level assemblies in the system (referred to as a *functional FMEA*). For each lowest level, a list of potential failure modes is generated. Effects of each potential failure mode are then determined.

For example, consider a piece part FMEA that needs to be done on a computer monitor. One component in that computer monitor might be a capacitor. If it is determined that there are 2 potential failure modes for the capacitor, and they are that the capacitor could fail 'open' or it could fail 'shorted'. If the capacitor fails open, the effect might be that the monitor appears with wavy lines. However, if the capacitor fails shorted, the effect might be that the monitor goes completely blank.

In the case above, if the capacitor fails shorted and the monitor goes blank, that failure mode could be considered more severe or critical than if the capacitor fails open and wavy lines appear. In this case, one would attempt to find ways to prevent these failures from happening or lessen their criticality. A FMECA can use failure rate calculations that were performed during the Reliability Prediction portion of an analysis to determine probability of occurrence. Failure Rate is a value describing how often a component or assembly will fail. In a FMECA, Failure Rate is used to compute *Mode Criticality*, or the probability that a particular failure mode is actually going to occur.

2.4.5 Life Cycle Costing

Life Cycle Cost (LCC) analysis and Total Cost of Ownership evaluation are the basis for decision making for the wide range of industries and equipment: from IT systems to submarines. LCC analyzes the total ownership costs of various design alternatives and system's components over the projected life cycle of a system.

Life cycle costs (LCC) are all costs from project inception to disposal of equipment. LCC applies to both equipment and projects. LCC costs are found by an analytical study of total costs experienced during the life of equipment or projects. LCC costs have two major elements: 1) acquisition costs and 2) sustaining costs. Acquisition and sustaining costs are not mutually exclusive. The object of LCC analysis is to choose the most cost-effective approach from a series of alternatives so the least long term cost of ownership is achieved. LCC analysis helps engineers justify equipment and process selection based on total costs rather than the initial purchase price of equipment or projects. LCC provides best results when both art and science are merged together with good judgment (as is true with most engineering tools).

2.4.6 Fault Tree Analysis

A fault tree analysis (FTA) is a deductive, top-down method of analyzing system design and performance. It involves specifying a top event to analyze (such as a fire), followed by identifying all of the associated elements in the system that could cause that top event to occur. Fault trees provide a convenient symbolic representation of the combination of events resulting in the occurrence of the top event. Events and gates in fault tree analysis are represented by symbols. Fault tree analyses are generally

performed graphically using a logical structure of AND and OR gates. Sometimes certain elements, or basic events, may need to occur together in order for that top event to occur. In this case, these events would be arranged under an AND gate, meaning that all of the basic events would need to occur to trigger the top event. If the basic events alone would trigger the top event, then they would be grouped under an OR gate. The entire system as well as human interactions would be analyzed when performing a fault tree analysis.

2.4.7 Event Tree Analysis

An event tree analysis (ETA) is a visual representation of all the events, which can occur in a system. As the number of events increases, the picture fans out like the branches of a tree. Event trees can be used to analyze systems in which all components are continuously operating, or for systems in which some or all of the components are in standby mode - those that involve sequential operation logic and switching. The starting point (referred to as the initiating event) disrupts normal system operation. The event tree displays the sequences of events involving success and/or failure of the system components. The goal of an event tree is to determine the probability of an event based on the outcomes of each event in the chronological sequence of events leading up to it. By analyzing all possible outcomes, one can determine the percentage of outcomes, which lead to the desired result.

2.4.8 Decision Trees

Decision Tree is a graphical method of expressing, in chronological order, the alternative actions that are available to the decision maker and the outcomes determined

by chance. The Decision tree is a good tool for decision making under uncertainty. Decision trees are viewed as a special type of event tree. The decision analysis is the framework for the assessment of the risks as well as for the evaluation of the how to reduce the risk most efficiently. It is important to note that the probabilities for the different events represented in the decision tree may be assessed by fault tree analysis, event tree analysis or a combination of these and thus the decision tree in effect includes all these aspects of systems and component modeling in addition to providing a framework for decision making (Nachdiplomkurs, Sicherheit). It is hence a good technique to experiment with maintenance alternatives when the decision maker has very little quantitative data about the outcomes of each maintenance alternative

2.5 Research in Maintenance Resource Allocation Modeling

Production costs have been coming down over the past two decades, owing to automation, computer integrated manufacture, cost reduction studies and more. On the other hand new technologies are expensive to buy, repair and maintain. So the demand on maintenance is growing and maintenance costs are escalating. This new environment is compelling industrial maintenance organizations to make the transition from being repair departments for fixing broken machines to that of high level business units for securing production capacity.

In the past, maintenance problems received little attention and research in this area did not have much impact. Today, this is changing because of the increasing importance of the role of maintenance. Maintenance, if optimized, can be used as a key

factor in organizations efficiency and effectiveness. It also enhances the organization's ability to be competitive and meets its stated objectives.

Research in the areas of maintenance management and engineering is on the rise and there has been a great deal of research done in the fields of maintenance modeling and optimization.

The following literature review outlines some of the research work done in the area of modeling maintenance and obtaining ideal maintenance strategies. The study also covers some aspects of optimizing these strategies. The tools and techniques used in each technical paper have been discussed and can be compared with the approach used in this thesis, which is explained in more detail in Chapter 3.

Vatn, Hokstad and Bodsberg's paper "An Overall Model for Maintenance Optimization" describe a global approach for quantifying the costs and benefits of the maintenance program of a production system/plant. This paper presents an approach for identifying the optimal maintenance schedule for the components of a production system. Safety, health and environment objectives, maintenance costs and costs of lost production are all taken into consideration, and maintenance is thus optimized with respect to multiple objectives. It is model based and thus will allow the user to carry out an optimization in a well defined sense. The method so far restricts to incorporate the most fundamental maintenance strategies, but the effect of these maintenance rules on the overall costs are explicitly modeled.

Ultimate system performance, as measured by

- Total system down-time, due to repairs (per year)
- Number of system shut-downs (per year)

- Number of injured persons at the plant (per year)
- Number of killed persons at the plant (per year)
- Total amount of pollution in cubic meters (per year)
- Hours of maintenance (per year)

The analysis method is carried out in four steps:

- Define the problem. System boundary and the objective of the analysis are defined.
- Establish the loss function and preferences. The main objectives of plant activity are identified, and the form of the loss function is decided in this step.
- Dependability modeling ("Description of the world"). Degree of goal attainment is quantified by a dependability model.
- Result compilation. The expected value of the overall loss function is established, and a minimization of this is carried out with respect to frequency of the identified PM activities.

Tools used in this study were decision theory, risk analysis and reliability and maintenance modeling.

Azadivar and Shu in their paper "Use of Simulation in Optimization of Maintenance Policies" study parameters of the production system, in particular the allowable in-process buffers, and the design parameters of the maintenance plan are considered simultaneously as integral parts of the whole decision process for selection and implementation of a maintenance policy. The results from the simulation experiments showed that the response surfaces for these systems were of the forms that yield

themselves to an optimization search. However, the optimization problem itself is not trivial, as the performance of the system depends on a combination of qualitative and policy variables (the choice of the maintenance policy) as well as a set of quantitative variables (allowable buffer spaces). The paper proposes a methodology for solving this class of problems that was based on a combined computer simulation and optimization integrated with a genetic algorithm search. The service level was used as the metric to determine the optimal maintenance strategy.

Tools used in this study were Response Surface Topology, genetic algorithms, simulation modeling and other optimization tools.

In Raivio, Kuumola, Mattila, Virtanen, Hämäläinen's paper - "A Simulation model for Military Aircraft Maintenance and Availability" the authors look at a specific application of a similar concept for obtaining the best maintenance plan that increases availability. The model describes the flight policy and the main factors of the maintenance, failure, and repair processes. Model implementation with graphical simulation software allows rapid what-if analysis for maintenance designers. More importantly, since the model can be verified, validated, and accredited using existing statistical data, it provides information on the level of detail on which such processes should be modeled.

The tools used in this study were Simulation modeling, sensitivity analysis and expert knowledge.

Joshi, Unal, White and Morris talk about some unique aspects have to be addressed while optimizing via stochastic simulation models. The optimization procedure has to explicitly account for the randomness inherent in the stochastic measures predicted

by the model. This paper outlines a general-purpose framework for optimization of terminating discrete-event simulation models.

The methodology combines a chance constraint approach for problem formulation, together with standard statistical estimation and analyses techniques.

There has also been work by researchers such as Enscore and Burns and Wu et al. Bruggeman and Dierdonck who suggested applying the Manufacturing Resource Planning (MRP II) concept to maintenance resource planning. For JIT type systems, Abdulnour et al., using computer simulation and experimental design, developed some regression models to describe the effects of three preventive maintenance policies on performance of a production system. Researchers Azadivar and Shu ranked maintenance policies in terms of their performance on JIT systems defined by certain characteristic factors. Figure 2.3 contrasts the tools and measurable used in the research work discussed above with the proposed approach of this thesis.

2.6 Software Available in the Market that Analyze System Reliability

The previous section dealt with some of the research techniques employed in handling maintenance modeling and maintenance resource allocation related issues. Some of these research approaches resulted in computer based software that are now available in the market. Most of these software are designed for maintenance management related issues and are well aligned to our area of research.

	Author	Paper	Tools used	Measurable
1	Vatn	An Overall Model for Maintenance	Decision theory	Total system downtime
	Hokstad	Optimization	Risk analysis	Number of system shutdowns
	Bodsberg		Reliability and maintenance modeling	Number of injuries/fatalities
				Pollution
				Hours of maintenance
2	Azadivar	Use of Simulation in Optimization	Response surface tapology	Allowable in-process buffers
	Shu	of Maintenance Policies	Genetic algorithms	Design parameters of maintenance plan
			Simulation modeling	
			Other optimization tools	
3	Raivio	A Simulation model for Military	Simulation modeling	Availability
	Kuumola	Aircraft Maintenance and	Sensitivity analysis	Repair process
	Mattila	Availability	Expert Knowledge	Failures
	Virtanen			
	Hamalainen			
4	Joshi Unal White Morris	A Framework for Optimization of	Chance constraint approach	This paper provides some future research
		Discrete Event Simulation models	Standard Statistical elimination	Direction to the approach proposed in this thesis.

Proposed Approach	
Tools Used	**Measurable**
Discrete Event Simulation Modeling	EBIT
Design of Experiments	ROI
Key Performance Indices	OEE
Life Cycle Cost model	JPH
	Overall equipment downtime
	Spares inventory
	Acquisition costs
	Operation costs
	* Total fixed costs
	* Total variable costs
	Unplanned Maintenance Costs
	* Planned maintenance costs
	* Unplanned maintenance costs
	* Reduced OEE costs
	Life cycle costs

Figure 2.3: Comparative Matrix of Research Work on

Maintenance Resource Allocation Modeling

2.6.1 ACARA (Availability, Cost and Resource Allocation)

ACARA is a program for analyzing availability, lifecycle cost (LCC), and resource scheduling for a system that undergoes periodic repair. ACARA was developed by a team of engineers at the NASA Glenn Research Center at Cleveland, OH. It uses a combination of exponential and Weibull distributions to simulate the useful life of each system component. The replacement of each faulty component is simulated to optimize system performance, and yet comply with constraints on component production and available resources (resupply vehicle capacity, on-site spares, manpower, etc.). ACARA evaluates the availability of the system at each capacity level based upon a system block diagram representation.

ACARA is capable of many types of analyses and trade studies because of its integrated approach. It can characterize system performance in terms of both state availability and equivalent availability (a weighted average of state availability). It can determine the probability of exceeding a capacity state to assess reliability and loss of load probability. It can determine the probability of failure for each component type during each period of system operation. ACARA can evaluate the effect of resource constraints on system availability and lifecycle cost.

2.6.2 APT-Lifespan/ Maintenance/ Inspection/ Stock/ Spares

APT – Lifespan handles life cycle analysis, asset replacement timing, repair versus replacement, life extension options, alternative designs, Capex/Opex

combinations. The APT – Maintenance calculates the best preventive maintenance interval or equipment replacement point and puts numbers to the costs, benefits and risks of alternative maintenance strategies. It is the most sophisticated (yet simple to use) tool in existence for balancing equipment reliability, performance & efficiency, maintenance costs, downtime impact and lifespan. It identifies the cost and risk optimal strategies, tests for sensitivity to weak and range estimated data and quantifies the impact of constraints or intangibles. Figure 2.4 illustrates a typical report that shows the optimum time to perform maintenance based on direct costs, risk exposure and lost performance.

APT-Inspection handles inspection, testing and monitoring intervals, optimal condition reaction points and cost/benefit comparison of monitoring methods. APT – Stock/Spares handles issues related to materials and spares strategies, min/max stock, re-order quantities, buffer storage of intermediates, supplier comparisons, stock pooling options.

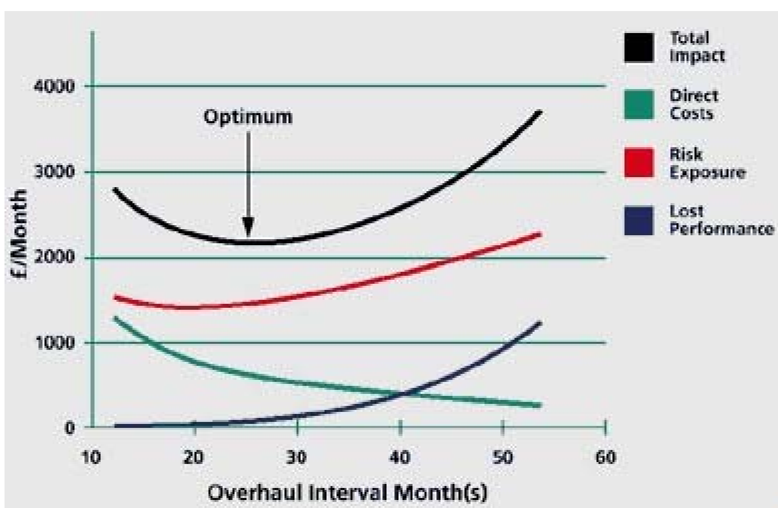


Figure 2.4: Compressor-major overhaul

2.6.3 D-LCC™

D-LCC (Decision by Life Cycle Cost) makes the LCC analysis easy and comprehensive. D-LCC is a key tool for managers, decision-makers, engineers, ILS personnel, and other staff involved in system acquisition, proposal writing, management, development, production and through-life support.

Total Cost of Ownership and Life Cycle Cost analysis with D-LCC:

- Evaluation and comparison of alternative design approaches.
- Comparison of alternative strategies
- Identification of cost effective improvements
- Project's budget and economic viability assessment
- Long term financial planning

Life Cycle Cost is defined by using a supplied or creating a new Cost Breakdown Structure (CBS) and allocating cost variables to each CBS primary element. D-LCC provides bottom-up cost estimating, supports detailed examination of the costs and parameters affecting LCC, and performs Net Present Cost analysis. D-LCC combines the Cost Breakdown Structure (CBS) with Product Breakdown Structure (PBS) and applies the bottom-up calculation incorporating the time-scale (life cycle phases).

D-LCC also performs cost analysis that allows the user to apply pre-defined LCC models as well as to create new Cost structures and models. An existing CBS can be easily tailored to meet all needs of any particular project. Product Tree Cost Calculation option allows for incorporating the Product Tree parameters in LCC model and

calculating any required cost elements (like spare parts cost for each Level of Repair) across all Product Tree items.

Other features and options include:

- **Net Present Cost (NPC)**

  In financial and budgetary analysis, a necessary requirement is to identify the present value of future cash flows called Net Present Cost. The NPC analysis also provides comparison of options with different inflation and discount rates, and is enhanced through sensitivity analysis of these rates.

- **Cost Profile Analysis**

  D-LCC supports detailed examination of dynamics of future cash flows over multiple time periods.

- **Sensitivity Analysis**

  D-LCC Sensitivity Analysis option in computes changes in the LCC/TCO according to changes of any global variable. The sensitivity analysis identifies major cost drivers (Pareto "vital few"), supports trade-off analysis and indicates the effect of altering critical parameters and assumptions.

- **Cost-Effectiveness evaluation**

  Managers are interested in cost-effectiveness, which is typically calculated in terms of performance per unit cost. D-LCC's Cost-Effectiveness module provides this insight as well as other effectiveness measures.

- **Cost Item analysis**

  D-LCC provides a utility to calculate the costs of a particular budget line item. This "Cost Item" function computes the contribution of any item, such as labor, or

material. Results are reported at the element level and rolled up into a project total.

- **Optimal Repair Level Analysis (ORLA)**

  D-LCC includes a powerful ORLA module for calculating the cost and effectiveness of various Level of Repair alternatives per product tree item, thus supporting optimal decision making

2.6.4 AvSim+ Version 8.0 (Reliability and Availability Simulation)

AvSim+ is a package analyzes availability and reliability of both complex and simple systems and which is easy and intuitive to use. AvSim+ is rich in features and can model a wide range of scenarios. Some of the program's capabilities are listed below.

- Interactive construction of RBD or fault tree diagrams
- Sub-system blocks allowing automatic RBD diagram pagination
- Blocks can incorporate bitmap pictures for convenient identification
- Pagination facilities for large fault trees
- Append projects created by different users
- Attributes of diagram objects can be edited via easy-to-use dialogs
- User control of scaling, shifting and font selection
- Data verification for consistency checks
- Simulation of production capacity levels cost penalties for not meeting targets
- Standby sub-systems modeled
- Modeling of spares dependencies and stock levels
- Models recycling of spares via a repair shop

- Spares optimization facilities provided
- Modeling of maintenance queuing
- Opportunistic maintenance and 'hold for repair' modeling
- Exponential and Weibull distributions for failure
- Lognormal, normal and exponential distributions for repair
- Directly analyze historical data with the Weibull Analysis facility
- Models ageing and effectiveness of preventive maintenance
- Scheduled maintenance interval optimization
- Define financial, safety, operational and environmental consequences
- Models changing network and fault tree configurations during different phases
- Phased time profiles
- Comprehensive reports interfacing with Microsoft Office products
- Graphs, plots, pie charts and time profile histograms
- Import and export facilities
- Interfaces with other reliability products

AvSim+ allows enables modeling costs as well as availability and reliability. Labor, spares and other miscellaneous costs are taken into account during each simulation. In addition, consequences may be assigned to system failures allowing the cost of failures to be included in the calculation.

The AvSim+ Monte Carlo simulator engine is the result of 7 years development during the evolution of the AvSim+ product. The simulator enables AvSim+ to model complex redundancies, common failures and component dependencies, which cannot be

modeled using standard analytical techniques. Some typical dependencies that can strongly affect the availability and reliability of a system are given below.

- Warm and cold standby arrangements
- Queuing for labor
- Queuing for spares from site, depot and factory

2.6.5 BlockSim System Reliability, Maintainability and Availability Software

ReliaSoft's BlockSim is the first integrated system for exact computations and predictions for advanced complex system reliability analysis and optimization. Part of ReliaSoft's suite of reliability software products, BlockSim uses a reliability block diagram (RBD) approach to perform system reliability, maintainability and availability analyses.

Use BlockSim to calculate the optimum reliability allocation scenario and determine the most cost-effective component reliability allocation strategy to meet a system Reliability Goal. Perform the allocation based on a system Reliability Goal and the following factors:

- Maximum Achievable Reliability
- Feasibility of increasing component Reliability (Use pre-defined Cost Functions or enter your own.)

For each block, and depending on the analysis desired, the block definition wizard can be used to define.

- Failure Distribution (*i.e.* Weibull, Mixed Weibull, Lognormal, Normal, Exponential). If life data for the component is available, BlockSim integrates with ReliaSoft's Weibull++ to compute the distribution parameters.
- A Repair Distribution (*i.e.* Weibull, Lognormal, Normal, Exponential).

In seconds, obtain a complete Algebraic formulation of the system Reliability Function (*i.e.*1-cdf), and utilize the Algebraic Formulation for multiple System Reliability Results, Tables, Reports and Graphs.

- Reliability for any mission time, or mission time for any given reliability.
- Probability of Failure for any mission time, or mission time for any given Probability of Failure.
- Conditional Reliability and Conditional Probability of Failure calculations.
- Failure Rate at any given time or age.
- System Mean Time to Failure (MTTF).
- *Pdf* plots.
- Component data.
- Importance Measures for each component relative to the system at any time (age) that is, which component(s) have the greatest effect on the system reliability.

2.6.6 CAME-LCC

CAME – LCC calculates cost drivers and full cost of each life cycle phase (investment, development, production, delivery, operation and disposal) as well as the total life cost using the user data or the recommendations of the CAMEâ optimization modules.

- Presents Reliability/ Availability vs. Cost results of all considered scenarios/options, thus enabling the user to choose the appropriate scenario/option or to define a new one.
- Considers multi-level systems (with blocks indenture breakdown) or 1 level system.
- Provides friendly cost data input for different scenarios.
- Compares results of different scenarios in united Trade-off table and graph.

This comparison enables an expert selection of the most appropriate scenario (the project variants) considering cost and reliability parameters, simultaneously. Usually the better are the reliability parameters, the more expensive is the product and the less expensive is the maintenance. The problem is to select the scenario with appropriate reliability parameters (Mission reliability, Availability, MTBF, Down time) at the minimal total life cycle cost. Various reports (summary, detailed, Pareto) can be generated by years and as total values. Pareto and detailed reports are effective for analytical purposes, when user seeks the factors of different cost drivers.

2.6.7 LOGAN Fault and Event Tree Analysis/ Monte Carlo Simulation

LOGAN Fault and Event Tree module enables the construction and evaluation of fault and/or event trees and is widely used for Quantified Risk Assessment (QRA). It allows the results from fault tree analysis to be incorporated into an event tree to provide a complete evaluation of the probability of hazards of various severities.The LOGAN Monte Carlo analysis module is suitable for the evaluation of the availability of complex systems or processes. It allows the effects to be assessed of different levels of

redundancy, standby arrangement, spares holdings, levels of manning, etc. It allows time dependent failure probabilities to be assessed.

2.6.8 MonteCarloSimulationS

It contains a series of simulation models written in Microsoft's Excel, which combines the use of spreadsheets, Weibull statistical failure data, and random numbers to solve difficult problems in reliability, availability, and cost. Some of the models are:

- Generate random numbers
- Competing series failure models
- Process diagram simulation
- Plant Manager's production model
- Simple reliability model
- Simple series failure models
- Optimum replacement intervals
- Air compressor life and cost
- Fix failures on overtime
- Complex reliability model

2.7 Conclusion for Literature Review

In a nutshell topics such as maintenance and reliability were discussed. Then the techniques in analyzing a system from a reliability standpoint were studied and academic

work in the area of maintenance modeling was reviewed. The most popular techniques in computer based maintenance resources allocation are

- Reliability Based Diagrams
- Monte Carlo Simulation
- Life Cycle Cost Analysis

These techniques cannot be directly used to address our problem statement, simply because each of the techniques is limited. RBDs analyze the system at a lower level of detail and do not have sufficient experimentation capabilities. A Monte Carlo Simulation tied with RBDs is still limited because of the level of inputs provided by the RBDs. A stand alone LCC model is an excellent tool to evaluate the economic implications of a maintenance program but lacks experimentation capabilities.

The research approach described in Chapter 3 uses a methodology that integrates the following components

- Flexible Discrete Event Simulation Modeling
- Design of Experiments
- Life Cycle Cost Model

that overcomes the drawbacks encountered with traditionally accepted reliability based maintenance resource assessment tools.

Chapter 3

Approach

Chapter 3 charts out the methodology involved in developing the model. The chapter deep dives into the components that make the model and how these components are linked together.

The model is designed to follow a black box approach, where the end-user inputs basic information into the system and without much further manipulation the results are provided at the back end of the system. Hence the individual components that make up the model are automated in order to meet our requirements.

3.1 Conceptual Design

A conceptual framework/ roadmap of the simulation based model that determines a maintenance strategy is presented in Figure 3.1. The four distinct phases of the conceptual design are: experiment setup, process simulation, financial analysis, and maintenance strategy.

The user inputs information that is needed to run the model at the "experiment

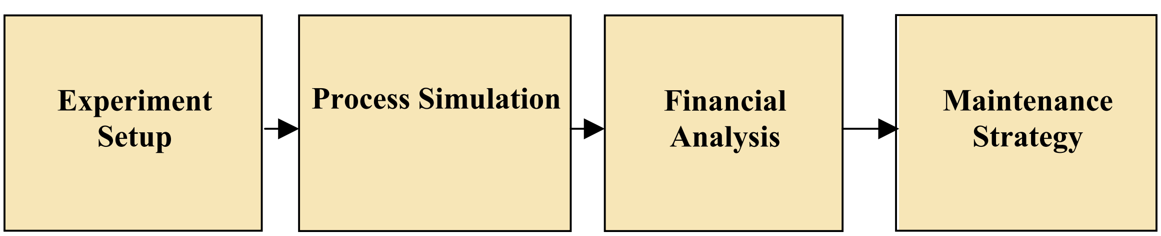


Figure 3.1: Approach

setup" stage. Here the user typically inputs data pertaining to mapping the process onto a computer model establishes economic/ cost parameters and sets up how the model needs to run and interpret the results.

"Process simulation" comprises of two components: a simulation model and design of experiments. Data is read from the "experiment setup" phase to build a computer model that represents the process and filter data that is needed to run the model. A simulation model by itself is incapable of testing alternate parameters, hence the design of experiments module automates the simulation model to run all possible combinations of experiments by changing related parameters.

The third phase – "Financial analysis", associates cost with "Process simulation's" output, quantifies the value of performance metrics in terms of dollars. Financial analysis can be either use a comprehensive cost model or use key performance indices to evaluate the best maintenance strategies that need to be used to best fulfill the company's business targets

The final phase is the reporting phase where the user is presented with the best alternatives to use based on how the user had set up the model to work in Phase 1. The user can trace back at how these results were arrived at. The user can then setup the model differently and run the model again. As discussed earlier, the only place where the user interacts with the model is at the experiment setup phase and the final phase.

A more detailed explanation of the process flow of information is presented in Figure 3.2.

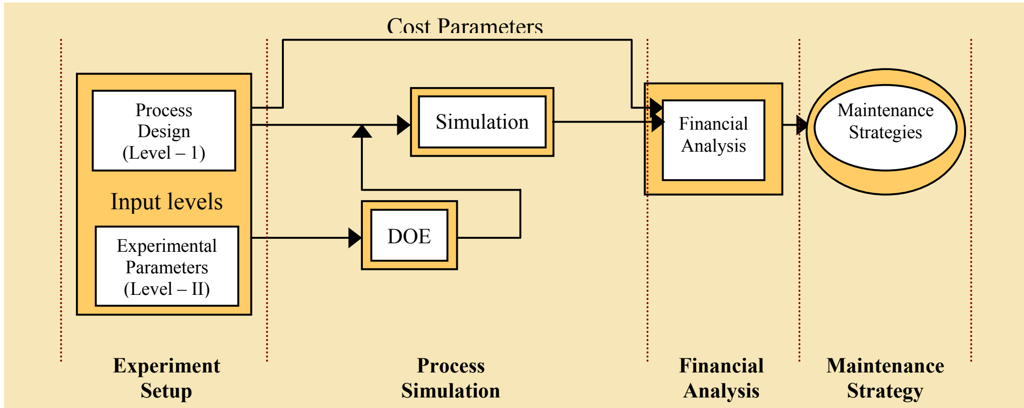


Figure 3.2: Flow of Information

3.1.1 Experiment Setup

The user input module in general terms allows the end user to input data to setup the experiment that will identify the optimal maintenance strategy. Specifically, the user input module is the mechanism that allows users to setup and modify the simulation model and the Design of Experiments (DOE). A key focus in the experiment setup phase is to allow the end user to develop and experiment with maintenance strategies without being constrained by the software and technical considerations. This eliminates the need for any end user to be familiar with the concepts of simulation modeling. The user interacts with the system on two levels. The first level provides the ability to design and modify the production parameters of a manufacturing process. Level one of the user input module allows the user to design the process in terms of number of equipment in the process, their process times, process flow, product routing and all other information required to build the simulation model. In addition, the end user can define relevant costs required for the financial analysis. Second, it allows the end user to define the

maintenance strategy. The maintenance strategy is defined at level two of the user input module by allowing the user to setup the DOE experiment. A maintenance alternative is determined by defining a maintenance plan for each piece of equipment in the manufacturing process. During this process the user defines the critical maintenance factors. The basic mechanism required for the development of such menus is well documented (Sawhney). After this informational process is achieved the end user proceeds to the process simulation module.

3.1.2 Process Simulation

The simulation model utilizes ARENA to predict the impact of any maintenance alternative on the performance of the manufacturing process. Such a model by itself is inefficient in developing a desired maintenance strategy because it is based on a trial and error approach. Hence, this approach can require a considerable amount of runs and time without any guarantee of the desired results. Another big hurdle to cross is that simulation modeling is a complex task, simply because of the programming involved. The program should be independent of the user's knowledge in simulation modeling. Simulation models in themselves are very specific in their design. It is very difficult to get two models to exchange information. It usually becomes necessary to build new models to suite the application.

3.1.3 Design of Experiments

DOE provides a structured approach to arrive at a desired result in a single iteration. The DOE utilizes JMPIN to establish all the possible combination of

maintenance alternatives that need to be simulated. This combination establishes the experimental set to be analyzed. The parameters that need to be tested are defined in the experiment setup phase and this data is used to arrive at the experiment set. The task of running numerous sets of experiments using simulation modeling is tedious and error prone. In order to run the experiment efficiently, one experiment at a time from the DOE is fed into the simulation model automatically and the responses stored in an Excel sheet template. Since the simulation runs are going to be automated, a full factorial experiment is run.

3.1.4 Financial Analysis

The financial analysis module is the critical component that helps us make the decision between alternative maintenance strategies. It utilizes information from the user input module as well as results from the process simulation module. This combined information is utilized to analyze each possible run defined in the DOE. For example, if the DOE has defined n different maintenance strategies that need to be evaluated, the financial analysis will perform an assessment on each one of these n experiments.

3.2 Model Design

There are three primary issues that must be addressed when properly designing a maintenance strategy model within the conceptual framework provided above. The first issue is the manner in which the end user identifies the maintenance strategy. Specifically, this specifies the maintenance determined for each piece of equipment in the given production process. The second issue is developing the link between the

maintenance strategy definition and its impact on the manufacturing process as represented in the simulation model. The third issue is to define the measures utilized to evaluate the impact of the maintenance strategy on the production process and the mechanism by which the best maintenance strategy is selected. The last issue is that of using a comprehensive cost model that looks various factors involved, including labor, spare parts, asset investment etc.

3.2.1 Developing a Saddleback, Flexible Simulation Model

Simulation modeling is a complex task, simply because of the programming involved. The program should be independent of the user's knowledge in simulation modeling. Simulation models in themselves are very specific in their design. It is very difficult to get two models to exchange information. It usually becomes necessary to build new models to suite the application. Hence the program should be capable of

- Communicate with the other components
- Keep the user away from programming
- A simulation model that is specific to addressing the issues that are tested
- Provide results that can be used by the other components.

The end user will define the maintenance on each piece of equipment or component of a piece of equipment. Using flexible simulation the user would be able to map the process into the simulation model using forms.

The saddle back program as shown in Figure 3.3 is a flexible simulation engine that can be used to model standard discrete event scenarios. It controls process times, setup times,

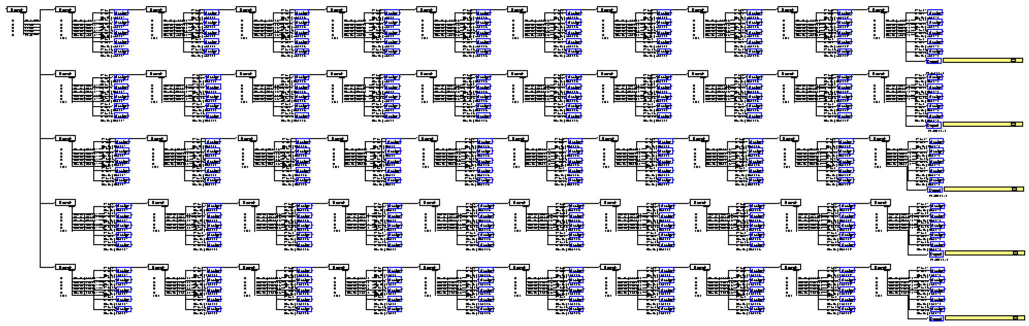


Figure 3.3: Snapshot of the Saddle Back Simulation Program

routing times and part routing. The saddle back program is like a simulation macro for the simulation software and was written in Rockwell's Arena Simulation Software.

3.2.2 Linking the Maintenance Strategy to the Manufacturing Process

The model allows the maintenance strategy to impact each piece of equipment and subsequently the manufacturing process in three primary ways: availability of the machine, functional productivity of the equipment, and the functional quality produced by the equipment.

3.2.2.1 Availability

Availability is defined as the probability that a system or component is performing its required function when operated and maintained in a prescribed manner (Ebeling, Charles). Within this context operational availability is defined as

$$A_o = MTBM / MTBM + M'$$

where MTBM is the mean time between scheduled and unscheduled maintenance. M' is the system downtime that includes time to repair as well as delays due to supply and maintenance issues (Ebeling, Charles). Based on this concept the model will utilize two different parameters: the equipment's Mean Time to Failure (MTTF) and Mean Lead Time (MLT). MTTF's role is self-explanatory. MLT on the other hand is defined as the time between recognizing the need for maintenance on a particular piece of equipment, to the actual performance of such maintenance and the subsequent production of good product. MLT enhances the concept of delays as defined by M' to include other delays beyond supply and maintenance delays. MLT more accurately determines availability and is further decomposed and represented by the equation below.

$$MLT = MTTI + MTTC + MTTA + MTTD + MTTL + MTTS + MTTR + MTTY$$

Where

MTTI = Mean Time to Identify - Identifying failure or maintenance requirement

MTTC = Mean Time to Communicate - Communicating maintenance requirements

MTTA = Mean Time to Assess - Assessment to identify source of the problem

MTTD = Mean Time to Determine - Determining correct parts and tools required

MTTL = Mean Time to Locate - Locating and/or ordering the required parts

MTTS = Mean Time to Schedule - Schedule maintenance for identified equipment

MTTR = Mean Time to Repair – Repair and maintenance of equipment

MTTY = Mean Time to Yield – Yield of good parts after maintenance

The MLT values will change given the different maintenance alternatives defined for each piece of equipment. MLT values for reactive, preventive, and predictive maintenance are dependent on many variables and therefore are difficult to ascertain.

Historically, MLT for reactive maintenance is multiples greater than the MLT for proactive maintenance. The progression from reactive maintenance to proactive maintenance options impacts each MLT component differently. For example, MTTI decreases as one shifts from reactive to preventive and subsequently to predictive maintenance. This implies that the response time becomes shorter, therefore, increasing the availability of the particular machine. On the other hand, MTTP as defined may not change between the two proactive maintenance options.

Finally, MTTS increases as one moves to a predictive maintenance from a preventive maintenance. Such movement implies that the response time increases and the availability of the machine decreases. The end user has the ability to modify any component of the MLT via user-friendly menus. This way of setting up MLT works great when different strategies need to be customized. The components that make up MLT in each maintenance strategy are used to represent the maintenance strategy in the simulation model.

3.2.2.2 Functional Productivity

In many cases systems continue to operate but in a degraded state. This is a state between which a piece of equipment is working to specifications and the complete failure of the piece of equipment. There are two critical issues when a piece of equipment is

operating in a degraded state. The first issue is the time the equipment spends in the degraded state. The second issue is the impact of the degraded state to the performance of the piece of equipment. The impact of the degradation can occur in two forms: functional productivity and functional quality. Functional productivity is defined as loss of capacity due to equipment inefficiencies. An example of equipment functional loss would be the producing of 800lbs/hr instead of 1000lbs/hr because a pump is not working efficiently. The degradation of the functionality is further explained by Figure 3.4.

A piece of equipment starts operating after a maintenance event in an acceptable operating state. This is represented by P(t1) which is the probability distribution for the time period in which the equipment operates in acceptable operating state. Figure 3.4 assumes a steady productivity of the equipment as long as it is in the acceptable operating state. There are two possible events that can occur after the acceptable operating state.

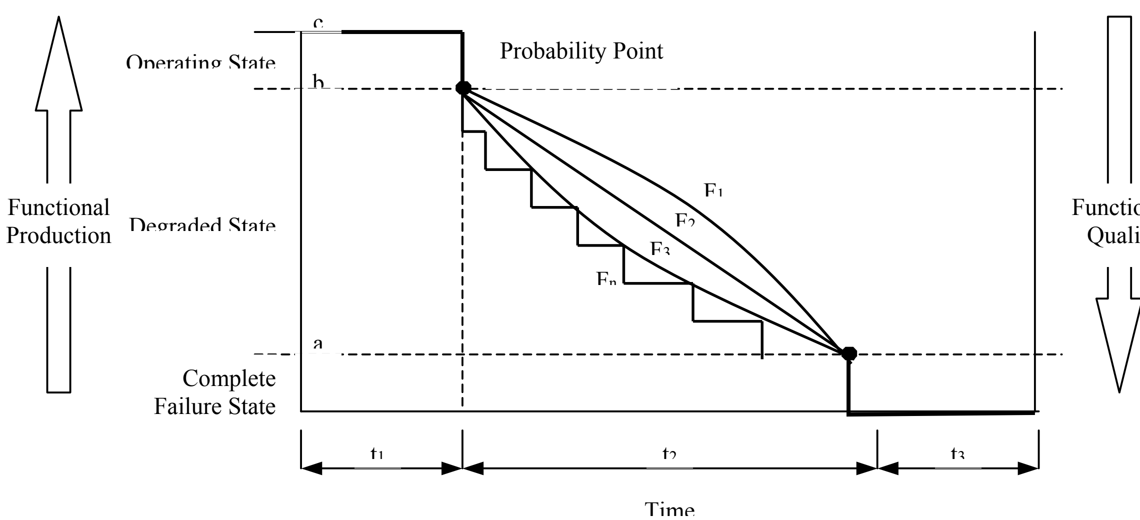


Figure 3.4: Functional Degradation

The first alternative is the complete failure of the equipment, which assumes no production by the equipment.

The second alternative is that the equipment enters into a degraded state of operations. P(f) represents the probability that the equipment will completely fail. Logically, 1 – P(f) is the probability that the equipment enters the degraded state. The probability associated with the time period that the equipment stays in this state is represented by P(t2). Further, there are infinite possible functions (F1…Fn) associated with the degradation of the equipment in the degraded state. Upon reaching the complete failure state the equipment is assumed to shut down. P(t1), P(t2), P(f), and Fn become the four critical metrics that determine the functional productivity of the equipment. The end user is allowed to define the above four metrics for each piece of equipment.

3.2.2.3 Functional Quality

Functional quality is the degradation of quality during the degraded state of the system. For example, the yield of a plastisol coating operation drops from 97% to 91%. The mechanics of functional quality are almost identical to functional productivity as illustrated in Figure 3.4. Once the equipment leaves the acceptable operating state it may fail completely or simply enter the degraded state. Degradation in this state simply refers to increased number of products produced that exceed the specifications. It is further assumed that the rate of producing products out of specification will increase unless there is an intervention. This will continue until the equipment fails completely. The same four metric types that define functional productivity define functional quality: P(t1)', P(t2)', P(f)', and Fn'.

3.2.3 Obtaining Metrics for Financial Analysis

Industry has historically made decisions regarding projects including maintenance based on some quantitative justification. The most commonly understood quantitative analysis is the financial justification including Earnings Before Interest and Taxes (EBIT) and Return on Investment (ROI). OEE tracks the value added productivity of equipment. It measures the percentage of time equipment in a factory is actually making product compared to a theoretical maximum. There are also other unique metrics that are of interest to various groups within an organization. For example top-level managers may be interested in a financial analysis, while operational and maintenance managers may be interested more in tactical metrics. The following are three categories of metrics desired by personnel associated with or having responsibility of maintenance functions.

1. **Business KPI's**
   - Earnings Before Interest and Taxes (EBIT)
   - Return of Investment (ROI)
2. **Operational KPI's**
   - Overall Equipment Effectiveness (OEE)
   - Production per time unit or Jobs per hour (JPH)
3. **Maintenance KPI's**
   - Equipment Overall Downtime

Shown below in Figure 3.5, is an example of how these KPI's can be used in combination to determine the best maintenance policy. The rating scheme for the different metrics is quantitative and depends on the range of values that were given by the simulation model. The output of each simulation run is integrated into a spreadsheet that calculates a given

	Use	Weight
Business KPI's		
Earnings Before Interest and Taxes (EBIT)	☑	25.00%
Return of Investment (ROI)	☐	
Operational KPI's		
Overall Equipment Effectiveness (OEE)	☑	50.00%
Production per time unit (JPH)	☐	
Maintenance KPI's		
Equipment Overall Downtime	☑	25.00%

	Business KPI's					Operational KPI's					Maintenance KPI's		
	EBIT rating	Weight	Adjusted EBIT rating	ROI rating	Disabled	OEE rating	Weight	Adjusted OEE rating	JPH rating	Disabled	Equipment Overall Downtime	Weight	Adjusted value
Run 5	9		2.25	5		8		4	6		9		2.25
Run 7	6		1.5	4		7		3.5	5		6		1.5
Run 3	5		1.25	3		6		3	4		5		1.25
Run 4	3	25.00%	0.75	4		5	50.00%	2.5	2		3	25.00%	0.75
Run 1	5		1.25	3		5		2.5	3		5		1.25
Run 6	2		0.5	1		4		2	4		2		0.5
Run 2	1		0.25	7		4		2	5		1		0.25

Figure 3.5: Using KPI's to Determine Maintenance Strategies

KPI. Hence the Run number gets reorganized based on the different metrics one chooses to use and its assigned weight. The user may select any one of the three alternative maintenance strategies.

3.2.4 Using a Cost Model

The maintenance records must provide for an acceptable level of downtime analysis, either from the records themselves or in direct summary form from the maintenance requests.

1. An indication of downtime per process line, per machine type or if necessary per operator.

2. The time taken for fault diagnosis and repair on various types of fault, or on particular machines, or by various personnel.
3. Indications of the causes of breakdown.

Analysis (1) reveals the following useful points

a. The true ratio of downtime to production time.
b. The need for further investigation by the maintenance management of high downtime areas.
c. The relationships between operator performance and downtime on individual machines.

Analysis (2) reveals the following useful points

a. High downtime areas where root cause analysis needs to be performed or permanent standby repair staff or zone workshops might be beneficial.
b. Machines to be avoided on future procurements.
c. A requirement for specific training (e.g. electronic fault-finding) for maintenance workers.
d. The most efficient personnel for repair work.

Analysis (3) reveals the following useful points

a. The spares requirement for the various machines.
b. Any requirement for increased operator training.
c. Problems caused by variations in the product materials.

Downtime can be a good measure to analyze a lot of problems related to manufacturing and not just maintenance. Hence a more robust financial analysis tool can be employed to solve these issues.

LCC helps change provincial perspectives for business issues with emphasis on enhancing economic competitiveness by working for the lowest long term cost of ownership. Too often parochial views result in ineffective actions best characterized by short term cost advantages (but long term costly decisions).

The basic tree for LCC starts with a very simple tree based on the costs for acquisition and the costs for sustaining the acquisition during its life as shown in the Figure 3.6.

Acquisition and sustaining costs are not mutually exclusive. If equipment or processes are acquired, they always require extra costs to sustain the acquisition, and one cannot sustain without someone having acquired the item. Acquisition and sustaining costs are found by gathering the correct inputs, building the input database, evaluating the LCC and conducting sensitivity analysis to identify cost drivers.

3.2.4.1 Focus of the LCC

The focus of this approach is cost reduction, during a second phase; the impact of improved maintenance upon availability and productivity will be analyzed. The key focus of the LCC is charted in Table 3.1. The LCC model used in this thesis study is based off

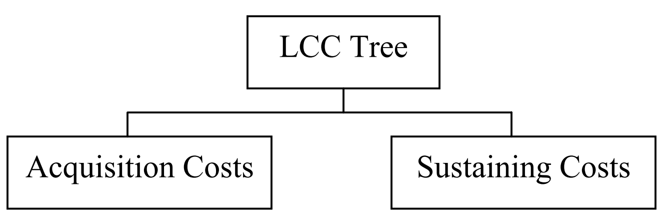


Figure 3.6: LCC Tree

Table 3.1: Focus of Life Cycle Cost Models

1	Increase in Industrial system availability	Manufacturing unit costs	↓
2	Increase of machine reliability	Manufacturing unit costs	↓
3	Increase of machine maintainability	Manufacturing unit costs	↓
4	Optimization of process cycle time	Availability Manufacturing unit costs	↑ ↓
5	Maintenance personnel reduction	Manufacturing unit costs	↓
6	Installation of better monitoring/information system	Process cycle time # of breakdown-errors Availability	↓ ↓ ↑
7	Effective Preventive maintenance strategy	# of breakdown-type maintenance Availability Manufacturing unit costs	↓ ↑ ↓
8	Corrective action focus maintainability	Machine maintainability Availability Manufacturing unit costs	↑ ↑ ↓
9	Corrective action focus reliability	Machine reliability Availability Manufacturing unit costs	↑ ↑ ↓
10	Reorganization of maintenance	Process cost Availability Manufacturing unit costs	↓ ↑ ↓
11	Maintenance strategy optimization	Availability Manufacturing unit costs	↑ ↓
12	Component standardization	Spare parts costs Manufacturing unit costs	↓ ↓
13	Spare part optimization	Spare part management Maintenance costs Manufacturing unit costs	↓ ↓ ↓

Siemen’s generic life cycle cost model. The LCC model has been adapted to read data from process simulation, instead of a static value from conventional study.

3.2.4.2 LCC advantages and benefits for industrial systems

Life cycle costing is a decisive approach for a systematic analysis, definition and cost reduction over the life cycle of an industrial system. Studies and practical experiences show that the six major life cycle phases of an industrial system as shown in Table 3.2.

In most cases the purchase department decides solely about acquisition costs, which in the case correspond to 37% of total cost. The larger block of total costs lies in the operation and maintenance cost that represent about 60% of total life cycle costs. Hence, an awareness of economic decision along the life cycle of industrial system must be promoted.

LCC offers an integral approach in comparing total costs of an industrial system and integrates various aspects of procurement, planning and operation/maintenance department on a common basis. i.e., cost blocks of each company department are cumulated in an aggregating cost model.

In order to understand the proposed model, the user must be familiar with

1. Basic understanding of LCC philosophy
2. Basic know-how of production parameters such as process times, quality parameters, scheduling etc.
3. Basic know-how of maintenance such as corrective maintenance, preventive maintenance, MTBF, MTTR, equipment degradation etc

Table 3.2: Life Cycle of an Industrial System

Life-cycle phase	Cost Contribution to total cost (LCC)	Cumulated costs	Type Non-recurring/recurring
Concept & definition	2%	2%	Non recurring costs
Design & development	6%	8%	
Manufacturing	21%	29%	
Commissioning/installation	8%	37%	
Operation & maintenance	60%	97%	Recurring costs
Reconstruction/disposal	3%	100%	Non recurring costs

4. Basic understanding in fixed and variable costs of industrial system
5. Basic understanding of industrial system investments.
6. Basic understanding of process cost

3.2.4.3 Assumptions

1. No inflation is integrated in the different cost factors
2. No insurance fee for the industrial system has been calculated as part of the fix costs
3. The life-cycle phases are *acquisition, operation and maintenance*
4. Costs for hourly rates for operations and maintenance are full costs (including all social and additional costs)
5. No net Present Value calculations have been integrated
6. The model does not include any cash-flow or Return on Investment (ROI) calculations
7. The model is suited for the calculation of an industrial manufacturing system
8. The focus industry of this study is discrete manufacturing processes

9. The cost drivers have been analyzed especially with maintenance focus; further costs such as logistics costs, IT costs are not analyzed
10. The model requires input data that is not always available. The data collection time must not be negligible.

3.2.4.4 Inputs

Simulation Inputs

i. Model

- Number of Machines
- Routing
- Scheduling
- Process Times for each machine
- Capacity of each machine
- Routing times

ii. Maintenance Strategies

Maintenance Strategy 1	***Maintenance Strategy 2***	***Planned Maintenance 3***
MTBF	MTBF	MTBF
MTR	MTR	MTR
Availability degradation	Availability degradation	Availability degradation
Functionality degradation	Functionality degradation	Functionality degradation
Quality degradation	Quality degradation	Quality degradation

iii. Global variables

- Simulation run time

Cost Model Inputs

i. General Organizational Schedule

- Number of weeks in year
- Number of work days per week
- Company closing
- Holidays
- Shifts per day
- Daily hours per shift
- Changeover time, Setup time etc
- Overhaul Maintenance time

ii. Basic Organizational Data

- Discount rate
- Manufacturing overhead cost rate
- Room rate
- Electricity rate
- Operation labor costs
- Mean maintenance labor costs

iii. Basic Industrial System Data

- Acquisition costs
- Infrastructure costs required for industrial system

- Industrial system cycle time
- Number of operational staff
- Operating time in years
- Space requirements
- Electrical consumption
- Auxiliary parts and consumables
- Tooling costs
- Quality costs
- Planned maintenance cost rate

iv. Spare parts and asset costs

- Spares and consumables
- Required for system
- Quantity in stock
- Unit price

v. Maintenance Strategy that needs to be tested (Option 1)

- Invest per main system (UC)
- Corrective Maintenance action period (every n operating hours)
- Required time (hours)
- # of maintenance personnel required
- Spares or auxiliary consumption per failure
- Maintenance downtime required (Yes/No)

vi. Maintenance Strategy that needs to be tested (Option 2)

- Invest per main system (UC)
- Preventive Maintenance 1 action period (every n operating hours)
- Required time (hours)
- # of maintenance personnel required
- Spares or auxiliary consumption per PM action
- Maintenance downtime required (Yes/No)

vii. Maintenance Strategy that needs to be tested (Option 3)

- Invest per main system (UC)
- Preventive Maintenance 2 action period (every n operating hours)
- Required time (hours)
- # of maintenance personnel required
- Spares or auxiliary consumption per PM action
- Maintenance downtime required (Yes/No)

3.3 Advantages of Using This Approach

This proposed approach has certain advantages over other approaches as listed below:

1. Instantaneous and predictive ability to analyze the impact of a maintenance strategy. The model can provide a detailed operational and financial analysis in a short time period.

2. Provides the ability to utilize model without knowledge of programming. This factor is critical since experience indicates few maintenance personnel know simulation or are interested in learning simulation.
3. Defines maintenance parameters that appropriate personnel should consider when developing a maintenance strategy.
4. Develops and aligns maintenance strategies that enhance production and financial metrics for the entire production system rather than sub-optimizing a system.
5. Performs both short term and long-term analysis.
6. Provides an outstanding venue for communicating maintenance strategies.

Chapter 4

Case Studies

Chapter four talks about a case study that illustrates an application of the model based on the approach suggested in the previous chapter. The case study illustrates

1. Allocating maintenance strategies based on Key Performance Indices.
2. Allocating maintenance strategies based on the cost model. This is a more in depth analysis of economic parameters that play a role in the decision-making.

4.1 Case Study

A continuous chemical pulping process as illustrated in Figure 4.1 will be the basis of illustrating the methodology described above. The processes circled in black are the processes for which the experiment is considered. This includes chipping, screening, digesting, washing, and bleaching. All other processes are considered auxiliary. The purpose of this case study is to develop a desired maintenance strategy for the facility by defining the appropriate maintenance for each station identified above.

4.1.1 Experiment Setup

This section illustrates the different types of screens available for the user to input the following data: designing the production process, setting up the experimental runs for all defined maintenance plans, and identifying cost parameters for maintenance alternatives.

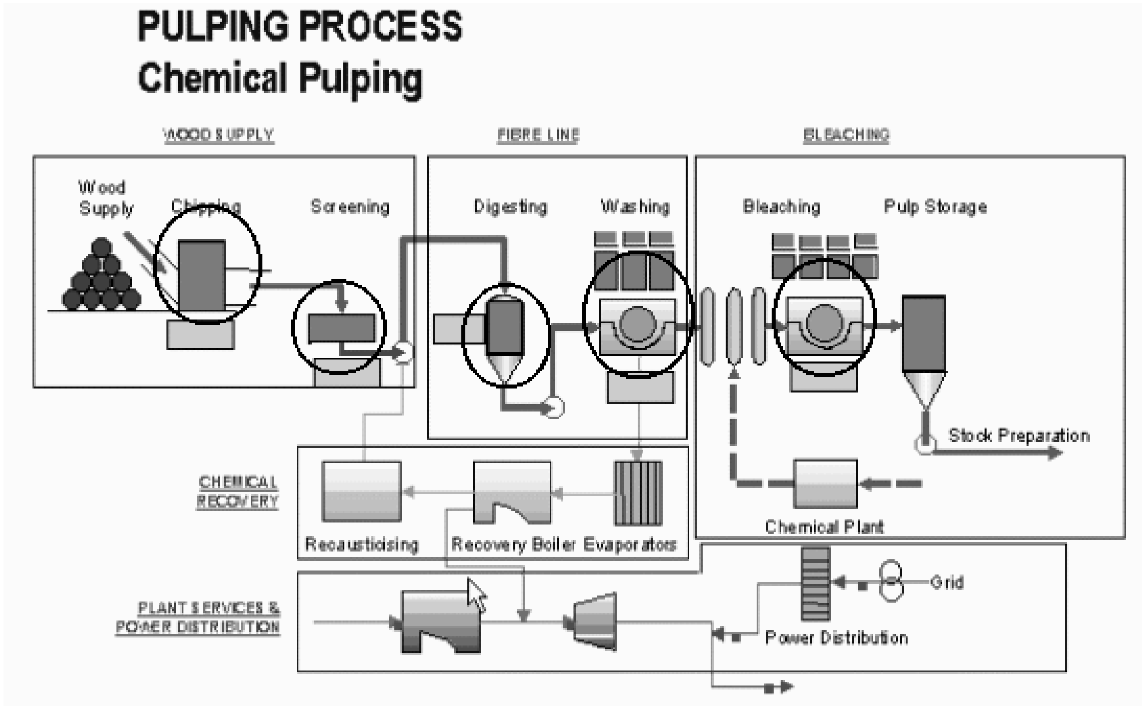


Figure 4.1: Paper Pulp Process

4.1.2 Screen 1: Designing the Production Process

The first screen allows the end user to design a manufacturing process. As illustrated in figure 4.2, the end user can define up to eight different types of sequential machine groups. However for this case study only five machine groups need to be defined. For each one of the defined machine groups the end user has the ability to define various production characteristics. Figure 4.2 allows the end user to define the processing time associated with each machine group as well as the capacity of each machine group. Note that the end user modifies the simulation model of the production process without any knowledge of simulation.

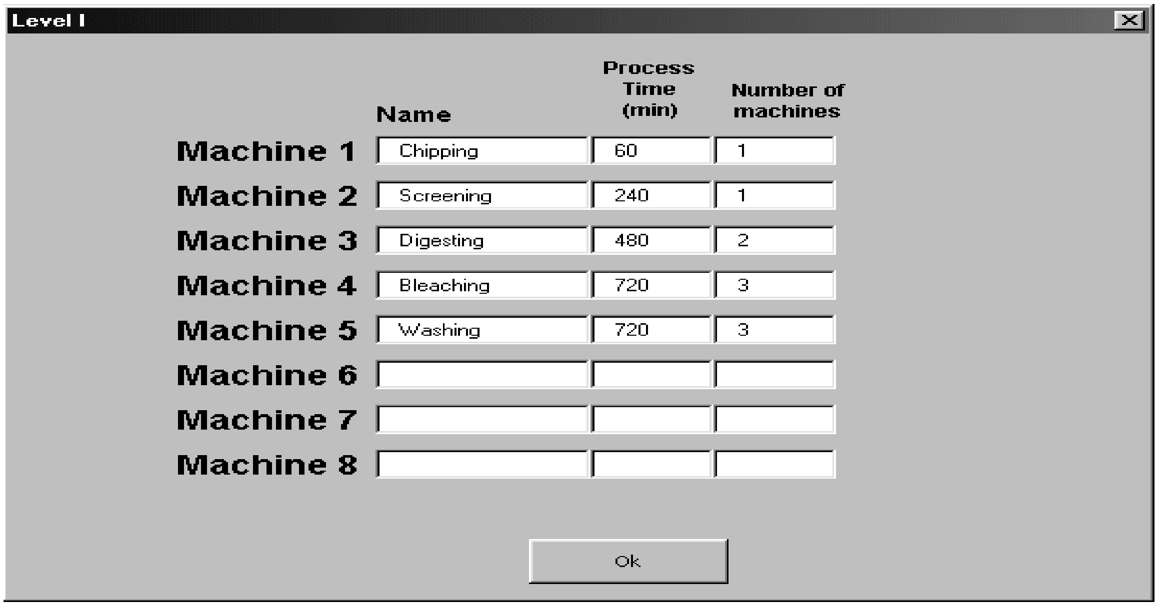


Figure 4.2: Screen1- Designing the Production Process

4.1.3 Screen 2: Defining the Impact of Maintenance on the Production Process

Screen 2 as illustrated in Figure 4.3 allows the end user to define the impact of alternative maintenance plans on the production process. The key concept is that the degradation of the condition of a piece of equipment can lead to degradation in availability, functional productivity, and functional quality. In addition the user has the option to define MLT and MTBF. For example the MLT will be considerably higher in a reactive maintenance alternative then in proactive maintenance alternatives because in the reactive scenario most of the downtime will be unplanned. This screen allows the user to define the impact of each of the five parameters for reactive, preventive, and predictive maintenance alternatives. The first parameter is the availability of the equipment, such as chipping, to produce.

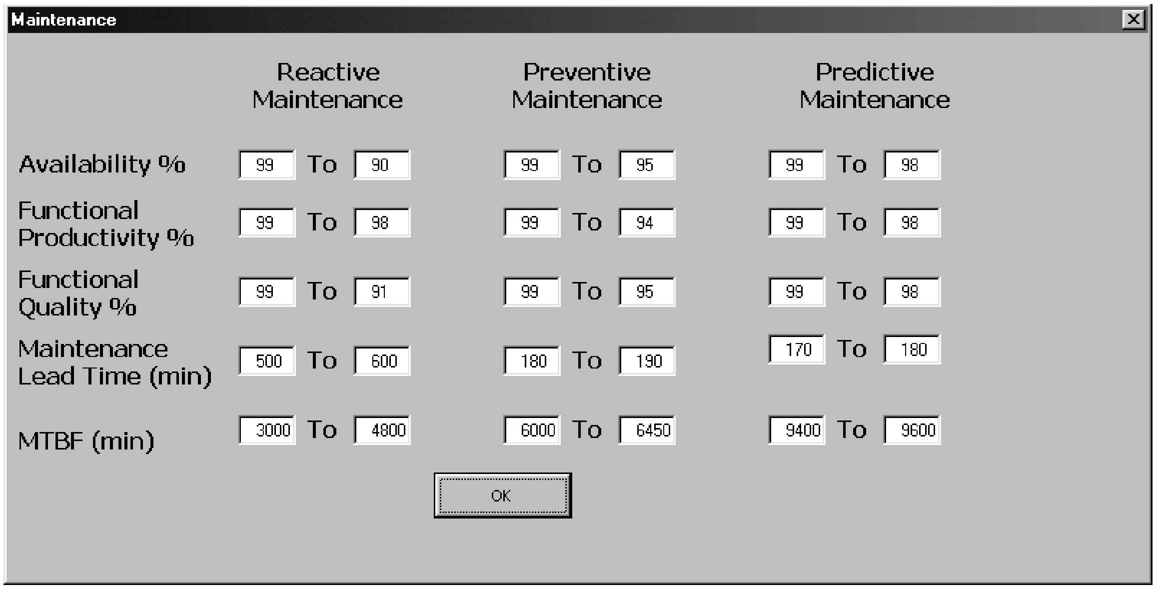


Figure 4.3: Screen 2 - Defining the Impact of Maintenance on the Production Process

In this case the availability of the chipping equipment given a reactive maintenance alternative will reduce linearly from 99% to 90% during time t2 as defined in functional degradation. The degradation from 99% to 90% is assumed to be linear in these specific maintenance alternatives. Similarly, the data is provided case. It is easily possible to define the degradation over time by non-linear functions. This type of data is also provided for preventive and predictive for functional productivity and functional quality. Finally, the end user has the ability to define MLT and the MTBF if the user senses that these values will change for different maintenance alternatives.

4.1.4 Screen 3: Defining the Cost Associated With Alternative Maintenance Plans

The inclusion of the cost data is extremely important for this analysis to be realistic. Most maintenance strategies are tempered with cost constraints. For example, it

has been observed by the authors that most manufacturers do not implement proactive maintenance because the initial cost of the strategy cannot be justified by the short term returns an organization requires for capital based projects. Screen 3, illustrated in Figure 4.4 establishes the cost parameters that are utilized for the metric analysis. This screen allows the user to input a range of maintenance cost data for each machine group. Further it allows the user to input additional cost data required for a financial analysis.

4.1.5 Screen 4: Setting Up the DOE

Screen 4, as illustrated in Figure 4.5, allows the end user to setup the number of experimental runs to be tested. In order to try to find desired maintenance strategies for

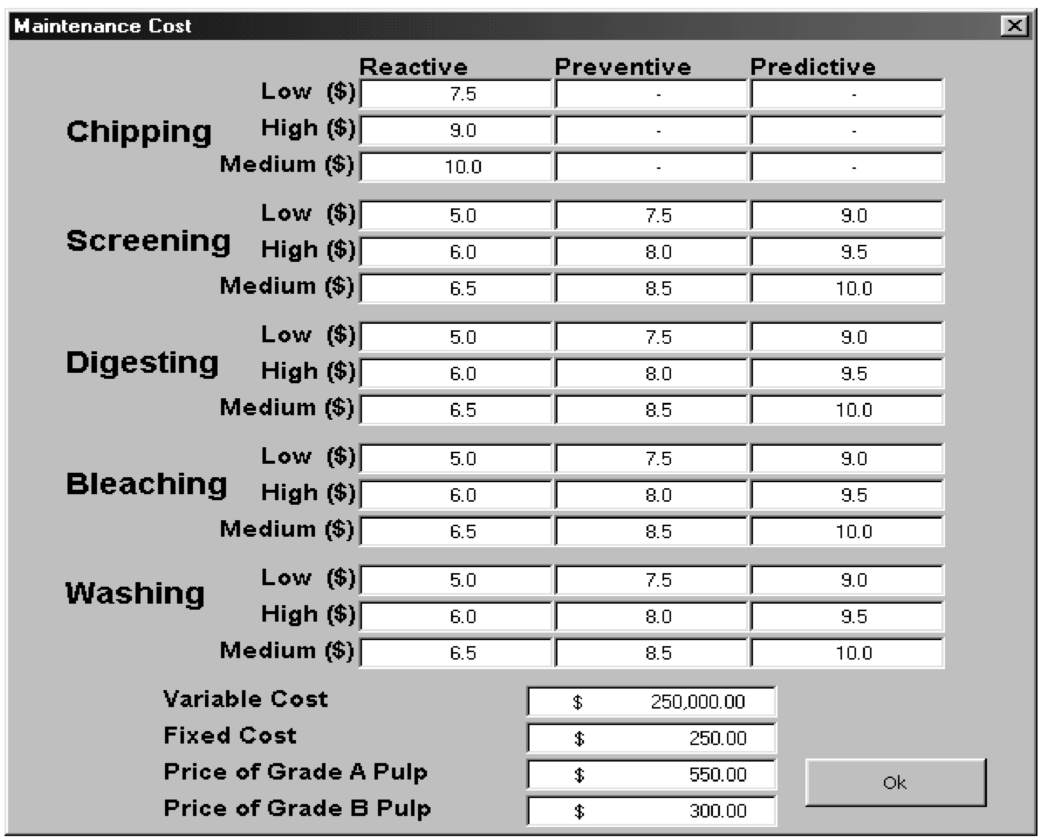


Figure 4.4: Screen 3 - Maintenance Cost Parameters

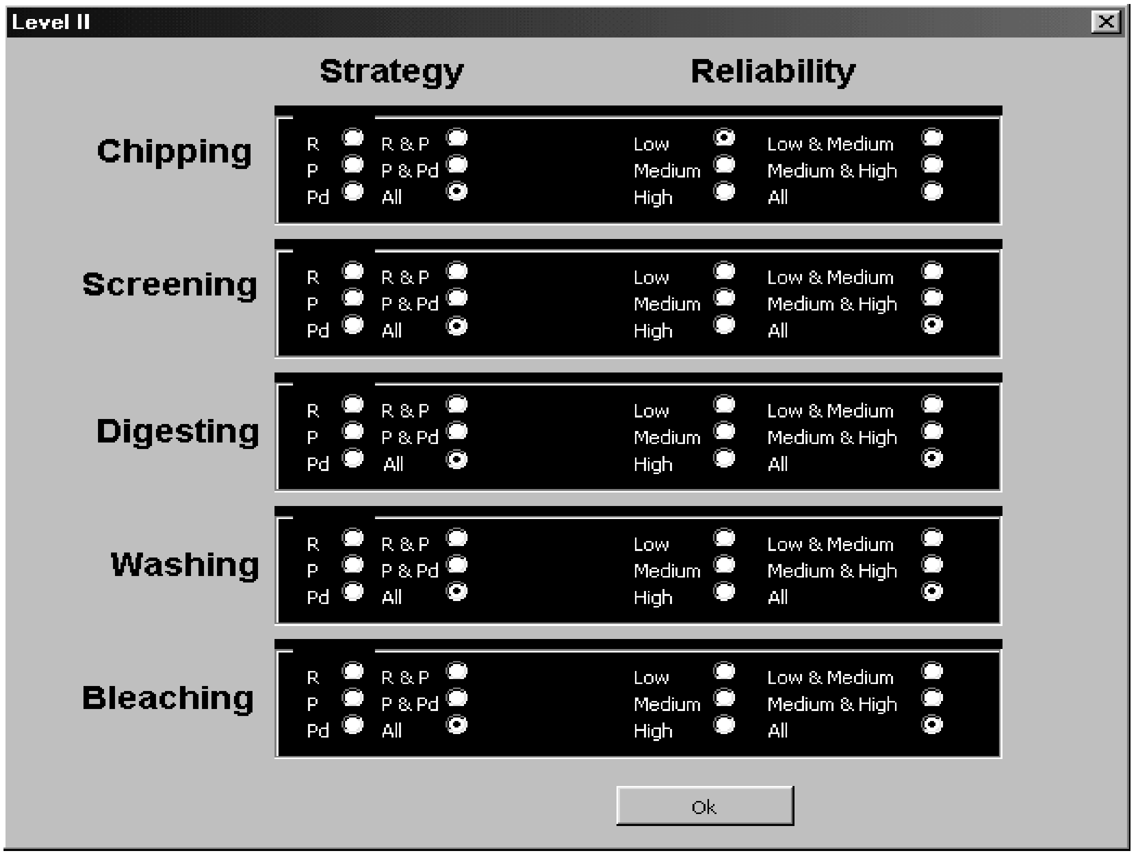


Figure 4.5: Screen 4 - Setup of Design of Experiments

the five-station paper pulp simulation; a DOE technique is utilized to identify the region of primary interest. The number of experimental runs is based on the number of factors to be tested. Nine factors were originally considered important in determining a cost effective maintenance strategy. These factors were the type of maintenance strategy (i.e., preventive, predictive, or reactive) for each of the five stations, and the reliability placed at stations (range of values could be low, medium, or high). Our method to evaluate the nine-factor, three-level experiment was to use a 3_{IV}^{9-5} fractional factorial (Wu and Hamada [6]). This design consists of 81 experimental runs, which allow us to estimate all main

effects and examine some of their two-factor interactions and the experiment is shown in Figure 4.6

4.2 Process Simulation

There are 81 defined experimental runs that will be conducted based on the DOE setup. A simulation run will be conducted for each experimental run. A sample screen of the feedback associated with each simulation run is represented in Figure 4.7. This screen provides the user information on availability, functional productivity, and

Run #	M1-maint	M2-maint	M3-maint	M4-maint	M5-maint	M2-reliab	M3-reliab	M4-reliab	M5-reliab
1	Reactive	Preventive	Preventive	Predictive	Preventive	Low	Low	High	Med
2	Predictive	Preventive	Predictive	Preventive	Preventive	High	Low	Med	High
3	Reactive	Predictive	Preventive	Predictive	Predictive	High	Med	Low	Med
4	Preventive	Preventive	Preventive	Preventive	Predictive	Low	Low	Low	High
5	Reactive	Preventive	Reactive	Reactive	Reactive	High	Med	Med	Med
6	Predictive	Reactive	Preventive	Reactive	Predictive	Med	High	Low	Low
7	Predictive	Preventive	Preventive	Preventive	Reactive	High	High	High	Med
8	Predictive	Preventive	Predictive	Reactive	Preventive	Low	Med	Low	Med
9	Predictive	Reactive	Reactive	Reactive	Preventive	Med	Med	Med	High
10	Preventive	Predictive	Reactive	Reactive	Predictive	Low	Med	Med	Low
11	Predictive	Reactive	Preventive	Predictive	Predictive	High	Low	High	High
12	Predictive	Predictive	Predictive	Predictive	Predictive	Low	Low	Low	Low
13	Reactive	Predictive	Reactive	Reactive	Preventive	Med	High	High	Med
77	Reactive	Preventive	Predictive	Predictive	Predictive	Low	Med	Med	High
78	Preventive	Predictive	Predictive	Predictive	Preventive	Med	Med	Med	Med
79	Preventive	Preventive	Reactive	Preventive	Preventive	Low	High	Med	Med
80	Reactive	Reactive	Predictive	Preventive	Preventive	High	Med	High	Med
81	Preventive	Predictive	Reactive	Preventive	Predictive	High	Low	High	Med

Figure 4.6: 81 Run 3_{IV}^{9-5} Fractional Factorial Experiment

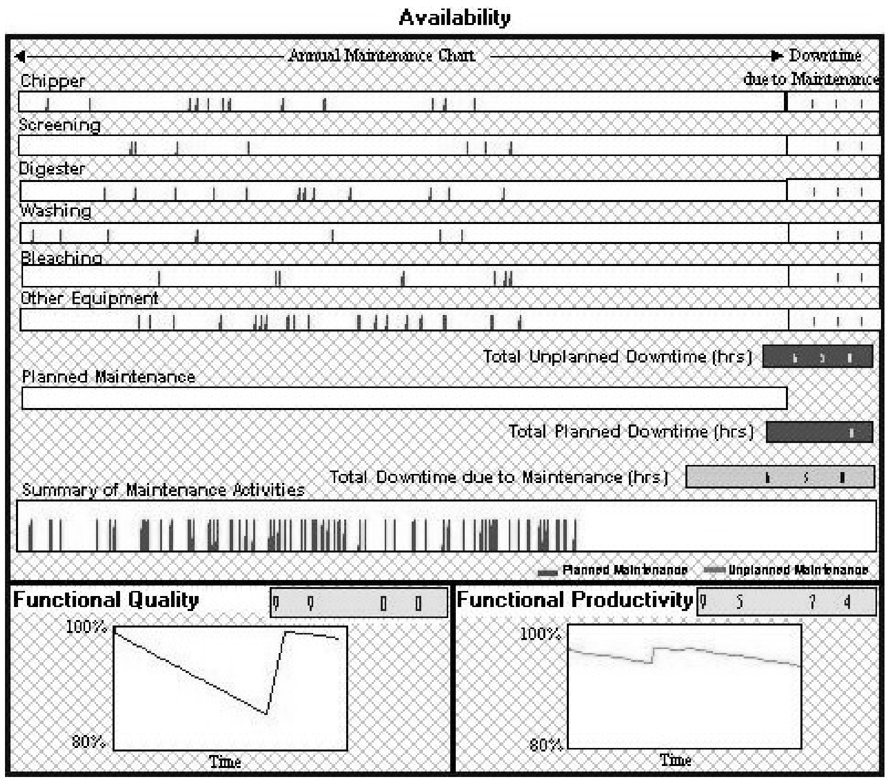


Figure 4.7: Sample Simulation Screen

functional quality. The spikes underneath each piece of equipment illustrate maintenance activities over time. To the right of this area the downtime is calculated for each piece of equipment. In addition the overall downtime is calculated and decomposed into scheduled and unscheduled downtime. The bottom of the screen summarizes all maintenance activities as well as presenting the degradation in functional productivity and quality.

4.3 Financial Analysis and Maintenance Strategy

The simulation results are next utilized to obtain the desired metrics. It is the intention of the case study to illustrate its ability to determine financial metrics, operational metrics, and maintenance related metrics.

The case study therefore determines Earnings Before Interest and Taxes (EBIT), Overall Equipment Effectiveness (OEE), and maintenance cost/ton. For example, Figure 4.8 illustrates the EBIT results for all 81simulation runs. Figure 4.8 further illustrates that the maintenance alternative associated with runs number 46, 58, 76 produce an extremely low EBIT, while the maintenance alternative associated with run number 55 produces an extremely high EBIT.

The model is currently setup to return the top three results for EBIT, OEE, and maintenance cost/ton. Each of these results is associated with a recommended maintenance strategy defining the type of maintenance for each machine group. Figure 4.9 presents the screen that summarizes the results for the end user. The period of study for each simulation run is 1 year and the top 3 recommended strategies are presented in the results based on OEE, maintenance cost/ton and EBIT. OEE and maintenance cost/ton imply that the best strategy is strategy 2, while EBIT suggests that the best strategy is strategy 1. The choice currently will depend upon the metric that is most critical to the end user.

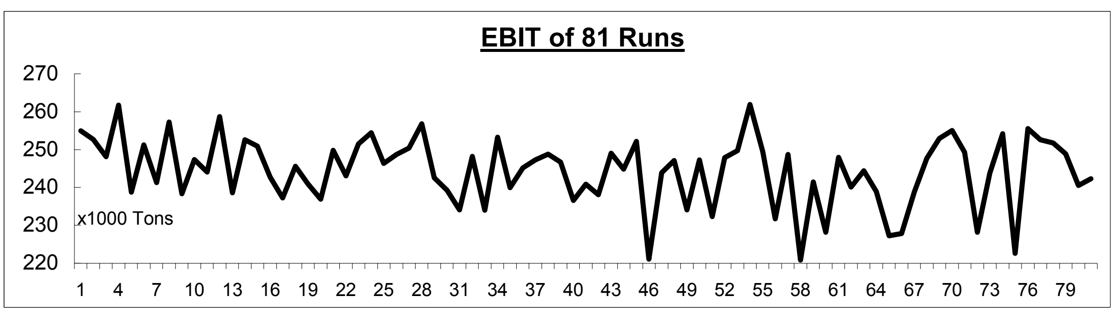


Figure 4.8: EBIT for All Simulation Runs

Summary of Experiment

Experiment runs executed: 81 Runs
Time study period: One year

Recommended strategies

	Strategy 1		Strategy 2		Strategy 3	
Machinery	**Maintenance**	**Reliability**	**Maintenance**	**Reliability**	**Maintenance**	**Reliability**
Chipping	Predictive	-	Preventive	-	Predictive	-
Screening	Predictive	Medium	Preventive	Low	Predictive	Low
Digesting	Preventive	Low	Preventive	Low	Predictive	Low
Washing	Preventive	Low	Preventive	Low	Predictive	Low
Bleaching	Preventive	Medium	Predictive	High	Predictive	Low

	OEE	Maintenance Cost / Ton	EBIT
Strategy 1	83.4%	$40	$261,922
Strategy 2	81.5%	$39	$261,725
Strategy 3	86.5%	$38	$258,694

Figure 4.9: Results - Recommended Maintenance Strategy

4.4 Financial Analysis Using Cost Model

This section makes use of a comprehensive LCC model to address the same issue of "Maintenance strategy allocation". This section also illustrates the ability of the model to cater to different levels of detail. In the previous sections the system under study was represented as 5 black boxes namely, chipping, screening, digesting, washing, and bleaching. Now we cascade down one level into one of the subsystems at greater level of detail. This particular section looks at the Washing process that is divided into 8

subsystems named System 1 through System 8. The target is to allocate appropriate maintenance strategies to these subsystems. In this case the simulation model determines the availability, functional productivity and functional quality based on the inputs similar to the ones explained in the earlier sections of this chapter.

4.4.1 Task

The task of this case study is to evaluate the impact of 2 maintenance strategies as summarized below.

In Table 4.1 the maintenance strategy described is a reactive maintenance task. This implies that anytime there is a failure the MLT value translates to 100% downtime.

Table 4.1: Maintenance Strategy 1

Main system	**Invest per main system (UC)**	**Corrective Maintenance action period (every n operating hours)**	**Required time (hours)**	**# of maintenance personnel required**	**Spares or auxiliary consumption per failure**
▶	▶	▶	▶	▶	▶
System 1	50,000.00	2000	1	1	900.00
System 2	60,000.00	1000	0.25	1	0.00
System 3	40,000.00	400	0.1	1	50.00
System 4	30,000.00	8	0.02	1	0.00
System 5	20,000.00	20	0.1	1	0.00
System 6	10,000.00	50	0.2	1	45.00
System 7	8,000.00	100	0.2	1	12.80
System 8	62,000.00	12	0.1	1	0.00

Table 4.2: Maintenance Strategy 2

Main system	Invest per main system (UC)	PM action period (every n operating hours)	Required time (hours)	# of maintenance personnel required	Spares or auxiliary consumption per PM action	Maintenance downtime required
▶	▶	▶	▶	▶	▶	▶
System 1	50,000.00	200.00	3	2	5	Yes
System 2	60,000.00	1,000.00	2	1	100	No
System 3	40,000.00	1,000.00	3	1	75	Yes
System 4	30,000.00	1,300.00	4	2	3000	Yes
System 5	20,000.00	8,000.00	2	1	250	Yes
System 6	10,000.00	1,200.00	1	2	230	Yes
System 7	8,000.00	6,000.00	4	1	120	No
System 8	62,000.00	20,000.00	8	1	270	Yes

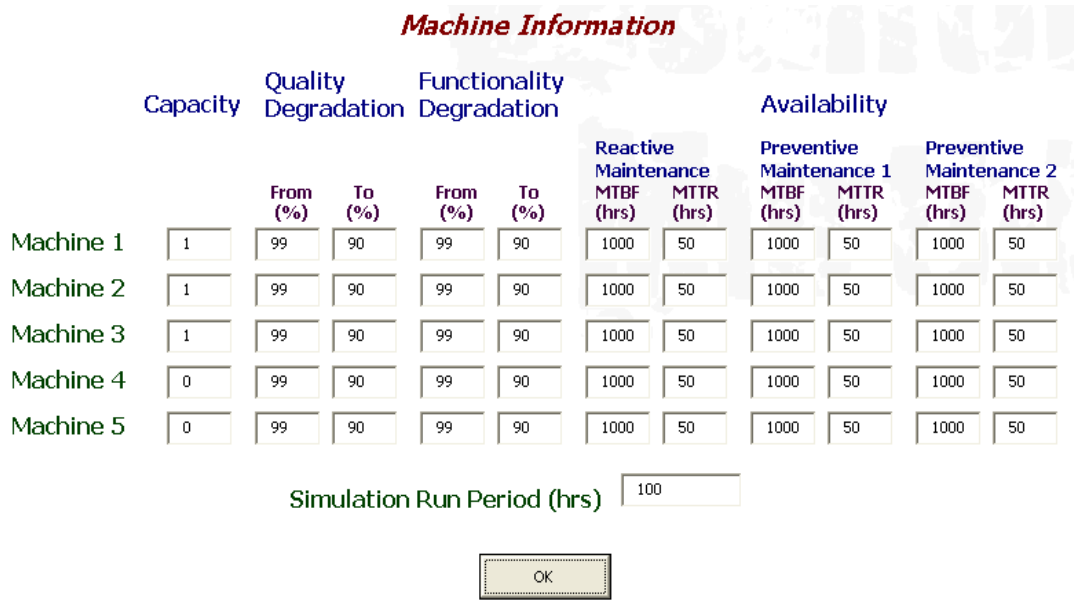
In Table 4.2 the maintenance strategy described is a preventive maintenance task. In this case there are certain tasks that are scheduled and do not require the system/ machine to be shut down. But there are also a percentage of tasks that involve disruption of the manufacturing process and are described in the last 2 columns.

4.4.2 Inputs for Simulation Model

The inputs for the simulation model includes

1. Setting up the model to represent the manufacturing process. Figure 4.10 is a snapshot of Inputs for the Simulation. The inputs are as follows,

    - Number of machines
    - Setting up different maintenance strategies.
    - Capacity of each machine



Machine Information

	Capacity	Quality Degradation From (%)	Quality Degradation To (%)	Functionality Degradation From (%)	Functionality Degradation To (%)	Availability: Reactive Maintenance MTBF (hrs)	Reactive Maintenance MTTR (hrs)	Preventive Maintenance 1 MTBF (hrs)	Preventive Maintenance 1 MTTR (hrs)	Preventive Maintenance 2 MTBF (hrs)	Preventive Maintenance 2 MTTR (hrs)
Machine 1	1	99	90	99	90	1000	50	1000	50	1000	50
Machine 2	1	99	90	99	90	1000	50	1000	50	1000	50
Machine 3	1	99	90	99	90	1000	50	1000	50	1000	50
Machine 4	0	99	90	99	90	1000	50	1000	50	1000	50
Machine 5	0	99	90	99	90	1000	50	1000	50	1000	50

Simulation Run Period (hrs) 100

OK

Figure 4.10: Snapshot of Simulation Input – Machine/ Subsystem Information

2. Setting up Routing information as shown in Figure 4.11. The inputs are
    - Part Routing
    - Routing Times
    - Process Times
3. Setting up different maintenance strategies.
4. Global Variables such as simulation run time and warm up period.

4.4.3 Inputs for LCC

4.4.3.1 Cost Model Inputs

1. General Organizational Schedule
    - Number of weeks in year - 52 weeks
    - Number of work days per week - 5 days

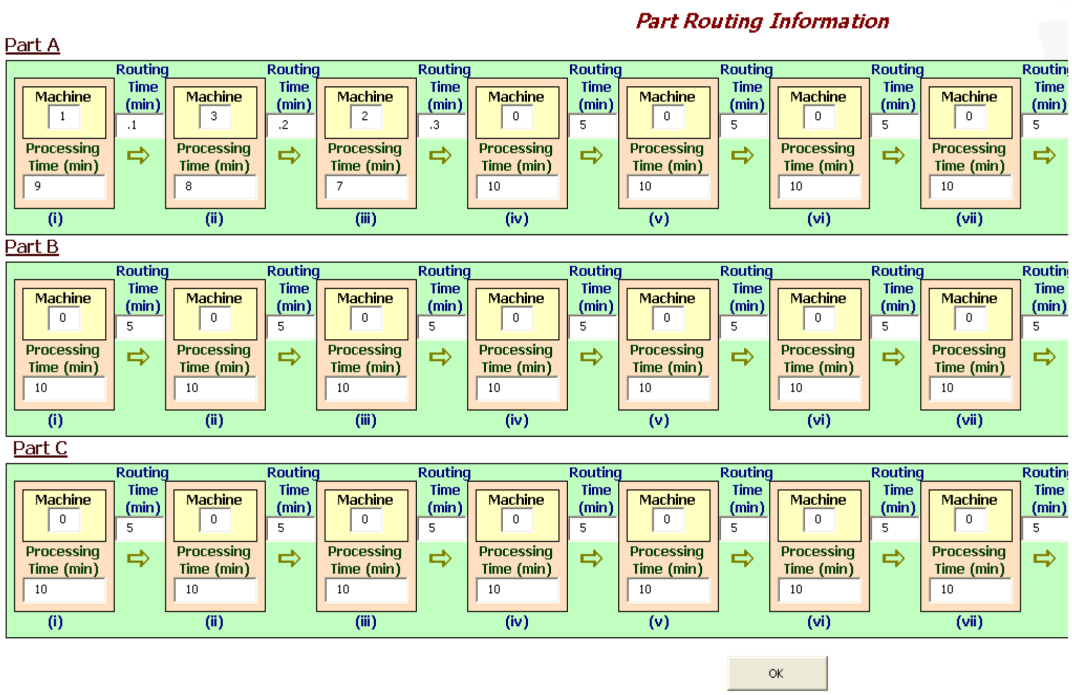


Figure 4.11: Snapshot of Simulation Input – Part Routing Information

- Company closing - 30 days
- Holidays - 12 days
- Shifts per day - 3 shifts
- Daily hours per shift - 7.5 hours
- Changeover time, Setup time etc - 100 hours/day
- Overhaul Maintenance time - 35 hours/day

2. Basic Organizational Data

- Discount rate - 5.5% per year
- Manufacturing overhead cost rate - 65 UC/Year
- Room rate - 15 UC/month

- Electricity rate - 0.15 UC/KWh
- Operation labor costs - 45 UC/ Hour
- Mean maintenance labor costs - 80 UC/Hour

3. Basic Industrial System Data

- Acquisition costs - 1,250,000.00 UC
- Infrastructure costs required - 320,000.00 UC
- Number of operational staff - 1 person
- Operating time in years - 8 years
- Space requirements - 85.00 m^2
- Electrical consumption - 85.00 KW
- Auxiliary parts and consumables - 300.00 UC/Month
- Tooling costs - 200.00 UC/Month
- Quality costs - 3.10 UC/Unit
- Planned maintenance cost rate - 5.5% per year

4. Spare parts and asset costs

Data related to spare parts consumption is illustrated in Table 4.3.

4.4.4 Life Cycle Costing Model

The calculation sheets that lead to the LCC results for each run are given below. The cells that have a

▶ Solid triangle – Inputs Values

▷ Empty Triangle – Calculated Values

Table 4.3: Spare Parts Consumption

Spares and consumables	Required for system	Quantity in stock	Unit	Unit price
▶	▶	▶	▶	▶
PLC simatic	System 1	5	pcs	2,500.00
ABB	System 3	1	pcs	60,000.00
Valves	System 5	10	pcs	23.00
Proximity switch	System 5	75	pcs	7.40
Drain filters	System 8	3	pcs	3,200.00
AP100/T pump valve	System 5	1	pcs	75,000.00
AP200A pump valve	System 6	2	pcs	5,600.00
Insulation Coils	System 6	4	pcs	2,400.00

▷▷ Double Empty Triangle – Outputs from the simulation model

With all this data the "Industrial System Operating time" is calculated, which is the total time, the machine is scheduled to manufacture.

4.4.4.1 Sheet 1 – General Organizational Schedule

Number of weeks in year	:	The number of weeks of a year
Number of work days per week	:	Number of days the plant operates
Company closing	:	The company shutdown period
Holidays	:	The number of general holidays per year
Shifts per day	:	The number of shifts per day
Daily hours per shift	:	The operating hours per shift, not including breaks, meeting times, etc,
Tool and Die exchange	:	Time required for changeover time, setup time etc
Overhaul Maintenance time	:	The total operating time, the machine is scheduled to manufacture

Data related to General Organizational Schedule is illustrated in Table 4.4.

Table 4.4: Sheet 1 - General Organizational Schedule

01.01	Number of weeks in year	▶	weeks/year	52
01.02	Number of work days per week	▶	days/week	5
01.03	Total number of work days	▷	days/year	260
01.04	Company closing	▶	days/year	30
01.05	Holidays	▶	days/year	12
01.06	Scheduled operating days	▷	days/year	218
	Shift Schedule			
01.07	Shifts per day	▶	shifts/day	3
01.08	Scheduled operating shifts	▷	shifts/year	654
01.09	Daily hours per shift	▶	hours/shift	7.5
01.10	Scheduled operating hours per year	▷	hours/year	4905
	Indirect Service Time during Operation			
01.11	Changeover time, Setup time etc	▶▶	hours/year	100
01.12	Overhaul Maintenance time	▶▶	hours/year	35
01.13	Industrial System Operating time	▷	hours/year	4770
01.14	Industrial System Operating time (min)	▷	min/year	286200

4.4.4.2 Sheet 2 - Basic Organizational Data

Discount rate	:	The cost for external money (e.g., for mortgage, loans) is defined
Manufacturing overhead cost rate	:	Aggregates the overhead costs (e.g., for manufacturing management, central workshops, manufacturing supervisors, etc. that is added to the fixed costs of the industrial system
Room rate	:	The internal price for the required space including infrastructure costs, e.g., lighting, cooling, etc.
Electric rate	:	The electric rate defines the full cost for electricity consumption based on KWh required
Operation labor costs	:	The full costs per hour for the personnel. It includes all social and employer costs including bonus and further personnel relevant costs as a full cost per hour
Mean maintenance labor costs	:	The full costs per hour for the maintenance personnel (e.g., fitters, mechanics, electricians, maintenance specialists). It includes all social and employer costs including bonus and further personnel relevant costs as a full cost per hour

Data related to Basic Organization Data is illustrated in Table 4.5.

Table 4.5: Sheet 2 – Basic Organizational Data

02.01	Discount rate	▶	%/year	5.50%
02.02	Manufacturing overhead cost rate	▶	UC/hour	36.00
02.03	Room rate	▶	UC/ (m2*month)	15.00
02.04	Electricity rate	▶	UC/KWh	0.19
02.05	Operation labor costs	▶	UC/ hour	45.00
02.06	Mean maintenance labor costs	▶	UC/hour	80.00

4.4.4.3 Sheet 3 - Basic Industrial System Data

Acquisition Cost	:	The investment or acquisition cost for the industrial system
Infrastructure costs required for industrial system	:	Investment required to integrate the industrial system into the production environment. This may be depreciated with the industrial system.
Cycle time (designed)	:	Number of manufactured units per hour under ideal conditions
Planned yearly production	:	Based on the cycle time and planned operating hours the planned yearly production is calculated.
Number of operational staff	:	Number of operators required to operate the industrial system, i.e., direct labor required for the industrial system
Operating time in years	:	Number of years the industrial system is scheduled to operate.
Planned hours of operation	:	Calculated scheduled operational hours from table 01.
Productive operating hours per year (OEE based)	:	The scheduled operational hours are reduced by the losses, quantified by the OEE. (From Simulation)
Technical Availability (TA)	:	Downtime due to preventive and corrective maintenance activities reduces operational time. The downtime relative to the scheduled operational hours defines technical availability.
Industrial system cycle time (actual)	:	Performance losses due to idling, stoppages, mechanical wear of transport systems lead to a reduced cycle time.
Technical Functionality (TF)	:	It is the ratio between designed cycle time and actual cycle time.
Quality Rate (QR)	:	Number of quality units produced to the total units produced
Overall Equipment Efficiency (OEE)	:	Product of technical availability, technical functionality and quality rate.
Space requirements	:	The space requirements for the industrial system
Electrical consumption	:	Electric power consumption of the machine (KW)
Auxiliary parts and consumables	:	Auxiliary parts and consumables required to operate and run the industrial system.
Tooling costs	:	Costs caused by tool wear, tool replacement, etc.
Quality costs (non quality conform units)	:	Costs required for rework and waste for non quality checked units.

Data related to Basic Industrial System is illustrated in Table 4.6.

Table 4.6: Sheet 3 – Basic Industrial System Data

03.01	Acquisition costs	▶	UC	1,250,000.00
03.02	Infrastructure costs required for industrial system	▶	UC	320,000.00
03.03	Industrial system cycle time	▶	Units/ hour	60.00
03.04	Planned yearly production	▷	Units/ year	286,200.00
03.05	Number of operational staff	▶	Persons	1.00
03.06	Operating time in years	▶	years	8.00
03.07	Planned operating hours per year	▷	hours/ year	4,770.00
03.08	Productivity operating hours per year (OEE-based)	▷	hours/ year	4,553.47
03.09	Technical availability (AV)	▷▷	%	95.46%
03.10	Industrial system cycle time (Actual)	▷▷	Units/ hour	57.00
03.11	Technical functionality (TF)	▷▷	%	95.00%
03.12	Quality rate (QR)	▷▷	%	98.00%
03.13	Overall Equipment Effectiveness	▷▷	%	88.87%
03.14	Space requirements	▶	m2	85.00
03.15	Electrical consumption	▶	kw	85.00
03.16	Auxiliary parts and consumables	▶	UC/ month	300.00
03.17	Tooling costs	▶	UC/ month	200.00
03.18	Quality costs	▶	UC/ unit	3.10

4.4.4.4 Sheet 4 - Spare Parts and Calculated Maintenance Costs

Spare parts	:	The total stock value of purchased assets. Calculated in *Spare parts (Stock Assets)*
Spares consumption per year	:	The assets required by preventive, corrective maintenance actions
Spares turnover per year	:	The ratio of used spares to the total stock value
Spare parts pre invest	:	Ratio of total stock value to the investment of the industrial system
Planned maintenance costs	:	The planned maintenance costs, calculated as planned maintenance cost rate multiplied with the investment value of the industrial system
Planned maintenance cost rate	:	Rate that was defined during planning and acquisition phase of the industrial system, based on the investment value of the industrial system
Calculated Maintenance Cost		
Preventive maintenance costs	:	Include spare parts, labor and if required downtime costs. Calculated in *preventive maintenance cost*.
Industrial system downtime cost (Preventive)	:	Cost caused by required downtime during preventive maintenance.
Spares and consumables cost (Preventive)	:	Spares and consumables cost required during preventive maintenance activities.
Corrective maintenance costs	:	Include spare parts, labor and if required downtime costs. Calculated in *corrective maintenance cost*.
Industrial system downtime cost (Corrective)	:	Cost caused by required downtime during corrective maintenance.
Spares and consumables cost (Corrective)	:	Spares and consumables cost required during corrective maintenance activities.
Inventory cost (Assets)	:	Stock value that is not used within the year during corrective and/or preventive activities costs money. Hence asset volume (fixed capital) is multiplied with the discount rate.
Real maintenance costs (as calculated in *PM and BdM, spares*)	:	Total costs of spares, corrective maintenance and preventive maintenance define the real maintenance costs.
Real maintenance cost rate (as calculated in *PM and BdM, spares*)	:	Ratio of real maintenance costs to the investment value of the industrial system defines the real maintenance cost rate.

Data related to Calculated Maintenance Costs is illustrated in Table 4.7.

Table 4.7: Sheet 4 – Calculated Maintenance Costs

04.01	Spare parts (stock volume)	▷	UC	178,685.00
04.02	Spares consumption per year	▷	UC/year	20,831.11
04.03	Spares turnover per year	▷	%	11.66%
04.04	Spare parts per invest	▷	UC	14.29%
04.05	Planned maintenance cost rate	▶	%/ year	5.50%
04.06	Planned maintenance costs	▷	UC/ year	68,750.00
	Calculated maintenance costs			
04.07	Preventive maintenance costs	▷	UC/ year	16,842.75
04.08	Industrial system downtime cost (Preventive)	▷	UC/ year	18,483.77
04.09	Spares and consumables cost (Preventive)	▷	UC/ year	13,184.80
04.10	Corrective maintenance costs	▷	UC/ year	30,607.54
04.11	Industrial system downtime cost (Corrective)	▷	UC/ year	18,707.51
04.12	Spares and consumables cost (Corrective)	▷	UC/ year	7,646.31
04.13	Inventory Cost (Assets)	▷	UC/ year	8,681.96
04.14	Real maintenance costs	▷	UC/ year	114,154.64
04.15	Real maintenance cost rate	▷	%/ year	9.13%

4.4.4.5 Sheet 5 - Fixed and Variable Machine Costs

Fixed industrial system costs

Depreciation of industrial system	:	Linear depreciation of the industrial system (including required infrastructure) based on the planned operational years per operating hour.
Account current of spares (assets)	:	The costs of fixed assets (spare volume)
Calculatory interest	:	The mortgage and load costs for the investment money
Space costs	:	The costs for the area and room for the installed industrial system
Manufacturing overhead costs	:	The cost rate required for manufacturing overhead costs
Industrial system costs (fixed)	:	The sum of the individual fix cost blocks

Variable industrial system costs

Operational labor costs	:	The labor costs for machine operators
Operational material and auxiliary costs	:	The costs for operational material and auxiliary costs
Tooling costs	:	The costs for tools, tooling and tool wear
Planned maintenance costs	:	As defined by the planned maintenance cost rate
Electricity costs	:	The electricity consumption
Quality costs (repair and waste costs)	:	The quality costs require for rework, repair and waste
Industrial system costs (variable)	:	The sum of the individual variable cost blocks

Data related to Fixed and Variable Machine Costs is illustrated in Table 4.8.

Table 4.8: Sheet 5 – Fixed and Variable Machine Costs

	Fixed industrial system costs			
05.01	Depreciation of the industrial system	▷	UC/ hour	41.14
05.02	Account current of spares (assets)	▷	UC/ hour	1.82
05.03	Calculatory interest	▷	UC/ hour	9.05
05.04	Space costs	▷	UC/ hour	3.21
05.05	Manufacturing overhead costs	▷	UC/ hour	36.00
05.06	Industrial system costs (fixed)	▷	UC/ hour	91.22
	Variable industrial system costs			
05.07	Operational labor costs	▷	UC/ hour	45.00
05.08	Operational material and auxiliary costs	▷	UC/ hour	0.75
05.09	Tooling costs	▷	UC/ hour	0.50
05.10	Planned maintenance costs	▷	UC/ hour	14.41
05.11	Electricity costs	▷	UC/ hour	16.15
05.12	Quality costs (repair and waste costs)	▷	UC/ hour	3.72
05.13	Industrial system costs (variable)	▷	UC/ hour	80.54

4.4.4.6 Sheet 6 - Industrial System Hourly Costs and Manufacturing Unit Costs

Industrial system hourly costs

Planned industrial system hourly rate	:	The sum of fixed and variable machine costs
Unplanned maintenance hourly costs	:	Cost difference of planned and unplanned maintenance costs, shown by the difference of planned and real maintenance cost rate
Real industrial system hourly costs	:	The real industrial system hourly cost including unplanned maintenance costs
Real industrial system hourly costs	:	The real industrial system hourly cost including unplanned maintenance costs.

Manufacturing Unit costs

Planned manufacturing unit costs	:	Hourly costs of the industrial system in relation to planned manufactured units
Real manufacturing unit costs	:	Real hourly costs of the industrial system in relation to real manufactured units, caused by OEE losses
Delta manufacturing costs unplanned maintenance	:	Additional maintenance costs caused by unplanned maintenance (without unit losses)
Manufacturing unit costs (reduced OEE)	:	Additional manufacturing unit costs caused by reduced OEE. It has 3 cost blocks reduced availability, reduced functionality and reduced quality
Manufacturing unit costs (reduced availability)	:	Additional non-planned manufacturing costs caused by reduced availability
Manufacturing unit costs (reduced functionality)	:	Additional non-planned manufacturing costs caused by reduced functionality
Manufacturing unit costs (reduced quality)	:	Additional non-planned manufacturing costs caused by reduced quality

Data related to Industrial System Hourly Costs and Manufacturing Unit Costs is illustrated in Table 4.9.

Table 4.9: Sheet 6 – Industrial System Hourly Costs and Manufacturing Unit Costs

	Industrial system hourly costs			
06.01	Planned industrial system hourly rate	▷	UC/ hour	171.76
06.02	Unplanned maintenance hourly costs	▷	UC/ hour	1.72
06.03	Real industrial system hourly costs	▷	UC/ hour	173.48
	Manufacturing unit costs			
06.04	Planned manufacturing unit costs	▷	UC/ Unit	2.86
06.05	Real manufacturing unit costs	▷	UC/ Unit	3.27
06.06	Delta manufacturing costs unplanned maintenance	▷	UC/ Unit	0.03
06.07	Manufacturing unit costs (reduced OEE)	▷	UC/ Unit	0.37
06.08	Manufacturing unit costs (reduced Availability)	▷	UC/ Unit	0.15
06.09	Manufacturing unit costs (reduced performance)	▷	UC/ Unit	0.16
06.10	Manufacturing unit costs (reduced quality)	▷	UC/ Unit	0.06

4.4.4.7 Sheet 7 - Manufacturing Yearly Production Output

Planned yearly production	:	It is defined by the operational hours and planned cycle time
Delta yearly production (maintenance impact)	:	Reduced yearly production caused by reduced availability
Delta yearly production (functionality impact)	:	Reduced yearly production caused by reduced functionality
Delta yearly production (quality impact)	:	Reduced yearly production caused by reduced quality
Real yearly production	:	The real yearly production in units
Total unit losses	:	The total unit losses per year due to reduced OEE
Real hourly production rate	:	The real hourly production rate as ratio of real yearly production to operational hours

Data related to Manufacturing Yearly Production Output is illustrated in Table 4.10.

Table 4.10: Sheet 7 – Manufacturing Yearly Production Output

07.01	Planned yearly production	▷	UC/ year	286,200.00
07.02	Delta yearly production (availability impact)	▷	UC/ year	12,991.65
07.03	Delta yearly production (functionality impact)	▷	UC/ year	14,310.00
07.04	Delta yearly production (quality impact)	▷	UC/ year	5,724.00
07.05	Real yearly production	▷	UC/ year	253,174.35
07.06	Total unit losses	▷	UC/ year	33,025.65
07.07	Real hourly production rate	▷	Units/ hour	53.08

4.4.5 Results

The LCC model is run for each simulation run. A sample run shows gives the following output in terms of Acquisition Costs, Operational Costs, Unplanned Manufacturing Costs and its impact on Life Cycle Cost. LCC results is tabulated in Table 4.11.

Once all the simulation alternatives were run in a full factorial experiment the following were the results obtained for the Systems under study. Figure 4.12 provides the proposed maintenance strategy allocation for each of the sub-systems.

Table 4.11: Sheet 8 – LCC Results for a Sample Run

	Acquisition costs			
08.01	Acquisition Costs	▷	UC/ life-cycle	1,570,000.00
	Operation costs			
08.02	Total fixed costs (without depreciation)	▷	UC/ life-cycle	1,911,015.71
08.03	Total variable costs (without planned maintenance)	▷	UC/ life-cycle	2,523,439.20
08.04	Total operation costs	▷	UC/ life-cycle	4,434,454.91
	Unplanned manufacturing costs			
08.05	Planned maintenance costs	▷	UC/ life-cycle	550,000.00
08.06	Unplanned maintenance costs	▷	UC/ life-cycle	363,237.13
08.07	Reduced OEE costs (for information)	▷	UC/ life-cycle	725,867.38
08.08	Total non-availability costs	▷	UC/ life-cycle	1,639,104.51
	Life-cycle costs (LCC)			
08.09	Total life-cycle costs	▷	UC/ life-cycle	6,917,692.04
08.10	Total manufactured units	▷	UC/ life-cycle	2,025,394.84
08.11	Life-cycle unit costs	▷	UC/ life-cycle	3.42

System 1	Maintenance Strategy 2
System 2	Maintenance Strategy 1
System 3	Maintenance Strategy 2
System 4	Maintenance Strategy 2
System 5	Maintenance Strategy 2
System 6	Maintenance Strategy 1
System 7	Maintenance Strategy 1
System 8	Maintenance Strategy 2

Figure 4.12: Proposed Maintenance Strategy Allocation

The LCC model feeds off most of the values offered by the utilization of the simulation model. The LCC simply adds the economic dimensions to the simulation results.

4.5 Conclusion

The case study illustrates the application of the approach described in Chapter 3. The case study sheds light on the working of the model. It also emphasizes on the flexibility offered by this tool. It can be used to represent any system that needs to be studied. It can also analyze systems at different levels of detail ranging from enterprise level to working level. The LCC model is a comprehensive approach to not only identify maintenance strategies but also pulls in data pertaining to a lot of decision-making nodes.

Chapter 5

Conclusion

5.1 Introduction

Simulation has been utilized to address the issue of maintenance (Schryver, Jack, Willis, Frank). The thesis presents a new risk free methodology of experimenting with various maintenance strategies. The black box approach takes the user from establishing parameters through the results eliminating the need for users to have expertise in dynamics of the model. This methodology powers simulation modeling with not only a structured approach to carrying out an experiment, but also analyzing results. It allows the user to not only design the manufacturing process via menus, but also to setup the maintenance experiment. Once the end user has entered the appropriate data, the system will initiate the simulation model and provide the results in the form of predefined metrics. The key challenge is to translate the user defined parameters into very detailed simulation modeling, making sure these factors are independent of each other. This type of a methodology seems more appropriate for manufacturers that seem to have a large set of equipment with complex interactions. Examples for complex interactions could be the actual process required by the product, fluctuating product demand, and a fluctuating product mix. This gears the model to handle situations that have varying degrees of details. It can be used to analyze a single conveyor line and it can also be used to model the entire plant.

The details encompassed by the cost model can be used to address various other issues related to manufacturing and process analysis. For example the same model can be used to study the level of spare parts inventory. The challenge is to determine the most

cost effective mix of spare parts and the optimal location to place spare parts in order to meet operational requirements at a minimum cost. The purpose is to maximize the utilization of the assets by ensuring that sufficient spares are available to sustain operations while ensuring that excess spares are not languishing on the storeroom shelf. By keeping the OEE constant and conducting a sensitivity analysis with varying spare parts inventory. The effect of this being tied to the mean lead-time value plugged into the simulation input while defining maintenance strategies. Likewise any variable can be optimized using this closed loop approach.

Another application of this model is given below. Consider a situation when management decides to downsize or expand their plant operation. This model can be used to estimate the best maintenance strategy for the new system and answer a lot of important questions.

1. How well will our equipment perform under this scenario?
2. How much extra will it cost to operate at this level?
3. Can a reliability improvement in system x improve the situation at lower cost?

The model can be used in "Level of Repair Analysis", which is an investment appraisal technique that assists in the decision to invest in a maintenance and support infrastructure and if so how close to the operation or to contract out the maintenance to a third party. This decision directly impacts operational effectiveness, availability and through life costs. Hence the model can be modified to deal with a lot of problems.

Simulation modeling can be used to study a wide range of problems. This approach in automating the simulation model to run different scenarios and adding the cost dimension is the element that brings great value.

5.2 Summary of Research Results with respect to Problem Statement

To address the questions that was sought after, at the beginning of this study –

- *"Develop a methodology that estimates the best maintenance strategies that are both adequate and economically feasible for a complex manufacturing system.*
- *Provide a feasible and exhaustive means of conducting experiments and analyzing the results"*.

Both these statements have been answered through the course of this research work. The model provides a structured methodology in balancing an adequate maintenance program and economic feasibility. As for maintenance resource allocation, this method proposes the best alternatives. They might not necessarily be the optimum solution, but the best alternatives are provided which can further be used in the decision making process. It provides a structured approach to conducting risk free experiments and means to evaluate the output of the simulation model and the other cost parameters.

5.3 Recommendations

The next step in taking this research approach would be focused at obtaining optimal solutions by plugging in OR models to the financial models. The flexibility of the model gives rise to a range of applications for this tool considering that a simulation

model representing the process has been developed. It can be used for any running any simulation-based experiment not just limited to reliability analysis. Future research could be directed towards real time reliability based simulation as used in real time control system analysis. In one such system, a simulation model runs synchronous with the actual system. When a maintenance task needs to be scheduled, different what if scenarios are run with a sensitivity analysis study that recommends the best way to schedule a maintenance task, optimum spares inventory level, resource allocation etc. in real time.

References

References:

1. Moore, Ron. 2002. Making Common Sense Common Practice: Models for Manufacturing Excellence, (pp. 34-36, 48). Boston: Butterworth-Heinemann.
2. Campbell, John Dixon 1995. UPTIME: Strategies for Excellence in Maintenance Management, (pp. 1-5, 9-21). Portland: Productivity Press Inc.
3. Mulvilill, Robert J., and Ramesh Gulati 2002. Maintenance Program Risk Management,.
4. Sawhney, R.S. 1998. The Role of Assisted PWB Manufacturers in Design and Improving Processes, Proceedings of the 1998, European Joint Conference 7 (pp. 138-148), Paris: EIPC.
5. Ebeling, Charles. E. 1997. An Introduction to Reliability and Maintainability Engineering, (pp. 117-118), New York: McGraw-Hills Companies, Inc.
6. John Moubray. 1997. Reliability-centered Maintenance, Chapter 1, pp 2-10, Terre Haute, IN
7. Wu, C. F. Jeff and Michael Hamada. 2000. Fractional Factorial Experiments at Two Levels. In: Wu, C. F. Jeff and Michael Hamada, Experiments: Planning, Analysis, and Parameter Design Optimization, (pp. 153-204), New York: Willey Europe Publishers.
8. Schryver, Jack C. 2002. ORSIM: Simulation-Based Reliability Prediction of FCS Concepts, Proceedings of the 2002 MARCON, Knoxville: University of Tennessee.

9. Willis, Frank Alan 1998. Utilizing Simulation to Optimize Maintenance Strategies, M.S, thesis, Knoxville, TN, University of Tennessee.
10. Priel, V.Z. 1974. Systematic Maintenance Organization, London: Macdonald & Evans Ltd.
11. Keceecioglu, Dimitri. 1995. Maintainability, Availability, and Operational Readiness Engineering Handbook, New Jersey: Prentice-Hall PTR.
12. Birger, Rapp. 1974. Models for Optimal Investment and Maintenance Decisions, New York: John W
13. E.N. White. 1975. Introduction to Maintenance Planning in manufacturing establishments, United Nations Publication, New York
14. M. Ben-Daya, S.O. Duffuaa, A. Raouf, 2000. Maintenance, Modeling and Optimization, Kluwer Academic Publishers, Norwell.
15. Patrick D.T. O'Connor With David Newton and Richard Bromley, T. A. Stolarski, Practical reliability engineering, Brunel University, Department of Mechanical Engineering, Uxbridge, Middlesex, UB8 3PH, UK
16. http://www.weibull.com/LifeDataWeb/a_brief_introduction_to_reliability.htm
17. Kececioglu, Dimitri. 1991. *Reliability Engineering Handbook*, Prentice Hall Inc, Engelwood Cliffs New Jersey, Vol 1.
18. Ned H Criscimagna. 2001. START - Selected Topics in Assurance Related Topics, Volume 8 No 2.
19. Nachdiplomkurs, Risiko und Sicherheit, Logical Tres in Risk Analysis, Lecture Notes on Risk and Reliability in Civil Engineering.

20. E. N. White. 1973. Maintenance Planning, Control & Documentation, Gower Press Limited, Essex

21. Liker, Jeffrey. 1998. Becoming Lean: Inside Stories of U.S. Manufacturers, (Chapter 12 - The Successes and Failures of Implementing Continuous Improvement Programs), New York, Productivity Press Inc.

22. Larry Rubrich, Madelyn Watson, Shirley Rubrich. 1998. Implementing World Class Manufacturing - Shop Floor Manual, Fort Wayne, IN, WCM Associates.

23. Peter Willmott. 2000. Total Productive Maintenance: A Route to World Class Performance, UK, Butterworth-Heinemann

24. Sohrab Asgarpoor, Mohamad Doghman. 1999. "A Maintenance Optimization Program for Utilities' Transmission and Distribution Systems", University of Nebraska-Lincoln

25. B. D. Joshi, R. Unal, N. H. White and W. D. Morris. 1996. A Framework for the Optimization of Discrete Event Simulation Models, Presented at the 17th ASEM National Conference.

26. Tuomas Raivio, Eemeli Kuumola, Ville A. Mattila, Kai Virtanen, Raimo P. Hämäläinen. 2001. A Simulation model for Military Aircraft Maintenance and Availability, ESM2001 15 th European Simulation Multiconference,

27. Farhad Azadivar and J. Victor Shu. 1998. "Use of Simulation in Optimization of Maintenance Policies", Proceedings of the 1998 Winter Simulation Conference.

28. Jorn Vatn, Per Hokstad and Lars Bodsberg. 1996. "An Overall Model for Maintenance Optimization". Reliability Engineering and System Safety 51(1996) Pages 241-257

VITA

Vasanth Murthi was born in Chennai, India on April 19 1979. He graduated from St. Michael's Academy – High School in 1996. He received his Bachelor of Science degree with a major in "Production Engineering" from University of Madras, India in 2000. He obtained his Masters of Science degree with a major in Industrial Engineering from University of Tennessee, Knoxville in December 2003