ANALYSIS, DESIGN AND OPTIMIZATION OF QRM ASPECTS IN PRODUCTION SYSTEMS

A THESIS

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ABSTRACT

In today's turbulent business environment, global competition characterized by both a technology push and a market pull had forced the organizations to compete themselves on various platforms such as faster delivery, price tags, state of art-technology and higher quality dimensions. Various innovative techniques and management practices such as *TPM, TQM, BPR, MRP, and JIT* etc. are being practiced by various business houses across the globe. However, benefits accrued from them have often been limited because of unreliable or inflexible nature of systems/components/parts.

In reliability and maintainability studies only few researchers have seriously addressed the issue of handling uncertainties related with Quality, Reliability and Maintainability (QRM) data (Fonseca and Knapp, 2001; Sergaki and Kalaitzakis, 2002; Majumder, 2004). The present study is an attempt to resolve such uncertain issues related with QRM aspects of systems. The central focus of the present work is to analyze, design and optimize QRM aspects of production systems. A comprehensive review of literature was conducted to identify the gaps and relevant research issues in these areas. Based upon the critical review, a framework (using both qualitative and quantitative techniques) has been developed to abridge the gaps. Owing to its sound logic, effectiveness in quantifying the vagueness and imprecision in human judgment, the fuzzy methodology has been used as an effective tool in the study to synthesize the information related to QRM aspects of production systems.

To cope with the complex, uncertain and subjective relationships between various cost segments and to help managers to set up/improve various quality improvement initiatives, the application of fuzzy methodology (FM), is proposed to elicit, aggregate and synthesize various quality costs under the four cost categories (Prevention, Appraisal, Internal

Failure and External Failure). Treating quality as a fuzzy notion, the information obtained from wide range of sources (supplier, operators experience, manufacturer's specification and expert opinions etc.) is synthesized with the help of well-defined fuzzy set principles. Capitalizing on the literature studies and identified gaps, an integrated, structured and systematic approach is proposed to plan, implement and sustain a quality-costing program, aimed at helping the managers to provide

(i) a structured framework for implementing, sustaining and managing a Quality Cost Accounting System (QCAS) in industry (after prioritization of alternatives under each cost category)

(ii) framework to implement Quality Costing System (QCS) based on Process Cost Modeling (PCM) (after prioritizing the processes)

In particular, the fuzzy logic approach used in the study to address the quality aspects related to the system is mainly concerned with the following three issues:

(i) Translation of linguistic/subjective assessments related to quality cost information under various cost segments into Fuzzy Number Representation (FNR)

(ii) Operation on Triangular Fuzzy Numbers (TFN)

(iii) Information aggregation using Choquet Fuzzy Integral (CFI)

With respect to the issue of handling uncertainties, related with failure data of the production systems, only limited research studies have been undertaken seriously (Fonseca and Knapp 2001, Sergaki and Kalaitzakis 2002). To this effect, the study provides application of non-probabilistic methods (Fuzzy and Grey theory) in conjunction with reliability analysis tools (Fault tree, Petrinets, FMEA) to treat the element of uncertainty associated with the data related to system performance. A unified and structured framework to model, analyze and predict the system behavior more realistically has been developed. The framework makes use of both qualitative and quantitative techniques to analyze the failure behavior of an industrial system (paper mill).

In the Quantitative framework first the Petri net model of the system is obtained from its equivalent fault tree model and then system failure rate and repair times have been computed (based on the steps as discussed in Section 4.3.3). For the system components, the fuzzification of data (failure and repair time) is done using Triangular Membership Function (TMF). After knowing the input fuzzy triangular numbers for all the components shown in Petrinet model the corresponding fuzzy values of failure rate (λ) and repair time (τ) for the system at different confidence levels (α) were determined using fuzzy transition expressions. Various system parameters are quantified in terms of fuzzy, crisp and defuzzified values. Depending upon the value of confidence level, the analyst can predict and analyze the behavior of the system.

In the Qualitative framework the in-depth qualitative analysis of all the subsystems is carried out using Root Cause Analysis (RCA) and Failure Mode and Effect Analysis (FMEA). Using the selected experts, possible failure modes, their causes and effect on system performance, with the values of failure of occurrence (O_f), likelihood of non-detection of failure (O_d), and severity (S) of failure of various components has been ascertained and resulting Risk Priority Number (RPN) is computed. The limitations of traditional RPN procedure are addressed by using fuzzy decision making system (FDMS) and Grey Relation Analysis (GRA). Finally, the results so obtained from traditional, fuzzy and grey approach are compared.

After knowing the behavior of system both in qualitative and quantitative terms, the management is highly concerned with reliable operation of the process / production systems. Thus, it becomes customary to plan and adapt a suitable maintenance strategy which ensures the reliable and trouble free functioning of the system. To this effect, a framework based on Fuzzy

Linguistic Methodology (FLM) is developed to assess and identify the effectiveness and efficiency of various maintenance strategies. As a case, three input parameters i.e. historical data [I_1], present data [I_2], and competence of data [I_3] related to failures of a component (gears in paper machines) has been taken to judge the effectiveness of nature of maintenance strategies followed in the mill. These parameters are represented as members of fuzzy set, combined by matching them against (If-Then) rules in rule base, evaluated in fuzzy inference system and then defuzzified to assess the capability or effectiveness of maintenance strategy. The various maintenance strategies considered were Frequency Based or Breakdown Maintenance (BDM), Preventive Maintenance (PM), Total Productive Maintenance (TPM), Condition Based Maintenance (CBM), and Reliability Centered Maintenance (RCM). From the results, it is observed that aggressive (TPM) and proactive (CBM) maintenance strategy gives high FIS output (0.859) and high performance index score (0.315) as compared to traditional, reactive (BDM) maintenance strategy.

As evident from FLM results that TPM as a maintenance strategy is more pragmatic in nature because it provides a company wide approach which includes plant, equipment, and asset care along with active participation of employees. Thus, a detailed and structured framework passing through four phases (preparation, introduction, introduction-execution and establishment) has been implemented in the cell with the help of Autonomous Maintenance (AM) and Focused Improvement (FI) teams. Its application has shown considerable improvement in various performance indices such as skill upgrading, increase in mean time between failure, reducing defect rate, rework percentage and maintenance versus operation costs. In order to make repair /replacement decisions for paper machine components (wire mat and vacuum pumps) a framework discussing the application of Non-Homogeneous Poisson Point Process (NHPPP) models to model, analyse the failure /repair data has also been purposed in the study. The model not only helps in forecasting future failures but also helps in optimizing the maintenance decisions (repair or replacements) based on cost dimensions.

Lastly, to take care of QRM aspects of system collectively, the resource allocation model based upon multistage dynamic programming is developed to optimize the maintenance and manpower cost decisions with respect to various interrelated sub-systems in a paper mill.

ORGANIZATION OF THESIS

The research reported in this thesis conceptualizes a framework to deal with QRM issues of production systems. In brief the work is organized as follows:

Chapter1: The basic concepts, historic developments and uncertain issues related to quality, reliability and maintainability aspects of production systems have been included in this chapter.

Chapter2: This chapter provides the holistic coverage of literature studies conducted by various researchers/practioneners/academicians in the areas of quality, reliability and maintainability in the last four decades and available research gaps, identified after critical review of literature.

Chapter 3: This chapter summarizes the major research issues and discusses the important tools and techniques (qualitative and quantitative) used in conjunction with the fuzzy methodology for developing a unified and structured framework to analyze QRM aspects.

Chapter 4: Evaluation aspects of the system performance have been detailed in this chapter. A practical system of paper mill is considered. The system details /configuration are discussed in detail and with the help of Root Cause Analysis (RCA), qualitative analysis of all the subsystems in the paper mill is carried out. In order to find out the potential failure causes, their effect on system performance, FMEA of each subsystem is carried out. The uncertainties related with respect to traditional FMEA are modeled with the help of Fuzzy Decision Making System (FDMS). The section–II of the chapter presents quantitative analysis of the system. The Petri net model for each subsystem is developed and the information obtained from various sources is used to build a knowledge base, which is used to derive fuzzy number representation for failure and repair times associated with each component of the subsystem.

Chapter 5: In this chapter Fuzzy Linguistic Methodology (FLM) is used to select suitable maintenance strategy in the mill. Based on FLM results, TPM as a maintenance strategy has been implemented and both tangible and intangible benefits were summarized. The findings indicate that TPM implementation leads to increase in efficiency and effectiveness of manufacturing systems, measured in terms of Overall equipment effectiveness (OEE) index. In last, NHPPP models have been used to optimize maintenance decisions (repair or replacements) for pumps and wire mat (essential components of paper machine) based on cost dimensions.

Chapter 6: To deal with Quality aspects in QRM, the chapter provides a holistic framework (using the principles of fuzzy methodology) to implement and sustain a Quality Cost Accounting System (QCAS) in the paper mill. The result (s) of successful application of QCAS in the mill is evident from the analysis of data, which showed a progressive and significant change in quality costs. In the second part of chapter a framework to implement Quality Costing System (QCS) based on Process Cost Modeling (PCM) (after prioritizing the processes) has been discussed.

Chapter 7: To optimize the maintenance and manpower cost decisions with respect to the production systems, a resource allocation model using multistage dynamic programming is developed. Treating the problem as multistage decision making the complete system of the paper mill has been modeled as an eight stage system in series operating under constraints such as availability of maintenance resources, manpower etc.

Chapter 8: The chapter contains the summary of research issues addressed in the study. Major contributions, key findings and managerial implications of the research have been highlighted. Finally, the chapter concludes with the limitations and scope for future extensions of the work.

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SYMBOLS

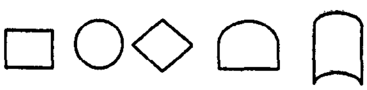
λ, τ	Respective failure rate and repair time
$\lambda_{(\alpha)}$, $\tau_{(\alpha)}$	Intervals for fuzzy failure rate and repair time
λ_{ij}, τ_{ij}	Fuzzy failure and repair time of component 'i' with j =1, 2, 3 being lower, mean and upper bounds respectively.
O_f	Probability of failure occurrence
O_d	likelihood of non-detection
S	Severity of failure
β_f	Weighting coefficient for occurrence of failure
β_s	Weighting coefficient for severity of failure
β_d	Weighting coefficient for non detection of failure
γ_f	Grey relation coefficient for occurrence of failure
γ_s	Grey relation coefficient for severity of failure
γ_d	Grey relation coefficient for non detection of failure
C_j	Resource allocated to the activity *j*
ε	State function (Total resource allocation)
ε_0	Optimal resource allocation
λ	Lagrange's multiplier [Budgeting coefficient]
R_J	Reliability of successful operation
C_s	Cost of sales
F_1	Coefficient for component cost

F_2	Coefficient of manpower cost
U	Statistic used in the Laplace test
V	Statistic (to test whether the ROCOF is constant)
ρ_t	Failure rate (ROCOF)
α_0, α_1	Parameters of NHPP model $\rho_1(t)$
λ, β	Parameters of NHPPP model $\rho_2(t)$

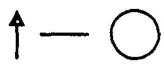
ACRONYMS

CMMS	Computerized Maintenance Management System
ENOF	Expected Numbers of Failures
FIS	Fuzzy Inference system
FDMS	Fuzzy Decision-Making System
FRPN	Fuzzy Risk Priority Number
FMEA	Failure Mode and Effect Analysis
MTTR	Mean Time to Repair
MTBF	Mean Time between Failures
OEE	Overall Equipment Effectiveness
ROCOF	Rate of Occurrence of Failures
FLM	Fuzzy Linguistic Modeling
PCM	Process Cost Modeling
TFN	Triangular Fuzzy Number
QCAS	Quality Cost Accounting System

SYMBOLS



Logic gate Symbols : Top event, Basic event, incomplete event, AND, OR gate respectively



In Petri net model : Arrow, transition, place respectively.

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Chapter 1

INTRODUCTION

1.1 INTRODUCTION

The growing complexity of technological systems as well as rapidly increasing Operation and Maintenance (O&M) costs incurred due to loss of operation as a consequence of sudden or sporadic failures have brought to the forefront the aspects of quality, reliability, availability, maintainability and safety associated with the production / manufacturing systems. The expectation today is that complex equipment and systems should not only be free from defects and systematic failures but also perform the required function for a stated time interval and should have a fail-safe behavior in case of critical or catastrophic failures. But failure is nearly an unavoidable phenomenon with mechanical systems/components. One can observe various kinds of failures in past under various circumstances such as nuclear explosions (Chernobyl nuclear disaster, 1986); Industrial plant (oil pipeline at Jesse Nigeria, 1998); aero plane crashes, and electrical network shutdowns.etc which may be due to human error, poor maintenance, inadequate testing / inspection.

The recent advances in technology have made the job of reliability/system analyst(s) more challenging as they have to study, characterize, measure and analyze the behavior of system using various qualititative and quantitative techniques (Cai 1996, Modarres and Kaminsky 1999, Adamyan and David 2002, 2004). As such, the reliability of a system is determined by the constituent sub-systems (SS_1.....SS_n) and reliability of each subsystem is, in turn, determined by the associated components and their possible failure modes. In a hierarchical structure (as depicted in Figure 1.1), it is usually important that the reliability or system analyst should make use of the information produced at lower level i.e. failure mode. There is, therefore a need to develop a structured framework to model, analyze, and predict the system failure behavior in a more realistic manner, which should take care of both qualitative and quantitative information related to system performance. The contemporaneous adoption of the various techniques for failure analysis will help the system reliability engineers/managers/practioneners to understand the uncertain failure behavior of component(s) in the system more realistically and also to plan/adapt suitable preventive measures to improve Quality, Reliability and Maintainability (QRM) aspects related to system performance.

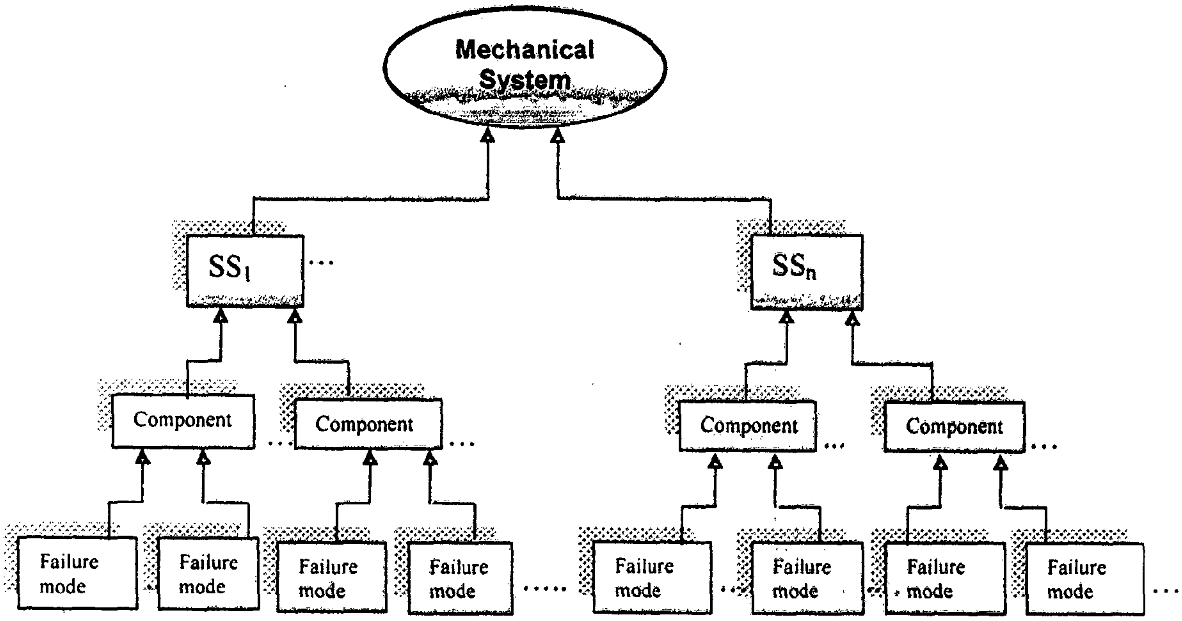

Figure 1.1 Hierarchical Structure of System [SS_1: Subsystem-1]

1.2 BASIC CONCEPTS

1.2.1 Quality

Various management practices such as *Total Quality Management (TQM), Business Process Reengineering (BPR)* etc. are becoming popular among the business houses to promote their products and processes (Carpinetti *et al.*, 2003, Najmi 2005). But among all of them, produc 'quality' is a buzzword. Besides the price and the punctuality of supplies, the quality becomes th governing factor, which determines the degree of the customer's satisfaction, thereby ensuring th producer's i.e. organization's success. Recognizing quality as an important strategic dimension an a key competitive weapon, most of the organizations respond to customer's quality demands b implementing quality management programs as a way to increase customer satisfaction. Juran an Gryna (1993) defined quality as 'fitness for use', whereas Crosby (1979) defined it a 'conformance to requirements'. According to Deming (1986) quality is uniformity with respect to correct target. Though quality costs is generally seen by many writers as a means used b companies to justify quality initiatives undertaken by them. Quality costing as a qualit management technique has been around for the last five decades, since then numerous approache i.e. (i) *Structured, and (ii) **Semi structured approaches have been undertaken by the researcher in variety of areas such as manufacturing, construction, building, and highway engineering.

*[(a) PAF Approach (BS.6143: Part 2 [1990]), (b) Questionnaire (c) Process Cost Modeling [B 6143: Part 1 (1992)].

** [(a) Departmental interviews (b) Problem Solving].

Juran has suggested that the cost of quality can be understood in terms of the economics of th end-product quality or in terms of the economics of the conformance quality. There is a direc correlation between quality and profitability i.e. higher quality results in lower costs, an profitability therefore increases. Feigenbaum (1956) categorized quality costs into (i) Preventio (P), (ii) Appraisal (A), and (iii) Failure (F), described in brief in the following paragraphs.

Prevention costs

Prevention activities are carried out to pinpoint the causes of problems at the first sight and eliminate them at the source. The costs associated with prevention costs are concerned with the enterprise's activity directed towards achieving the adequate quality level by creating and sustaining efficient quality management system. Examples of such costs include design reviews, education, training, supplier selection, capability reviews, and process improvement projects. The main aim of prevention costs is to improve product quality, without considerable increase in quality control costs.

Appraisal costs

Appraisal costs include all costs associated with measuring, evaluating, or auditing products to determine whether they conform to their requirements. Requirements include specifications from customers, as well as from engineering people for information pertaining to procedures and process design. For instance, cost incurred on conducting inspections and examinations of the quality of raw materials, semi-manufactured products and final products, material reviews, and calibration of measuring / testing equipment. The main aim is to measure the level of deviation and eliminate the errors. The most important characteristic of appraisal costs is that they are associated with managing the outcome, whereas prevention costs are associated with managing the intent.

Failure costs

These are classified as internal and external failure costs. Internal failure costs are associated with product failures, with in an enterprise, which are found before the product is shipped to the customer. These costs mainly results when products fail to meet the quality requirements in the pre-production / production stages such as reprocessing, rework, retest and recontrol, scrap associated with materials, labour, and overheads engaged in production work

External failure costs are the costs that occur when a non-conforming product reaches the customer i.e. after delivery such as those associated with receipt, handling, repair, and replacement of non-conforming products. Warranty claims and returns, product recall costs, allowances and liability costs due to customer complaints are included in external failure costs. External failures can include loss of future business through customer dissatisfaction, lost sales and loss in goodwill. According to Hays, (1983), the failure costs accounts for 70-85 % of the Cost of Quality (COQ) in most organizations. These can be eliminated with little investment in prevention and appraisal costs. To achieve reduction in failure costs, the Pareto logic (80-20 rule) can be utilized. According to this rule, only about 20% of the failure incidents accounts for approximately 80% of the failure cost. The rule can be used to select the major non-conformance costs.

1.2.2 Reliability

Reliability techniques have been applied in three main areas in process industry (i) Production availability studies (RAM analysis), (ii) Safety (risk analysis), and (iii) Maintenance (criticality analysis, life cycle cost). Much effort has been made by various authors/researchers tc compile and analyze reliability data for generic use. Reliability is defined as a measure of *the probability for failure-free operation* during a given interval, i.e., measure of success for a failure free operation. The reliability of a component is calculated as

$$R(t) = e^{-\lambda t} \qquad (1.1)$$

Where, 'λ' is the constant failure rate of the component [h^{-1}] and 't' is the operational time.

In reliability analysis of engineering systems it is often assumed that the hazard rate of the systems follow a shape of bath-tub curve. The hazard rate versus time curve (bath-tub curve) is shown in Figure 1.2. It has three distinct regions (i) Burn-in also called 'debugging' or 'Infant mortality region', (ii) Useful life period, and (iii) Wear out period. Table 1.1 summarizes the distinguished features of the bath-tub curve.

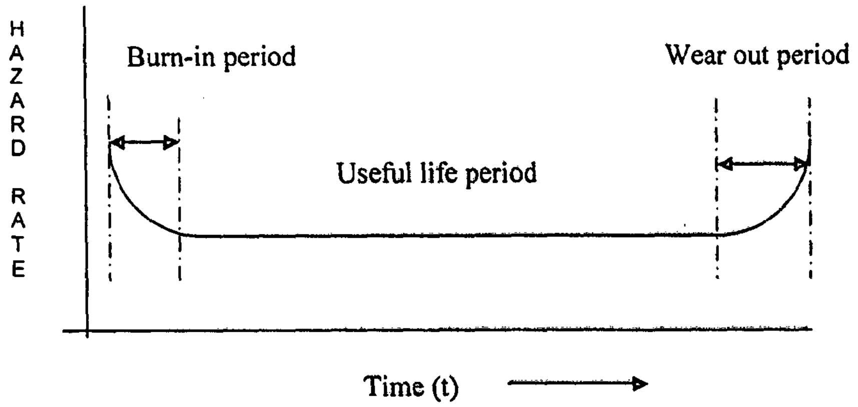

Figure 1.2 Bath-tub Curve

Table 1.1 Features of the Bathtub Curve

Period	**Characterized by**	**Caused by**	**Reduced by**
Burn–in	Decreasing Failure Rate (DFR)	Manufacturing defects, cracks, incorrect installation or setup, mishandling defective parts, contamination, and poor workmanship	Burn-in testing ,screening ,quality control and acceptance sampling
Useful life	Constant Failure Rate (CFR)	Environment, random loads, human error	Redundancy, excess strength
Wear out	Increasing Failure Rate (IFR)	Fatigue, corrosion, aging, friction and cyclic loading	Derating, preventive maintenance, parts replacement

1.2.3 Availability

In an industrial system, high plant availability plays an important role in the direction o industrial growth as the profit is directly related with the production volume which depends upoı the plant availability. To achieve high system availability, proper maintenance management systen supported by adequate resources such as manpower, spares and machines etc. is required. Thus, i is a cyclic chain, better the maintenance facilities, better the system availability, higher th production rate and hence, higher the profit. Mathematically the term 'Availability' is used t indicate the probability of a system or equipment being in operating condition at any time (t). I includes both the aspects reliability and maintainability. The various ways in which the availabilit can be defined are as follows:

1. Instantaneous availability, A (t), is the probability that the system is operational at any arbitrar time t. It is given by the expected up-time of the system.

$$A(t) = E[Z(t)] \tag{1.2}$$

Where: Z (t) is an indicator variable,

Z (t) = 0; if the system is in operating state at time t, and

Z (t) = 1; if the system is in failed state at time t

2. Average uptime availability, A (T), is the proportion of time during which the system i available for use in a specified interval (0, T).

$$A(T) = (1/T) \int_0^T A(t)\, dt \tag{1.3}$$

3. Steady state availability A (∞), is the probability that the system is operational for infinite tim interval.

$$A(\infty) = \lim_{T \to \infty} A(T) = \lim_{T \to \infty} (1/T) \int_0^T A(t)\, dt \tag{1.4}$$

4. Inherent availability, A_i, is the proportion of time during which the system is operational, by considering only corrective maintenance downtime and excluding ready time, preventive maintenance down time, logistics (supply) down time and waiting down time etc.

$$A_i = MTBF / MTBF + MTTR \quad (1.5)$$

Where: MTBF = Mean Time between Failure, MTTR = Mean Time to Repair

1.2.4 Maintainability

Maintainability deals with duration of maintenance outages or how long it takes to complete the (ease and speed) maintenance actions. Maintainability characteristics are usually determined by equipment design, which then sets maintenance procedures and determine the length of repair times. A key maintainability figure of merit is the Mean Time to Repair (MTTR) and a limit for the maximum repair time. Qualitatively, it refers to the ease with which hardware or software is restored to a functioning state. Quantitatively, it has probabilities and is measured based on the total down time for maintenance including time for diagnosis, trouble shooting, tear-down, removal/replacement, active repair time, verification testing that the repair is adequate, delays for logistic movements, and administrative maintenance delays. It is often expressed as

$$M(t) = 1 - \exp(-t / MTTR) \quad (1.6)$$

1.3 HISTORIC DEVELOPMENT OF QRM ISSUES

Numerous methods and procedures of quality assurance and reliability and maintenance engineering have been developed extensively over the last six decades. Table 1.2 shows the details regarding development of QRM issues (Birloni 2001, Connor 2002, Waeyenbergh and Pintelon 2002, 2004, Madu 2005, Pintelon 2006).

Table 1.2 Historic Development (QRM issues)

Before1940	Quality attributes and characteristics have been defined. In process and final tests were carried out, usually in the department with in the production area. The concept of *quality of manufacture* is introduced. Regarding maintenance (period up to World War II), the industry was not mechanized and equipment were simple. Hence, the maintenance task was easy. The concept of *"Fix it when breaks"* emerged.
1940-1950	Defects and failures were systematically recorded and analyzed. Corrective actions were carried out. The technique of statistical quality control developed. It is recognized that quality and reliability must be built into the product. The *quality of design* becomes important.
1950-1960	Quality assurance is recognized as a means for developing and manufacturing an item with a specified quality level. Design reviews and systematic analysis of failures were performed in the area of reliability. Large-scale industrialization in Europe and America lead to increased mechanization as a result of which complex machines were evolved. Machine downtime became significant aspect. Hence, the concept of Preventive Maintenance (PM) was introduced. i.e. *"I operate –You Fix"*. In 1960s, this consisted of mainly equipment overhauls at regular periodic intervals of time.
1960-1970	Difficulties with respect to reproducibility and change control, as well as interfacing problems during integration phase are dealt with. Reliability engineering is recognized as a means of developing and manufacturing an item with specified reliability. Reliability estimation and demonstration tests were developed. Instead of a reliability figure *Mean Time Between Failures* (MTBF), the contractual requirement for reliability assurance program has been developed. Maintainability, Availability, and Logical support became important.
1970-1980	Due to increasing complexity and cost for maintenance of equipment and systems, the aspects of man-machine interface and lifecycle cost become important. Terms like *product assurance, cost effectiveness and systems engineering* were introduced. Since the mid-1970s, the changes in industry

	gathered momentum. Due to automation and mechanization, reliability and availability became key issues. Conventional preventive maintenance methodology fails to fulfill the challenges put forward by modern, complex manufacturing systems. So, the need to develop decision support systems, new maintenance management techniques was felt.
1980-1990	The aspects of testability gains in significance. Test and screening strategies were developed to reduce testing cost and warranty services. Because of rapid progress in micro electronics, greater possibilities in microelectronic areas were discovered. The concept of software quality is introduced. To improve the asset performance at reduced cost, strategies like *Design out Maintenance (DOM), Total Productive Maintenance (TPM), Condition based Maintenance (CBM), and Reliability Centered Maintenance (RCM)* evolved with passage of time.
1990-till date	Due to large scale automation and mechanization in mid 90s the reliability and availability became key issues. The necessity to shorten the product development time leads to the concept of *Concurrent Engineering (CE), Business Process Reengineering* (BPR). During this era, Global competition characterized by both technology push and market pull forced the organizations to compete themselves on various platforms such as faster delivery, price tags, state of art-technology and higher quality dimensions. Various innovative techniques and management practices such as *Total Quality Management (TQM), Business Process Reengineering (BPR), Supply Chain Management (SCM), Customer Relationship Management (CRM), and Agile/Lean Manufacturing etc.* became popular among the industrial houses to promote their product(s) and processes. Recently with the recognition of maintenance as a profit generator the concept of outsourcing (external partnerships) and information processing through Information and Communication Technology (ICT) means has emerged. The evolution of newer maintenance management strategies such as *Early Equipment Management (EEM), Use Based Maintenance (UBM), Business Centered Maintenance (BCM), and Detective Based Maintenance (DBM) etc.* requires greater commitments in terms of training, resources, and integration.

1.4 UNCERTAINTY IN QRM ASPECTS

With respect to the causes, uncertainties related to QRM aspects can be grouped in two ways (i) Aleatory and (ii) Epistemic uncertainties. Aleatory uncertainty is caused by random variations in samples and is also known as *'stochastic', type 'A' or 'irreducible' uncertainty.* Sources of such uncertainty can commonly be singled out from other contributors to uncertainty by their representation as randomly distributed quantities that can take on values in an established or known range, but for which the exact value will vary by chance from unit to unit or from time to time. For treating aleatory uncertainty most commonly used mathematical representation is a probability distribution. Propagation of these distributions through a modeling and simulation process is well developed and is described by various researchers (Parry et al., 1996, Cizelj *et al.*, 2001, Oberkam *et al.*, 2004).

Epistemic uncertainty is caused by lack of knowledge about a system or phenomenon and is also known as *'subjective', type 'B' or 'reducible' uncertainty.* The key feature that this definition stresses is that the fundamental cause is incomplete information or incomplete knowledge of some characteristic of the system or the environment. As a result, an increase in knowledge or information can lead to a reduction in the predicted uncertainty of the response of the system, all things being equal. Examples of sources of epistemic uncertainty are: when there is little or no experimental data for a fixed (but unknown) physical parameter; limited understanding of complex physical processes; and the occurrence of fault sequences or environmental conditions not identified for inclusion in the analysis of the system. As opposed to aleatory uncertainty, the mathematical representation of epistemic uncertainty has proven to be much more of a challenge. In fact the prominent issue in uncertainty analysis related to QRM aspects of systems is the *representation, aggregation, and propagation* of epistemic uncertainty, as well as mixtures of epistemic and aleatory uncertainty. To this effect, both probabilistic and non-probabilistic methods are used in the study to treat the element of uncertainty in associated with QRM aspects. Based on mature scientific theory, the probabilistic methods deals with uncertainty which is essentially random in nature but of an ordered kind. For instance, Bayesian methodology, appeared in late 1970s is widely used in probabilistic risk assessment, an exercise aimed at estimating the probability and consequences of accidents for the facility / process under study. In the Bayesian framework, the analyst's uncertainties in the parameters due to lack of knowledge are expressed via probability distributions. The non-probabilistic / inexact reasoning methods (i) Rule-based Systems, (ii) Knowledge-based Systems, (iii) Neural Networks, (iv) Fuzzy Expert Systems, (v) Object-Oriented systems, (vi) Case-based reasoning, on the other hand, study problems which are not probabilistic in nature but cause uncertainty due to imprecision associated with the complexity of the systems as well as vagueness of human judgment. For instance, Sergaki and Kalaitzakis (2002), in their work developed a fuzzy relational database model for manipulating the data required for criticality ranking of components in thermal powers plants. Liu *et al.* (2005) in their work proposed a framework for modeling, analyzing and synthesing safety aspects of engineering systems on the basis of rule-based inference methodology using evidential reasoning.

1.5 PROBLEM DEFINITION

Based on the review of literature studies it was felt that in reliability and maintainability studies a small number of researchers have seriously addressed the issue of handling uncertainties associated with QRM data (Fonseca and Knapp 2001, Sergaki and Kalaitzakis 2002). The traditional analytical techniques (mathematical & statistical models), needs large amount of data to analyze various situations. Moreover it is difficult to obtain the data, because of numerous constraints such as rare events of occurrence of failure of components, human errors and economic considerations. Even if data is available, it is often inaccurate and thus, subjected to uncertainty.

Further, age, adverse operating conditions and the vagaries of manufacturing /production processes affects each part/unit/ of system differently. However, it may be difficult or even impossible to establish rational database to accommodate all operating and environmental conditions. Though, virtually all the commercially available Computerized Maintenance Management Software (CMMS) packages offer data collection facilities but lack any decision analysis support for management (Ebeling 2000, Connor 2001, Labib 2003). However, it may be difficult or even impossible to establish rational database to accommodate all operating and environmental conditions. In the absence of accurate data, rough (approximate) estimates of probabilities can be worked out. To this effect both probabilistic and non-probabilistic methods are used to treat the element of uncertainty. The non-probabilistic methods are still developing and often use fuzzy sets, possibility theory and belief functions (Sergaki and Kalaitzakis 2002, Majumder 2004). Owing to its sound logic, effectiveness in quantifying the vagueness and imprecision in human judgment, the present study provides a qualitative and quantitative framework which makes use of fuzzy approach in conjunction with other tools and techniques to model and analyze the QRM aspects related to production systems.

Recently fuzzy methodology has been widely applied in fault diagnosis (Ogaji *et al.*, 2005), structural reliability (*Bing et al.*, 2000, Savoia, 2002), human reliability (Konstandinidou *et al.*, 2005), safety and risk engineering (Cai 1996, Guimarães and Lapa 2005), and quality (Noci and Toletti 2000, Chan *et al.*, 2005). In the words of Cai, 1996 "*Undoubtedly fuzzy methodology in system failure engineering is noticeable and growing area and is still lying in speculative research period and is premature. From a speculative research period to an engineering practice period lo of work has to be done*. As such the use of fuzzy methodology lacks on-line engineering research Also, Elasyed (2000) stressed on the need for development of new and efficient methods for quality engineering, reliability estimation and prediction of systems. Hence, the present work aims at analysis, design and optimization of quality, reliability and maintainability issues with respect to production systems.

1.6 RESEARCH ISSUES

The major issues addressed in the research work are

- To understand and analyze production systems, subsequent sub-systems and their functions
- To conduct Failure Mode and Effect Analysis (FMEA) and to develop Fuzzy Decision Support System (FDSS) for failure analysis of the system
- To perform qualitative analysis of system using Root Cause Analysis (RCA), Fault Tree (FT) and its equivalent Petrinet (PN) modeling and quantitative analysis of system using Fuzzy Methodology (FM) to determine system failure and repair rates
- Determination of system parameters such as availability, expected number of failures, mean time between failures and mean time to repair, necessary for maintenance planning of system
- To facilitate the maintenance managers/decision makers to select the suitable maintenance strategy for the components /parts associated with the system
- To examine the need to develop, practice and implement such maintenance practices, which not only reduce sudden sporadic failures in semi-automated cells but also reduce both operation and maintenance costs and to optimize maintenance decisions (repair or replacements) based on cost dimensions
- To develop a structured approach to implement, sustain and manage a quality-costing program in a process industry and provide a framework to implement Quality Costing System (QCS) based on Process Cost Modeling (PCM)
- To develop resource allocation model in order to optimize maintenance and manpower decisions taking care of QRM aspects of system

2.1 INTRODUCTION

Various innovative techniques and management practices such as Total Preventive Maintenance (TPM), Total Quality Management (TQM), Business Process Reengineering (BPR), Materials Requirement Planning (MRP), Enterprise Resource Planning (ERP) and Just in Time (JIT), Supply Chain management (SCM) etc. are becoming popular among the business houses (Goyal and Deshmukh 1998, Ljungberg 1998, Jonsson and Lesshammar 1999, Nikolopoulos *et al.* 2003, Leem and Kim 2004, Rodney and Galloway 2005, Agbasi *et al.* 2004 and Chou and Hsu 2005). With increased competition, demands on products with higher quality, faster delivery time had forced the managers to convert conventional manufacturing practices to computer controlled manufacturing practices such as flexible manufacturing systems and computer integrated manufacturing systems. In past various authors studied and worked separately upon quality, reliability and maintainability aspects related to production/process systems in industries. Following paragraphs were excerpted from the literature which deals with different aspects of quality, reliability analysis, and maintainability design and optimization of complex industrial systems.

2.1.1 Quality aspects

Recognizing quality as an important strategic dimension and a key competitive weapon most of the organizations respond to customers quality demands by implementing quality management programs as a way to increase customer satisfaction. Despite increased awareness of importance and potential benefits of quality programs, managers often find it difficult to assess quality improvement benefits from them (Czuchry 1999, Noci and Toletti 2000, Carpinetti *et al.* 2003, Babu *et al.*,2005).

Quality costs are generally seen by many researchers as a means used by companies to justify quality initiatives undertaken by them. But establishing a Quality Costing System (QCS) is not a straightforward and easy task. Numerous studies have been undertaken by various authors in variety of areas such as manufacturing, construction, building, and highway engineering. Carr and Ponoemon (1994), Willis and Willis (1996), Zhao (2000), and Carpinetti et al. (2003) concluded in their studies that with increase in appraisal and prevention costs there is considerable reduction in failure cost, as a result of which the productivity of processes improves and quality level increases. Quality through quality cost reduction initiatives such as defect reduction, waste elimination, rework reduction and machine idle time reduction leads to productivity improvement (Harrington, 1999). Israeli and Fisher (1995) concluded that quality costs helps as a means .to reduce manufacturing costs by identifying and eliminating waste and non-value adding activities.

Measuring and reporting the Cost of Quality (COQ) is the first step in a quality management program. Bohan and Horney (1991), Ravitz (1991), Carr (1992), concluded that COQ systems receive considerable attention in service industries and they are bound to increase in importance because COQ related activities consume as much as 25 percent or more of the resources used in companies. Also, the COQ information can be used to indicate major opportunities for corrective action and to provide incentives for quality improvement.

Carson (1986), Johnson and kliener (1993), concluded that quality costs helps as a means to reduce manufacturing costs by identifying and eliminating waste and non value adding activities. Bell *et al.* (1994) estimated that quality cost in the manufacturing industry lies between 5% to 25% percent of sales. Plunkett and Dale (1988), Ittner (1994, 1996), in their studies concluded that investments in prevention cost would definitely bring down both appraisal and failure costs.

Israeli and Fisher (1995) also highlighted that quality costs helps as a means to trim down manufacturing costs by reducing waste and non-value adding activities. Carr and Ponoemon (1994), Willis and Willis (1996), observed that with increase in appraisal and prevention costs there is considerable reduction in failure cost, as a result of which the productivity of processes improves and quality level increases. According to Harrington (1999), the improvement of quality through quality cost reduction initiatives such as defect reduction, waste elimination, rework reduction and machine idle time reduction leads to productivity improvement.

Gunasekaran *et al.* (1999) discussed the application of Activity Based Costing (ABC) system in some companies from Belgium and Dutch. A conceptual model has been developed to provide a framework for the decision concerning the implementation of ABC system. They concluded that ABC systems trace more exactly the real costs to the products than any other volume-based cost systems. They recommended (i) change in the management structure while implementing an ABC system (ii) Change in a business and operations strategy (iii) application of ABC for re-engineering business processes. Lai and Cheng (2003) explored the quality initiatives of various industries and examined the links between quality management implementation and quality outcomes. They illustrated a case from a company in Hong Kong.

Supervillie and Gupta, (2001) reported that the importance of quality costing cannot be ignored by an organization. A survey conducted by AMA (American Management Association) revealed that three quarters of managers pointed towards the quality of products and services, as key strategic dimensions to be successful in business. Many empirical studies demonstrated that most of the quality costing methods such as (i) Structured [(a) PAF checklist (BS.6143: Part 2, 1992) (b) ABC (activity-based costing BS.6143: Part 1,1990) (c) PCM (Process Cost Modeling)], and (ii) Non-structured [(a) departmental costing (b) questionnaire approach (c) problem solving approach] provides ways for registering and analyzing the quality cost information but fails to improve the small firms competitiveness and profitability (Porter and Rayner 1992, Czuchry *et al.* 1999, Noci and Toletti 2000, Dale and Wan 2002). The reasons may be

- lack of an operating tool to support managers in the identification of quality-based priorities
- general problems such as (a) lack of information and accountability (b) blame game (c) lack of interest (d) lack of company-wide culture.

2.1.2 Reliability Aspects

Reliability is a popular concept that has been celebrated for years as a commendable attribute of a person or an artifact. The Oxford English Dictionary defines it as 'the quality of being reliable, that may be relied upon; in which reliance or confidence may be put; trustworthy, safe, sure'. From its modest beginning in 1816, the word reliability was first coined by Samuel Coleridge.

Today reliability grew into an omnipresent attribute with qualitative and quantitative connotations- that pervades every aspect of our present day technologically intensive world. For the last few decades reliability analysis has been established as a useful tool for risk analysis, production availability studies and design of systems. For reliability analysis variety of methods exists in literature. These include *Reliability Block Diagrams (RBDs), Monte Carlo Simulation (MCS), Markov Modeling (MV), Failure Mode and Effect Analysis (FMEA), Fault Tree Analysis (FTA) and Petrinets (PN)* (Misra and Weber 1989, Singer 1990, Bradley and Dawson 1998, Modarres and Kaminsky 1999, Bing *et al.*, 2000, O'Connor 2001, Gandhi *et al.*, 2003, Parveen *et al.*, 2003, Bowles 2003, Adamyan and David 2004, Bertolini *et al.*, 2006, Bunea *et al.*, Jose *et al.*). Both Petrinets and fault tree methods are used for Software reliability analysis (Kumar and aggarwal, 1993); Analysis of coherent fault trees (Hauptmanns, 2004), and Fault diagnosis (Papadopoulos, 2003; Yang *et al.* 2004).

Exclusively in the field of reliability engineering the application of Petrinets has been presented for Reliability evaluation (Adamyan and David, 2002, 2004); Markov analysis (German, 2000, Aneziris and Papazoglou 2004, Schoenig *et al.* 2006); Stochastic modeling (Ciardo *et al.* 1994, Sahner and Trivedi 1996) respectively), and Safety analysis (Vernez *et al.* 2003).

Failure Mode and Effect Analysis (FMEA) was developed at Grumman Aircraft Corporation in the 1950 and 60s (Coutinho, 1964) and was first applied to naval aircraft flight control systems at Grumman. Since then, it has been extensively used as a powerful technique for system safety and reliability analysis of products and processes in wide range of industries--particularly aerospace, nuclear, automotive and medical (Bowles and Pelaez 1995, Sankar and Prabhu 2001, Connor 2001, Eblieng 2001, Xu *et al.*, 2002, Bowles 2003, Seung and Kosuke 2003, Tellefsen 2005, Hosseini *et al.* 2006). Monte Carlo technique has been used by many authors to model the behavior of complex systems under realistic time-dependent operational conditions.

Much effort has been made by various authors to compile and analyze reliability data for generic use (Cochran *et al.*, 2000, Dai and Jia 2001, Hauptmanns 2004, Liberopoulos and Tsarouhas 2005). Following paragraphs were excerpted from the literature which deals with different aspects of reliability analysis, design and optimization of complex industrial systems.

Barlow and Poschan (1965) dealt with preventive and repair maintenance policies related to process industries. Buzacot (1970) examined the computation of reliability measures based on successive reduction of complex models and determination of intervals based on parallel and series sets referred to as minimal cut and path sets. He studied the effect of redundancy by making use of exponential distribution to model system failure and repair distribution.

Kim *et al.* (1972) suggested a technique for computing the reliability of complex systems and suggested a three phase approach in which at first phase all series parallel subsystems are reduced to non series parallel subsystems. At second stage all the possible paths are traced from source to sink and in third phase system reliability is calculated based on these paths. Henley and Gandhi (1975) developed a unified approach to obtain reliability parameters based on reliability block diagrams (RBDs) for process industries and thus provide a means to automate the task.

Cherry *et al.* (1978) performed reliability analysis of the system by calculating long run availability of plant assuming constant failure and repair time for each of the components. Arid (1980) used reliability engineering techniques in order to chalk out maintenance policies for the process plants. Ascher *et al.* 1984, 1992 in their work presented the application of Non-Homogeneous Poisson Point Process (NHPPP) models for analysis of repairable mechanical systems, which shows the tendency towards long-term reliability degradation (with repeated overhauls and replacements) of system component (s).

Wang and Pham (1996) developed optimal age-dependent preventive maintenance policies with imperfect maintenance for the repairable systems. Coetzee, (1997) discussed the role of NHPPP models in practical analysis of maintenance failure data. Calabria and Pulcini (2000), presented a detailed study on inference and test in modeling the failure and repair process of repairable mechanical components. They concluded that repairable mechanical systems shows the tendency towards long-term reliability degradation with an accompanying increase in the failure rate. Saldanha *et al.* (2001) discussed the application of NHPPP to analyze the reliability of service water pumps in a typical pressurized water reactor.

Dhillion (1981) described application of reliability engineering principles for carrying out stochastic analysis of parallel systems with common cause failures and critical human errors. Rooney *et al.* (1988) conducted a preliminary hazard analysis on actual fluid catalytic cracking units in chemical refineries using fault tree representations and suggested qualitative recommendations for improving availability. Kelly (1991) gave the important guidelines regarding analysis of maintenance planning and control in a large chemical refinery. Kumar and Pandey

(1993) analyzed reliability and availability of refining system in sugar industry and developed a maintenance planning system to help the maintenance managers in effective decision making related to resource allocation and maintenance activities.

McClure and Whittle (1992) in their work reviewed three petroleum refineries with reliability block diagrams (RBDs) to identify potential effects of single failures. Cafaro *et al.* (1986) explained the use of Markov chains in evaluating the reliability and availability of a system with time-dependent transition rates using analytical matrix-based methods.

Aghayeri and Telen (1996) reported the failure frequency of repairable redundant systems and proposed an optimum production and maintenance planning model for process industry. Parry (1996) discussed the issue of the characterization of uncertainty in a Probabilistic Risk Assessment (PRA) of a complex system; a nuclear power plant. Hibi (1997) suggested methods to estimate maintenance performance for complex systems. Aven and Kvaløy (2002) discussed some of the practical challenges of implementing Bayesian thinking and methods in risk analysis, emphasizing the introduction of probability models and parameters and associated uncertainty assessments with the help of a simple risk analysis case. They concluded that there is a need for a pragmatic view in order to 'successfully' apply the Bayesian approach, such that one can do the assignments of some of the probabilities without adopting the somewhat sophisticated procedure of specifying prior distributions of parameters.

Cochran (2000) *et al.* developed Generic markov models for availability estimation and failure characterization of reactor regeneration system in fluid catalytic cracking unit for one of the petroleum industry. It was concluded from the study that markov models possess the same modeling power as that Petri nets, and provide the same results as Petri nets. They do not require any statistical validation and are easy to implement. In addition, generic Markov models provide the individual probabilities of failure for components in different failure states which help in grouping components into classes.

Dai and Jia (2001) collected failure data of vertical machining center, analyzed it and based on the analysis provided ways to improve the reliability of machining centre. Goel *et al.* (2002) developed an optimization frame work by combining reliability and process synthesis challenges. A profit objective function, which takes into account the trade-off between initial capital investment and the annual operational costs by supporting appropriate estimation of revenues, investment cost, raw material and utilities cost was made. The effectiveness and usefulness of the proposed optimization framework is demonstrated for the synthesis of the hydrodealkylation process.

Adamyan and David (2002) stressed upon the assessment of reliability and safety of a manufacturing system with sequential failures. The reliability and safety of the system depend not only on all failed states of system components, but also on the sequence of occurrences of those failures. They presented a methodology to identify the failure sequences and assess the probability of their occurrence in a manufacturing system. The method employs Petrinet modeling and reachability trees. Further, Adamyan and David (2004) analyzed the capability of Petrinets to model the dynamics of system failure behavior. They combined the Petrinets with fault tree analysis to determine average rate of occurrence of failure of system.

Hauptmanns (2004) developed a system called SQUAFTA (Semi-Quantitative Fault Tree Analysis) based on describing the required input data for fault tree analysis by different classes characterized by probability or frequency ranges. The system provides characterization of the expected frequency of an undesired event in the analyzed plant in terms of qualifiers such as *"highly probable", "probable", "possible", "improbable" or "highly improbable.* Yuhua and Datao (2006) analyzed the failure of oil and gas transmission pipelines using fuzzy fault tree analysis.

They concluded that in conventional fault tree analysis, probabilities of the basic events were treated as precise values, which could not reflect real situation of system because of ambiguity and imprecision of some basic events but this disadvantage is overcomed with fuzzy set theory as it makes use of expert knowledge and expertise in more efficient manner.

Liberopoulos and Tsarouhas (2005) presented a statistical analysis of failure data of an automated pizza production line. The analysis includes identification of failures, computation of statistics of the failure data, and parameters of the theoretical distributions that best fit the data, and investigation of the existence of autocorrelations and cross correlations in the failure data. The analysis is meant to guide food product machinery manufacturers to improve the design and operation of the production lines. Schoenig *et al.* (2006) presented an aggregation method using markov graphs for the reliability analysis of hybrid systems .The method allows the designers to have an exact representation and better overview of various system states.

Marquez *et al.* (2005) in their work on reliability estimation of cogeneration plant concluded that when modeling the availability and reliability of complex modern engineering systems, analytic methods are difficult to be used. Compared to them simulation methods, such as the Monte Carlo technique, which allows modeling the behavior of complex systems under realistic time-dependent operational conditions, are more suitable. Zio *et al.* (2006) presented a Monte Carlo simulation model for the evaluation of the availability of a multi-state, multi-output offshore installation. They developed a stochastic model of the plant from the standpoint of its production availability of three different outcomes and had also taken into account the components' reliability parameters, process capacities and operational dependencies as well as the corrective and preventive maintenance policies.

2.1.3 Maintainability Aspects

In the past few years, manufacturing coupled with new methodologies (*JIT, CIM, SCM, RCM, TQM, BPR, and TPM*) has placed the need for maintenance effectiveness clearly on the radar screen. Numerous authors had studied and worked on maintainability aspects related to systems in industries (Deshpande and Modak, 2003; Eti *et al.* 2004, 2006, 2007; Bertolini and Maurizio, 2006 *Felix et al.* 2006; Garg and Deshmukh, 2006; Pinjala, 2006; Kiureghian *et al.* 2007; Aghezzaf *et al.*). Following paragraphs were excerpted from the literature which deals with aspects of maintainability design and optimization of complex industrial systems.

Dekker (1995) in his work introduced a framework for maintenance planning; providing an option to combine and prioritize maintenance activities. He analyzed single unit maintenance optimization model providing necessary input for the multi-item planning problems. Christer and Wang (1995) discussed the problem of how to select an appropriate time for the next inspection based on the status or condition of equipment. Boland and Neweihi (1995) compared expected cost of various repair and inspection strategies based on availability estimates in practical scenarios.

McKone and Weiss (1995) identified significant gaps between industry practice and academic research and emphasized upon the need to abridge these gaps. Canel (1997) discussed the need for development of information systems for successful operation of flexible manufacturing system so that the problems of idle time can be taken care of. Vanneste and Van Wassenhove (1995) placed recent developments in maintenance modeling in the context of information technology and decision support systems. They presented an integrated approach for maintenance management using problem analysis methods from industrial engineering and quality control. An industrial application is presented to clarify the integrated approach. He also analyzed a maintenance decision model and concluded that the decision to start preventive maintenance on a production unit not only depends on the condition of the unit but also on the content of its subsequent buffer. Kelly (1997) views maintenance strategy as the identification, resource allocation and execution of repair, replacement and inspection decisions. Saldanha *et al.* (2001) discussed the application of Non Homogeneous Poisson Point Processes (NHPPP) to analyze the reliability of service water pumps in a typical pressurized water reactor.

Abdul-Nour *et al.* (1998) described a methodology to select critical machines and to develop an optimum maintenance policy based on reliability data. Jonsson (1999) in his work discussed the maintenance/production interface and emphasized on the importance of integration for organizational design and strategic planning. Data was gathered from 293 Swedish maintenance managers in manufacturing firms and comparative analysis was carried out to differentiate various parameters i.e. maintenance visions, goals and plans and companywide integration of maintenance. They observed that integration and long-term planning of maintenance affect prevention, quality improvement and manufacturing capabilities. In his subsequent research, Jonsson (2000) clustered manufacturing companies into three configurations i.e. based on their emphases on preventive maintenance, hard maintenance integration and soft maintenance integration. The identified taxonomy showed that there was a variety of maintenance investment approaches and that each configuration could be profitable by itself. The analysis revealed that preventive and company-wide integrated maintenance were important for companies, with high breakdown consequences and stop costs. Bevilacqua and Braglia (2000) in their work used analytical hierarchy process to select suitable maintenance strategy. They considered each maintenance policy as a separate strategy.

Swanson (1999) analyzed the impact of Advanced Manufacturing Technologies (AMT) and Just-in-Time (JIT) production concepts on some of the maintenance strategy elements shown in Table 2.1. Swanson (2001) stressed upon the need of replacing fire-fighting strategies for maintenance with proactive strategies like preventive and predictive maintenance and aggressive strategies like Total Productive Maintenance (TPM) in order to achieve world-class performance. Their work reports the relationship between maintenance strategies and performance. Based on the responses of a survey of plant managers and maintenance managers, the analysis showed strong positive relationships between proactive and aggressive maintenance strategies and performance.

Table 2.1 Summary of Maintenance Strategy Decision Elements

Structural decision elements	
Maintenance capacity	Capacity in terms of work force, supervisory and management staff. Shift patterns of work force, temporary hiring of work force
Maintenance facilities	Tools, equipment, spares, workforce specialization (mechanics, electricians, etc.), location of workforce
Maintenance technology	Predictive maintenance, or condition monitoring technology, expert systems, maintenance technology (intelligent maintenance)
Vertical integration	In-house maintenance versus outsourcing and relationship with suppliers
Infrastructure decision elements	
Maintenance organization	Organization structure (centralized, decentralized, or mixed), responsibilities
Maintenance policy and concepts	Policies like corrective, preventive and maintenance. Concepts like Total Productive Maintenance (TPM), Reliability Centered Maintenance (RCM)
Maintenance planning and control systems	Maintenance activity planning, scheduling. Control of spares, costs, etc. Computerized Maintenance Management Systems (CMMS)
Human resources Recruitment policies.	Training and development of Workforce and staff. Culture and management style
Maintenance machine design support	Maintenance modifications, equipment design improvements, new equipment installations
Maintenance performance measurement and reward systems	Performance recognition, reporting and reward systems, Overall Equipment Effectiveness (OEE) and Balanced Score Card (BSC)

Marquez and Heguedas (2002) discussed the problem of selecting a suitable maintenance policy for repairable systems for a finite time period. They used a general continuous-time model known as Semi-Markov Decision Process (SMDP) to pattern the impact of maintenance strategies in a system and for a finite number of time periods. They concluded that these models are very flexible to represent a given system and on the other hand are also complex and therefore very difficult to handle when the number of the system states increases. Further, Marquez *etal.* (2006) developed a holistic framework for managing the maintenance function in an organization. The authors closely analyzed the strategic, tactical and operational aspects of maintenance and set up a structure to help to complete the tasks /functions within maintenance management. The structure is analyzed in depth, and characterized according to three main pillars namely, Information Technology (IT), Maintenance Engineering (ME), and Relationship Management (RM). These are used to characterize maintenance with an aim to enable an organization to develop various maintenance-related functions.

Waeyenbergh and Pintelon, (2002) described a framework to develop maintenance concept. The important feature of the framework is that it allows to incorporate all information available in the company, ranging from experience of maintenance workers to data captured by modern Information and Communication Technology (ICT) means. Further, Waeyenbergh and Pintelon (2004) presented case of successful implementation of a maintenance concept with the aid of a 7-step modular framework. The authors provided some information on how to use this framework which can prove helpful while making the decision regarding selection of the maintenance policy.

Tsang, (2002) identified four strategic dimensions of maintenance (1) service-delivery options, (2) organization and work structuring, (3) maintenance methodology, and (4) support systems. Cholasuke *et al.* (2004) studied the status of maintenance management in U.K manufacturing organizations based on a pilot survey. They categorized the maintenance effectiveness measures into the following nine areas.

(1) Policy deployment and organization

(2) Human resources management

(3) Financial aspects

(4) Continuous improvement

(5) Contracting out maintenance

(6) Maintenance approach

(7) Task planning and scheduling

(8) Information management and CMMS, and

(9) Spare parts management.

Madu, (2005) in his paper on "Strategic value of reliability and maintainability" emphasized the need of maintaining the equipment in good condition in order to eliminate the sudden and sporadic failures resulting in production loss. Various models such as RCA, FMEA and Pareto charts were discussed to uncover the problems related to system unreliability.

Bertolini and Bevilacqua (2006) in their work presented a Lexicographic Goal Programming (LGP) approach to define the best strategy for the maintenance of critical centrifugal pumps in an oil refinery. They developed a model for each pump failure mode. The model takes into account the maintenance policy defined in terms of (i) inspection or repair, and (ii) the manpower involved, linking them to efficiency-risk aspects (quantified using FMEA methodology) through the use of the FMEA parameters i.e. Occurrence (O), Severity (S) and Detectability (D), evaluated through an adequate application of the Analytic Hierarchy Process (AHP) technique. Pintelon and Pinjala, (2006) provided a framework to identify and evaluate the effectiveness of maintenance strategy. The framework developed by them helps in stimulating practicing managers to manage maintenance with a strategic thinking and mindset and also to visualize the capabilities of maintenance in enhancing the competitive advantage of a company.

Eti *et al.,* (2006, 2007) presented a methodology for the development of Preventive Maintenance (PM) using the modern approaches of FMEA, root-cause analysis, and fault-tree analysis. They concluded that application of PM leads to (i) cost reduction in maintenance and (ii) less overall energy expenditure.

2.2 GAPS AND CONCLUDING REMARKS

This section presents the gaps which are identified after critical review of literature on QRM aspects related to system performance.

Based on the studies on quality aspects related to quality costing practices, it is concluded that the incidence of quality costs is very broad as it falls through MDMIS (*Marketing –Design-Manufacturing-Inspection and Shipping*) cycle covering each department. Further, these difficulties are compounded by vagaries of manufacturing processes, system configurations, product varieties and company culture. Thus, an integrated, structured and systematic approach is required to plan, implement and sustain a quality-costing program, which could help the managers in assessment and setting up of quality-based priorities. To this effect Fuzzy Methodology (FM), *a Knowledge Based Approximate Reasoning Tool (KBART)* is used to treat the uncertain, imprecise and subjective information related to quality costs in more consistent and logical manner. The approach presented in the proposed work capitalizes on the studies discussed in literature, attempting to overcome the gaps / shortcomings by treating quality as a fuzzy notion.

From the studies on reliability aspects related to production systems, it is concluded that as such the reliability of system is affected by many factors such as design, manufacturing, installation, commissioning, operation and maintenance. Consequently it may be extremely difficult, if not impossible, to construct accurate and complete mathematical model for the system in order to assess the reliability because of inadequate knowledge about the basic failure events. This leads to problems of uncertainty in reliability assessment. To this effect, both probabilistic and non-probabilistic methods are used to treat the element of uncertainty in reliability analysis. Based on mature scientific theory, the probabilistic methods deals with uncertainty which is essentially random in nature but of an ordered kind. For instance, Bayesian methodology is widely used in probabilistic risk assessment, in which the analyst assesses uncertainties in the parameters due to lack of knowledge and express them via probability distributions. The non-probabilistic methods on the other hand study problems, which are not probabilistic but cause uncertainty due to imprecision associated with the complexity of the systems as well as vagueness of human judgment. These methods are still developing and often use fuzzy sets, possibility theory and belief functions. For instance, Sergaki and Kalaitzakis (2002) in their work developed a fuzzy relational database model for manipulating the data required for criticality ranking of components in thermal powers plants. Liu et al. (2005) in their work proposed a framework for modeling, analyzing and synthesing safety of engineering systems on the basis of rule based inference methodology using evidential reasoning. The framework has been applied to model safety aspects of an offshore and marine engineering system. These methods are still developing and often use fuzzy sets, possibility theory and belief functions (Sergaki and Kalaitzakis 2002, Majumder 2004). In the words of Cai (1996), "*Undoubtedly fuzzy methodology in system failure engineering is noticeable and growing area and is still lying in speculative research period and is premature*. From a speculative research period to an engineering practice period lot of work need to be done. Elasyed (2000) in his paper on "*Perspectives and challenges for research in quality and reliability engineering*" stressed on the need for development of new and efficient methods for reliability estimation and prediction of systems. In light of above discussed issues the study presents contemporary adoption of various techniques such as RCA, FTA, FMEA, PNs for reliability analysis of systems in a paper mill.

With increased competition, demands on products with higher quality, faster delivery time had forced the managers to adopt modern manufacturing practices such as flexible manufacturing systems and computer integrated manufacturing systems. The trends are apparent from concepts such as *CIM, CAD, CAM, JIT, and FMS.* Significant improvements in inventory levels, space requirements, lead and cycle times, scrap and yield rates and other quality measures have been reported from numerous studies as discussed under section 2.1.3. But the troubled free operation of systems had not been completely ruled out. For instance, in a highly integrated manufacturing system such as an FMS, machinery is integrated with complex computer network (CNC or DNC). Each machine in an FMS is a combination of many sub-assemblies, where each sub-assembly is itself complex and consists of many dissimilar interdependent components (mechanical, electronic, hydraulic, software). Owing to their complexity, the systems are vulnerable to various kinds of disturbances, the nature and number of failures and the time required to locate them. It is quite evident that the traditional maintenance activities based on fire-fighting approach (fix it, when breaks) called reactive maintenance will no longer satisfy the needs of modern manufacturing systems. Therefore, the development, adoption and practice of new maintenance strategies with a focus on how to increase the productive time by maximizing availability and how to avoid unplanned breakdowns, had become essential. The management of many companies (such as Procter and Gamble, Dupont, Ford and Eastman chemicals) have looked towards adoption of effective and efficient maintenance strategies such as Condition Based Maintenance (CBM); Total Preventive Maintenance (TPM) and Reliability Centered Maintenance (RCM) over the traditional firefighting reactive maintenance approaches (Tajiri and Gotoh 1992, Coetzzee 1999, Swanson 2001, Tsang 2002, Wayenbergh and Pintelon 2002).

With respect to maintainability aspects related to production systems, it is observed from the critical review of literature studies that currently, the majority of maintenance planning is based on mathematical optimization (Dekker 1996, Sherwin 2000, Sarker and Haque 2000, Crowder and Lawless, 2007). Many of the models have been developed by highly skilled mathematicians, but often without too much regard to the practical applicability of the models. Some of the models are based on assumptions that can never be fulfilled, and data collection is a tough task. Another problem is that the models are presented with a mathematical terminology that is very difficult to understand. One of the nestors within maintenance optimization has claimed that there is no other scientific discipline where the gap between theory and practice is bigger than for maintenance optimization (Castanier and Rausand, 2006). Added to its disadvantage various traditional mathematical & statistical models, needs large amount of data and even if data is available, it is often inaccurate and thus, subjected to uncertainties. Further, age, adverse operating conditions and the vagaries of manufacturing /production processes affects each part/unit of system differently and hence the maintenance policy.

Though, virtually all the commercially available computerized maintenance management system (CMMS) packages offer data collection facilities but lack any decision analysis support for management. According to study reported by Mobley (1990), 15-40% of total production cost is attributed to meet maintainability requirements (spares, labor, and material costs). As such many companies think maintenance as an inevitable source of cost. For these companies the maintenance operations have a corrective function which is to be normally executed in emergency/ fire-fighting conditions. This practice not only increases the total down time but also hampers production. In the present time due to automation and increased sophistication (put forward by *CAD, CAM, CIM, JIT and FMS)*, this form of maintenance intervention is no longer acceptable. The maintenance function has undergone a sea change, which has forced the maintenance managers to pay more attention towards adoption and practice of suitable maintenance strategies for each piece of equipment or system. It is particularly difficult for them to choose the best mix of maintenance polices as selection criteria involves several attributes such as investment required, failure cost, MTBF and MTTR, environmental and operating conditions related to the facilities. Many of these factors are not easy to evaluate because of uncertainties associated with estimation of the failure /repair characteristics of the components /units. Therefore the justification of any given maintenance strategy or practice within an organization must consider multiple criteria to assess the merit of a particular maintenance strategy. To fill this gap the study develops both methodology and theory using fuzzy linguistic approach to deal with subjective assessments of maintenance strategies, somewhat in more realistic manner.

Various algorithms and models related to loading and scheduling problems of flexible manufacturing systems have been developed (see for example, Cho and Parlar 1991, Chaturvedi 1993, Paulli 1995, Liu and McCarthy 1997, Prickett 1997, Lawrence 1999, Chan 1999, Gamila and Motavalli 2003, Somlo 2004, Das and Canel 2005). But very little effort has been made on analysis and development of maintenance strategies in this area. Bateman, (1995) discussed the impact of reactive maintenance strategy on production. He concluded that overall maintenance cost increases because of increase in down time, scrap rate and deterioration of quality.

Today as more and more industries are going to employ the new technology, the subject of maintenance management becomes crucial because the failure of even a single component can not only idle the machine/facility but the failure can quickly idle an entire production system. The failures may come from (i) lack of maintenance, (ii) improper or intensive operation, (iii) unstable operating environment, and so on. These failures not only add to downtime but also additional operation and maintenance costs. Quickly finding out the cause(s) of failure(s) and taking appropriate remedial actions is very important. So, the need to design and implement a company wide maintenance planning system which not only investigates the causes of failures but also integrates the resources i.e. man, machine and materials is felt. In this respect the study attempts to provide an in-depth, case based approach to implement TPM in a semi-automated cell of paper mill. This will not only help in identification of the nature failures, their documentation and analysis but also help maintenance managers / practioneners to understand the reality of failures, their nature and to reduce their effect by adopting suitable repair /replacement strategies. For assisting the maintenance analyst in development of suitable maintenance strategy by properly understanding the mechanism of failure (through modeling of failure data) and adopting adequate aging management actions (such as predictive or periodic testing) to predict or detect the degradation of components the study makes use of NHPPP models to help the maintenance managers in understanding the failure behavior of aging components by providing mathematical model. The model not only helps in forecasting future failures but also helps in optimizing the maintenance decisions based on cost dimensions (repair or replacements).

Chapter 3

RESEARCH ISSUES AND SOLUTION TECHNIQUES

3.1 INTRODUCTION

After studying the existing literature on QRM aspects related to system performance the present chapter summarizes the major research issues and discusses the important tools and techniques (qualitative and quantitative) used in conjunction with the fuzzy methodology for developing a unified and structured framework to analyze QRM aspects. For the ready reference the major issues addressed (section1.6) in the research work are presented as below:

- To understand and analyze production systems, subsequent sub-systems and their functions
- To conduct Failure Mode and Effect Analysis (FMEA) and to develop Fuzzy Decision Support System (FDSS) for failure analysis of the system
- To perform qualitative analysis of system using Root Cause Analysis (RCA), Fault Tree (FT) and its equivalent Petrinet (PN) modeling and quantitative analysis of system using Fuzzy Methodology (FM) to determine system failure and repair rates
- Determination of system parameters such as availability, expected number of failures, mean time between failures and mean time to repair, necessary for maintenance planning of system
- To facilitate the maintenance managers/decision makers to select the suitable maintenance strategy for the components /parts associated with the system
- To examine the need to develop, practice and implement such maintenance practices, which not only reduce sudden sporadic failures in semi-automated cells but also reduce both operation and maintenance costs and to optimize maintenance decisions (repair or replacements) based on cost dimensions

- To develop a structured approach to implement, sustain and manage a quality-costing program in a process industry and provide a framework to implement Quality Costing System (QCS) based on Process Cost Modeling (PCM)
- To develop resource allocation model in order to optimize maintenance and manpower decisions taking care of QRM aspects of system

Owing to its sound logic, and effectiveness in quantifying the vagueness and imprecision in human judgment, the fuzzy methodology in conjunction with other tools and techniques is used to address the above listed issues, generally faced by QRM analysts/engineers/practioneners.

3.2 QUALITATIVE AND QUANTITAIVE TECHNIQUES

The framework used in the study to analyze, design and optimize quality, reliability and maintainability aspects of production systems makes use of the following qualitative and quantitative tools of technology:

- Root Cause Analysis (RCA)
- Fault tree analysis (FTA)
- Petrinets (PN)
- Failure Mode and Effect Analysis (FMEA)
- Non-Homogeneous Poisson Point Process (NHPPP) models, and
- Fuzzy set theory

Briefly these are discussed in the following paragraphs:

3.2.1 Root Cause Analysis

Root Cause Analysis (RCA) is common terminology found in the reliability literature to avoid future occurrence of failures by pinpointing the causes of problems. It provides comprehensive classification of causes related to 4 M's i.e. *Man, Machine, Materials and Methods* and thus helps in establishing a knowledge base to deal with problems related to process/product reliability, availability and maintainability. For instance, Figure 3.1 shows that how RCA is used to diagnose an unreliable mechanical system? with respect to man inadequate training, operator's errors, attitude, can contribute to unreliability and with respect to machine problems such as, poor calibrations or misalignments may result in loss in operational efficiency.

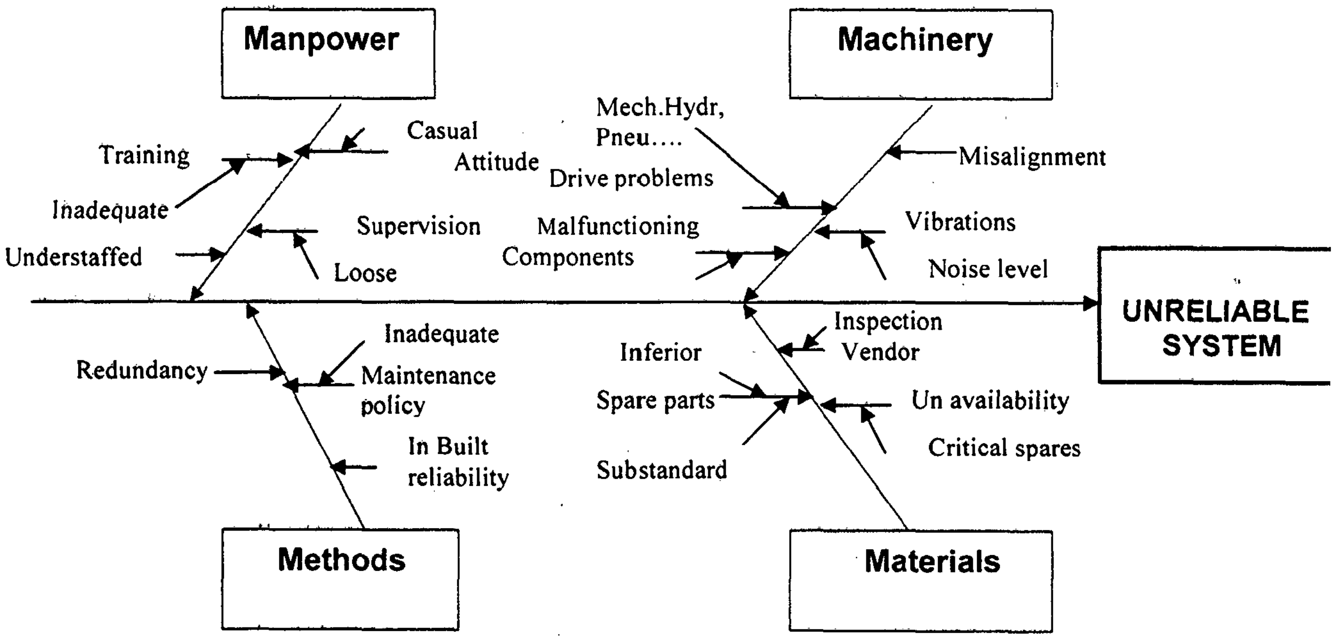

Figure 3.1 Root Cause Analysis

The study makes use of RCA to list out all the possible failure causes related to the units in the system in Chapter 4 and also to identify and segregate various quality cost elements under each cost category i.e. prevention-appraisal-failure costs in Chapter 6.

3.2.2 Failure Mode and Effect Analysis

Failure mode and effect analysis is a structured, bottom-up approach that starts with known potential failure modes at one level and investigates the effect on the next subsystem level. All complex mechanical systems are composed of several subsystems, which can be further broken down up to a component level (Wang *et al.* 1996). FMEA as a formal design methodology was developed at Grumman Aircraft Corporation in the 1950 and 60s (Coutinho, 1964) and was applied to naval aircraft flight control systems. Since then, it has been extensively used as a powerful tool for safety and reliability analysis of products and processes in a wide range of industries particularly, aerospace, nuclear and automotive industries (Gilchrist 1993, Eblieng 2000,Connor 2001). In 1977, it was adopted and promoted by Ford Motor Company. The Ford procedure extended FMEA methodology in automotive sector to assess and prioritize potential process and design-related failures. The main objective of FMEA is to discover and correct the potential failure problems during the stages of design and production. The two phases of FMEA, are described below:

- The first phase is concerned with identification of the potential failure modes and their effects. It includes defining the potential failures of product's component, subassemblies, final assembly and its manufacturing processes.
- The second phase is concerned with obtaining scores for *Probability of occurrence of failure* (S_f), *Severity* (S), *and Chance of the failure being undetected* (S_D) and, computing Risk Priority Number (RPN) i.e. RPN= $S_f.S.S_d$

Figure 3.2 shows the flow chart revealing general procedure for carrying out FMEA process. In brief the steps involved are as described as follows:

1. Identify the system to be analyzed. Divide the system into subsystems and /or assemblies in order to localize the search for components and develop a list of components for each assembly.
2. Construct the block diagram of the system. Use structural (hardware), functional, combined, master logic diagram and cause and effect diagram to identify relations among components.
3. Determine all potential failure modes of each component, their causes and the effects of failure modes on the immediate function or item, on sub- systems and the entire system.

4. Evaluate each failure mode in terms of worst potential consequence (severity)

5. Identify failure detection methods and compensating provision(s) for each failure mode

6. Estimate the probability of occurrence (S_f) using both qualitative and quantitative techniques.

7. Calculate the Risk Priority Number (RPN), using relation RPN = $S_f.S.S_d$

8. Determine whether corrective action is required or not depending upon the *RPN*. If required than identify corrective design or other actions required to eliminate the causes of failure. The actions may be

(i) compensatory to minimize the loss in event of failure occurrence.

(ii) preventive to avoid a failure situation.

9. Develop recommendations to enhance the system performance.

10. Prepare FMEA report by summarizing the analysis in tabular form (Table 3.1).The criticality or risk assessment in FMEA is executed in two ways

(i) By calculating a Criticality Number (CN)

(ii) By developing a Risk Priority Number (RPN) [described in US MIL-STD-1629A "Procedures for performing a failure mode, effects and criticality analysis". The first technique is used mostly in the high-risk plants, such as nuclear and aerospace industries and second is used in consumer goods, manufacturing and process industries.

The Equation 3.1 is used for calculating criticality number (CN) for each item failure mode 'i'.

$$C N_i = a_i b_i I_i t \tag{3.1}$$

Where,

a_i: Failure mode ratio, b_i: Failure-effect probability, l_i: Part failure rate, and t: Operating time

The Equation 3.2 is used to calculate Risk priority number (RPN).

$$RPN = S_f.S.S_D \tag{3.2}$$

Where the terms,

S_f: frequency of occurrence

S: severity of its failure effects, and

S_D: chance of the failure being undetected

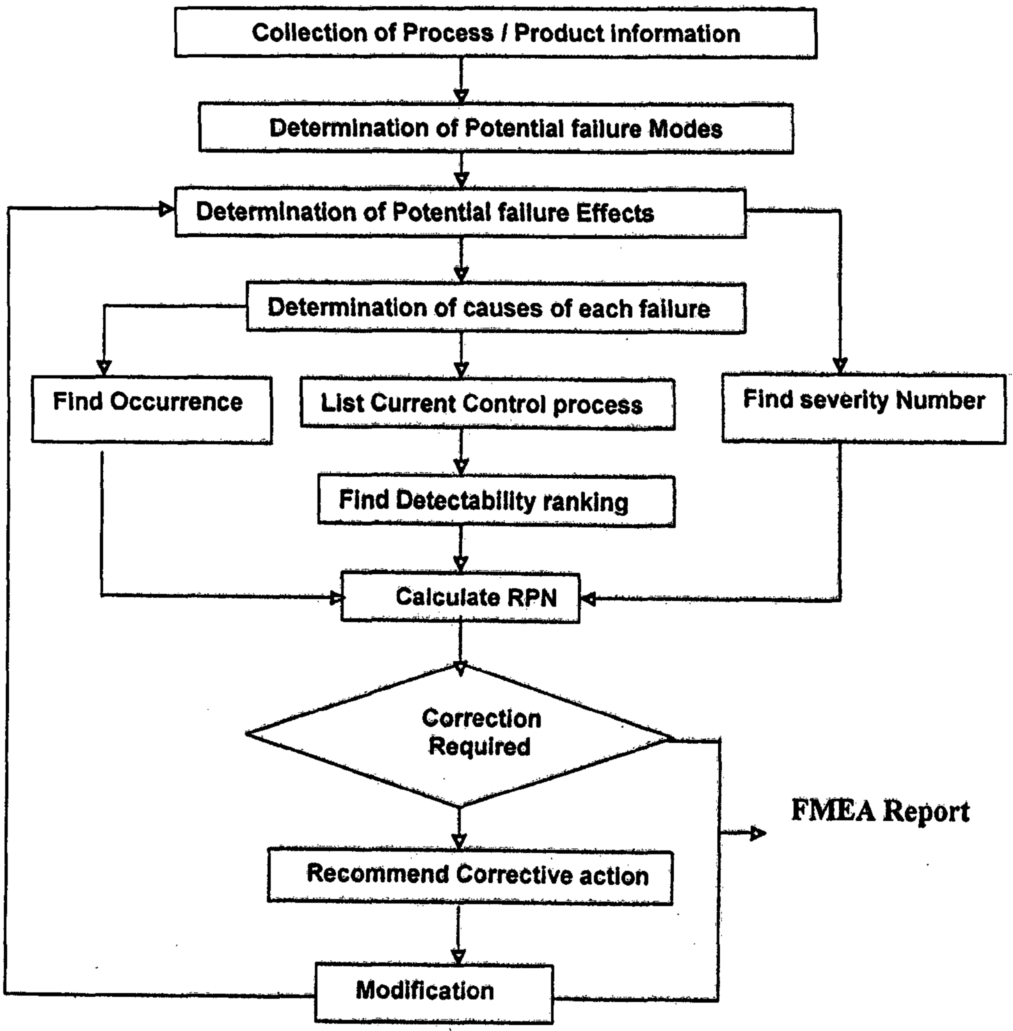

Figure 3.2 Flowchart of FMEA Process

Table 3.1 Typical FMEA Format

System.................................. FMEA No....................................
Subsystem........................... Page...
Component.......................... Prepared by..................................
Core team............................ FMEA Date (org.).......... (Rev)..........

										Action results			
Item /Function	Potential failure mode	Potential effects of failure	Severity	Potential causes of failure	Occurrence	Current Design controls	Detection	Recommend actions	Action taken	Severity	Occurrence	Detection	RPN

In the present study the RPN approach is used to rank the failure causes associated with the various sub-systems in process (paper mill) industry. The main disadvantage of RPN approach is that various sets of input terms i.e. S_f, S, S_D may produce an identical value, however, the risk implication may totally be different, which results in high-risk events and subsequently they may go unnoticed. For instance, consider two different events having values of $S_f = 3$, $S = 4$, $S_d = 5$ and $S_f = 1$, $S = 10$, $S_d = 6$ respectively. Both these events will have a total RPN value of 60, however; the risk implications of these two events may not necessarily be the same which may result in high-risk events may go unnoticed. The other disadvantage of the RPN ranking is that it neglects the relative importance among S_f, S and S_D. The three factors (S_f, S, S_d) are assumed to have the same importance but in real practical applications the relative importance among the factors exists.

For instance, a failure mode with a very high severity, low rate of occurrence, and moderate detectability (say 9, 3, and 5 respectively) may have a lower RPN (135) than one with all parameters moderate (say 5, 6, and 6 yielding an RPN of 180) even though it should have a higher priority for corrective action. Such types of limitations associated with the traditional approach are addressed by developing a Fuzzy Decision Making System (FDMS).

3.2.3 Fault tree and Petrinets

A Fault Tree (FT) is used to analyze the probabilities associated with the various failure causes and their effects on system performance. It starts by identifying a problem (an accident or an undesirable event) and all possible ways that the problem (failure) occurs. Since, 1960 the tool has been widely used for obtaining reliability information about the complex systems. The system failure analysis using fault tree methodology makes use of either qualitative or quantitative techniques. In quantitative technique Monte-Carlo simulation and analytical solution approach is used to determine system reliability parameters where as in qualitative technique minimal cut set and path sets are used to determine system reliability parameters. A cut set is a set of components whose failure will result in a system failure and a minimal cut set is one in which all components must fail in order for system to fail. A path set is a set of components whose functioning ensures that the system functions and a minimal path set is one in which all components, with in the set, must function (For more details, please refer to Singh and Dhillion 1991, Connor 2001).

Similar to fault tree, Petrinets makes use of digraph to describe cause and effect relationship between conditions and events. Petrinets have two types of nodes named place 'P' and transition 'T'. These nodes are connected by arcs 'A', i.e., arcs connect transitions to places or places to transitions. The basic symbols used in Petrinet model are defined as follows:

O : Place, drawn as a circle

— : Transition, drawn as a bar

↑ : Arc, drawn as an arrow, between places and transitions

• : Token, drawn as a dot, contained in places

Formally Petrinet, a directed bipartite graph is defined by a 6-tuple represented as in Equation 3.3. (Peterson 2000).

$$N = [T, P, A, M_0, I(t), O(t)] \tag{3.3}$$

Where; $T = \{t_1, t_2 \ldots t_n\}$: a set of transitions, each transition representing an event or an action

$P = \{p_1, p_2 \ldots p_l\}$: a set of places, where a place is used to represent either the condition for the event or the consequences of the event

$A = \{T \times P\} \cup \{P \times T\}$: a set of directed arcs that connect transitions to places and places to transitions

M_0 : the initial marking of the system that represents initial state of the system

$I(t) = \{p | (p, t) \in A\}$: a set of input places of a transition t, and

$O(t) = \{p | (t, p) \in A\}$: a set of output places of a transition t.

Petrinet has two parts i.e. static and dynamic. The static part consists of *Places (P), Transitions (T) and Arrows (A)*, while the dynamic part is related with marking of graph by tokens which are present, not present or evolves dynamically on firing of valid transitions. As shown in Figure 3.3 (a), the static part, and 3.3 (b) the dynamic part i.e. before firing there is one token in each of input places P_1 and P_2 but no token in output place P_3. Accordingly, the Petrinet marking is M = (1, 1, and 0) and after firing of transition based on enabling rules the token moves from each of P_1 and P_2 to the output place P_3 (For more details, please refer to Peterson , 2000).

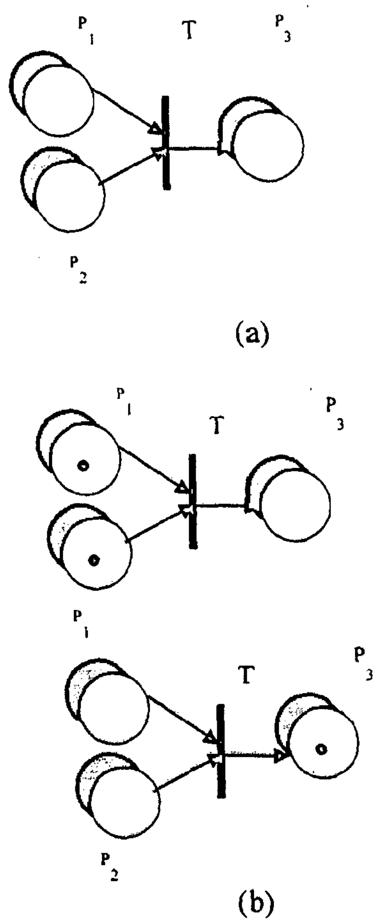

Figure 3.3 (a) Static Petrinet (b) Dynamic Petrinet before Firing M_0= (1, 1, 0) and after Firing M_1= (0, 0, 1)

Contrary to fault trees, Petrinets can more efficiently derive the minimal cut and path sets using the *matrix method (Liu & Chou 1997, Adamyan and David 2002). Also, the absorption property of Petrinets helps to simplify the Petrinet model and determine minimal cut set and path sets by reorganizing the transitions which is possible as long as the firing time is not taken into consideration i.e. transfer of tokens does not take place (static condition).The algorithm based on matrix method for determination of minimal cut sets and path sets consists of following steps:

1. Numbers of places (P) are written in a horizontal manner if the output place is connected by multi-arcs to transitions (T)
2. Numbers of places are written in vertical arrangement if the output place is connected by an arc

to a common transition (T)

3. Matrix is established when all the places (P) are replaced by basic places (P). The common entry located between rows or columns, is shared by each row or column. The column vectors of the matrix represent cut sets while row vectors path sets.
4. Lastly, minimal cut sets and minimal path sets are obtained by removing all the supersets.

*(The description with a case is provided in Appendix A-3)

3.2.4 Non-Homogeneous Poisson Point Process

Many repairable mechanical systems show tendency towards long-term reliability degradation (with repeated overhauls and replacements) of system component(s). These typically include equipment (systems) and sub-units (sub-systems) where repair of the system (or sub-system) consists of the replacement or repair of only a small part of the system (or sub-system). The system is thus not in the 'good-as-new' condition after repair, but in the 'bad-as-old' (BAO) condition (the same condition the system was in prior to failure) known as 'minimal repair'. This leads the system being subjected to reliability degradation, with an accompanying increase in the failure rate (ROCOF) (the so called 'sad' trend of Ascher), such systems are not modeled by the conventional fitting of a statistical distribution function, as successive failures are not identically and independently distributed. In this case, the Non-Homogeneous Poisson Point Processes (NHPPP) are used to model failure/repair process. Log-linear and power law are the two mathematical models, which are generally used for analysis of non-homogeneous Poisson processes (Ascher and Feingold 1984, 1992; Calabria and Pulcini, 2000).

(a) The first NHPPP model with a log-linear rate of occurrence of failures discussed by Cox and Lewis (1966) behaves well with $\alpha_1 > 0$ and is given as:

$$\rho_1(T) = e^{\alpha_0+\alpha_1 T}, -\infty < \alpha_0, \alpha_1 < \infty, T \geq 0 \quad (3.4)$$

Where;

ρ_t = Failure rate (ROCOF)

α_0, α_1 = Parameters of NHPP model $\rho_1(t)$

Using maximum likelihood estimates, the parameters for the model can be obtained from Equation 3.5 (Connor, 2002).

$$\sum_{i=1}^{n} T_i + n\alpha_1^{-1} - nT_n\{1 - e^{-\alpha_1 T_n}\}^{-1} = 0 \qquad (3.5)$$

$$\hat{\alpha}_0 = \ln\left[\frac{n\hat{\alpha}_1}{e^{\hat{\alpha}_1 T_n} - 1}\right]$$

Where: T_i: Time of i^{th} failure, T_n: Time of n^{th} failure

The process trend is determined by conducting a natural test of hypothesis i.e.Centeroid or Laplace test. If x_0 is the period of observation, and $x_1, x_2, x_3 \ldots x_n$ are the arrival values of the independent variables (e.g. time) from x=0 at which event occurs, then the test static is given by Equation (3.6)

$$*U = \frac{\sum x_i / n - x_0/2}{x_0\sqrt{1/(12n)}} \qquad (3.6)$$

Where; n = Number of observed failures for a component or system

The statistic compares the centroid of the observed arrival values with the mid-point of the period of observation. Under the null hypothesis, *U* approaches a standard normal distribution.

If H_1: $\alpha_1 \neq 0$, one rejects H_0 if U is large. On the other hand, if H_1: α_1 >0, one rejects H_0 if *U* is large, and if H_1: α_1 <0, one rejects H_0 if $-U$ is large.

(i) If U=0 there is no trend, i.e. the process is stationary

(ii) If U<0 the trend is decreasing, i.e. inter arrival values are tending to become larger

(iii) If U>0 the trend is increasing, i.e. inter arrival values are tending to become progressively smaller.

**U* Statistic used in the Laplace test

(b) The second model (Ascher, 1984) based on weibull distribution is known as the *'Power law process'* and is given by Equation (3.7)

$$\rho_2(T) = \lambda\beta T^{\beta-1}, \lambda, \beta > 0, T \geq 0 \qquad (3.7)$$

Where,

λ, β = Parameters of NHPPP model $\rho_2(t)$

(i) If $\beta > 1$, the rate of occurrence of failure increases.

(ii) When $0 < \beta < 1$, the rate of occurrence of failures decreases.

The maximum likelihood estimates for the parameters of $\rho_2(T)$ 'Power law process are given as

$$\hat{\beta} = \frac{n}{\sum_{i=1}^{n} \ln \frac{T_n}{T_i}} \quad \text{and} \quad \hat{\lambda} = \frac{n}{T_n^{\beta}} \qquad (3.8)$$

In order to test whether the rate of occurrence of failures is constant, that is $\beta=1$, the following statistic given by Equation (3.9) is employed (Crowder *et al.* 1996).

$$*V = 2 \sum_{i=1}^{n} \ln \frac{t_0}{t_i} \qquad (3.9)$$

Under the null hypothesis, it follows a χ_{2n}^{2} (chi-squared) distribution with $2n$ degrees of freedom. Large values of V indicate reliability growth ($0 < \beta < 1$), whereas small ones indicate deterioration ($\beta > 1$).

*V statistic for testing whether the rate of occurrence of failures is constant.

3.2.4.1 Algorithm for Model Selection

The steps for selection of appropriate model for rate of occurrence of failure $\rho(t)$ are:

(i) Obtain the plot of operational time t_i against the failure number n_i.

(ii) Obtain expressions for $\rho_1(t)$ & $\rho_2(t)$ using log-likelihood methods.

(iii) Perform linear regression (graphical method, as discussed in appendix) and select $\rho(t)$.

3.2.5 Fuzzy Concepts

Fuzzy sets: Crisp (classical) sets contain objects that satisfy precise properties of membership functions. Only two possibilities whether an element belongs to, or not belongs to a set exist. A crisp set 'A' can be represented by a characteristic function $M_A / u = \{0, 1\}$.

$$M_A(x) = \begin{cases} 1 \text{ if } & x \in A \\ 0 \text{ if } & x \notin A \end{cases} \quad (3.10)$$

Where:

U: universe of discourse; X: element of U; A: crisp set, and M: characteristic function

On the other hand fuzzy sets contain objects that satisfy imprecise properties of membership functions i.e. membership of an object in a fuzzy set can be partial. Contrary to classical sets, fuzzy sets accommodate various degree of membership on continuous interval [0, 1], where '0' conforms to no membership and '1'conforms to full membership. Mathematically defined by Equation 3.11 as

$$\mu_{\tilde{A}}(x) : U \rightarrow [0,1] \quad (3.11)$$

Where: $\mu_{\tilde{A}}(x)$: Degree of membership of element x in fuzzy set $\tilde{A}$.

Membership functions: Various types of Membership Functions (MF) such as triangular, trapezoidal, gamma and rectangular can be used for reliability analysis. However Triangular Membership Functions (TMF) are widely used for calculating and interpreting reliability data because of their simplicity and understandability (Yadav *et al.* 2003 , Bai and Asgarpoor 2004). For instance, imprecise or incomplete information such as low/high failure rate i.e. about 4 or between 5 and 7 is well represented by TMF. In the study triangular membership function is used as it not only conveys the behavior of various system parameters but also reflect the dispersion of the data adequately. The dispersion takes care of inherent variation in human performance, vagueness in system performance due to age and adverse operating conditions. Thus, it becomes intitutive for the engineers to arrive at decisions.

For instance, a triangular fuzzy number is defined by triplets (m_1, m_2, m_3), with introduction of α cut, $M^{\alpha} = [m_1^{(\alpha)}, m_3^{(\alpha)}]$, the number is defined as shown in Figure 3.4. The cut is used to define the interval of confidence of triangular membership function and is written as

$$\tilde{M}^{\alpha} = [(m_2 - m_1^{(\alpha)})\alpha + m_1^{(\alpha)}, -(m_3^{(\alpha)} - m_2)\alpha + m_3^{(\alpha)}] \quad (3.12)$$

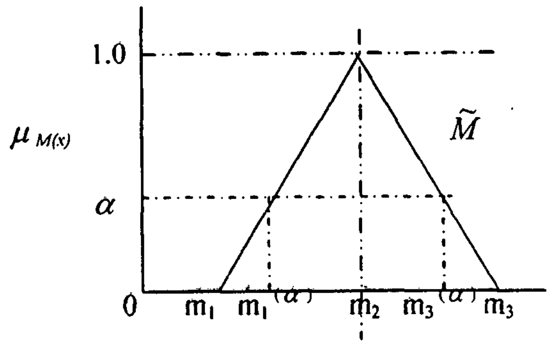

Figure 3.4 A Triangular Membership Function with α cut

Linguistic variables: Moreover, when an event is imprecisely or vaguely defined, the experts would simply say that the possibility of occurrence of a given event is *'low'*, *'high'*, and *'fairly high'*. To estimate such subjective events linguistic expressions are used. The analyst can use linguistic variables to assess and compute the events using well-defined fuzzy membership functions (Tanaka, 2001). In the study, the linguistic terms such as *Remote, Low, Moderate, High, & Very High* are used to represent probability of occurrence, severity and non-detectability in FMEA.

Fuzzy rule base and inference system: The rule base describes the criticality level of the system for each combination of input variables. Oftenly expressed in *'If-Then'* form [where, *If*: an antecedent which is compared to the inputs & *Then*: a consequent, which is the result/output], they are formulated in linguistic terms using two approaches i.e. Expert knowledge and expertise and Fuzzy model of the process

For instance, the format of rules is defined as

R_i: *If* x is M_i *then* y is N_i; i = 1, 2, 3...K (3.13)

Where, x: the input linguistic variable

M_i: the antecedent linguistic constants (qualitatively defined functions)

y: the output linguistic variable, and

N_i: the consequent linguistic constants

By using the inference mechanism an output fuzzy set is obtained from the rules and the input variables. There are two most common types of inference systems frequently used; the max-min inference and the max-prod inference method (Zimmermann 1996, Kokso 1997, Ross 2000) Examples of t-norms are the minimum, oftenly called "mamdani implication" and the product, called the Larsen implication. In the study mamdani's *max-min* inference method is used. For instance, a fuzzy rule expressed by Equation (3.13) is represented by a fuzzy relation R: (X x Y), which is computed by using Equation (3.14)

$$\mu_R(x, y) = I[\mu_A(x), \mu_B(y)] \quad (3.14)$$

Where, the operator *I* can be either an implication or a conjunction operator.

Figure 3.5, shows the schematic representation of the fuzzy reasoning mechanism with two rules. First, the numerical input variables (occurrence, severity) are fuzzified using appropriate membership functions. Then, the min operator is used for the conjunction and for the implication operations. The outputs (individual fuzzy sets) are aggregated by using the max operator and finally, the aggregated output is defuzzifed to obtain a crisp value.

Defuzzification: In order to obtain a crisp result from fuzzy output deffuzification is carried out .In the literature various techniques for defuzzification such as centroid, bisector, middle of the max, weighted average exist. The criterions for their selection are disambiguity (result in uniqu value), plausibility (lie approximately in the middle of the area) and computational simplicit: (Ross, 1995& Zimmermann, 1996).In the study, the centroid method is used for defuzzification a it gives mean value of the parameters.

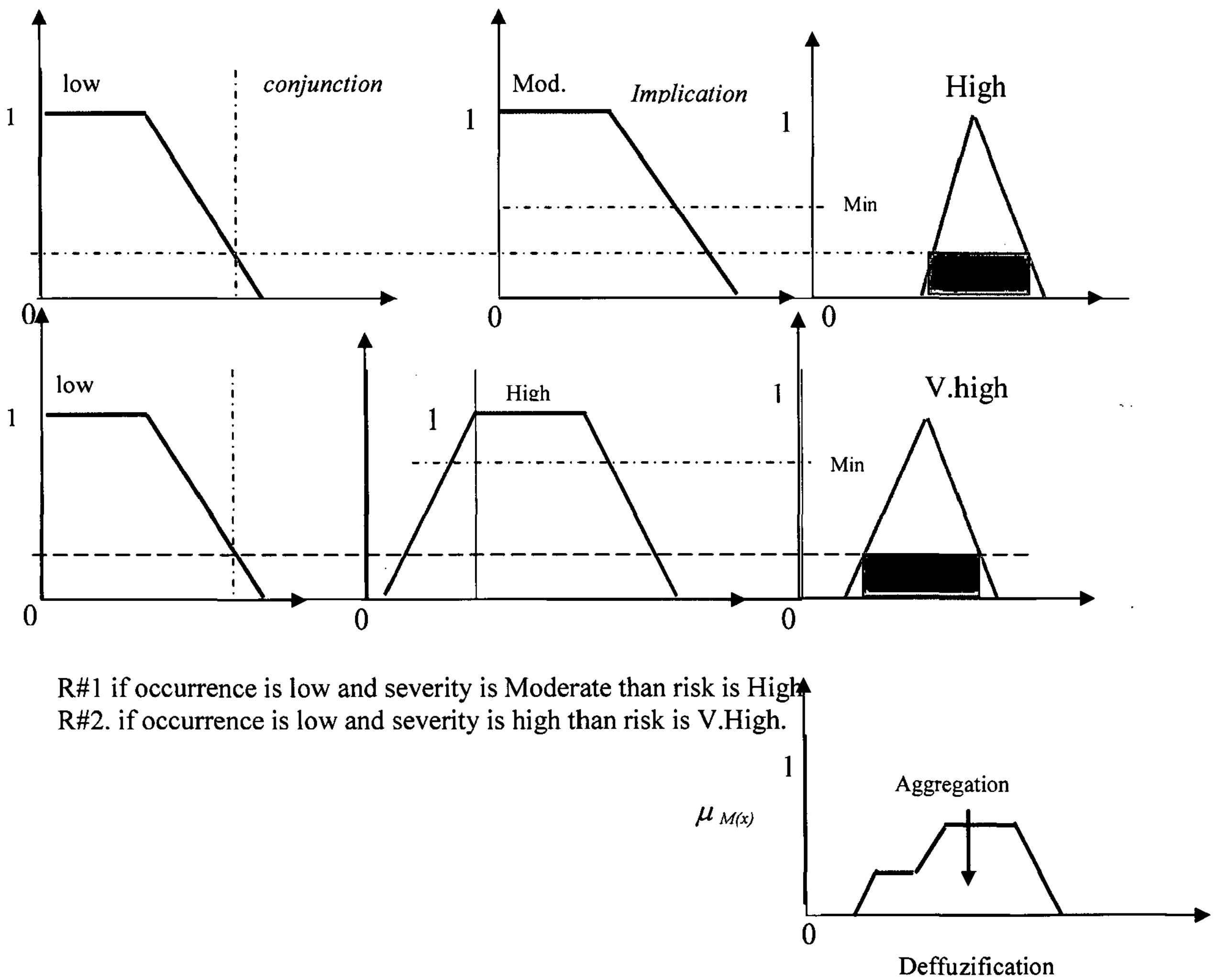

Figure 3.5 Schematic Representation of Fuzzy Reasoning Mechanism.

3.2.5.1 Rule-based algorithm:

In the Equation 3.13, the values of x and y, and M_i and N_i are fuzzy sets defined in t domains of their respective base variables. The linguistic terms M_i and N_i are usually selected fro sets of predefined terms, such as *low, medium, high etc.*

The rule base $R = \{R_i \,/\, i = 1, 2, 3..........k\}$ and the sets 'M' and 'N' constitute the knowledge base of the linguistic model. Each rule is regarded as a fuzzy relation

$$R_l\,(X,Y) = [0, 1] \quad (3.16)$$

This relation can be computed in two ways by using fuzzy implications or fuzzy conjunctions (Mamdani method). In this study, the Mamdani method is used, in which conjunction $M \wedge N$ is computed by a *minimum* operator (a *t*-norm):

$$R_i = M_i \times N_i;\ \text{i.e., } \mu_{Ri}(x, y) = \mu_{Mi}(x) \wedge \mu_{Ni}(y) \quad (3.17)$$

The *minimum* operator is computed on the Cartesian product space of X and Y, i.e., for all possible pairs of x and y. The fuzzy relation R represents the entire model Equation (3.17) and is given by the disjunction (union or maximum, i.e., *s*-norms) of the K individual rule's relations,

$$R = \bigcup_{l=1}^{K} R_i\ \ \textit{i.e.,}\ \mu_{Ri}(x, y) = \max_{1 \le l \le K}\ [\mu_{Mi}(x) \wedge \mu_{Ni}(y)] \quad (3.18)$$

Now the entire base is encoded in the fuzzy relation $\boldsymbol{R}$ and the output of the linguistic model can be computed by the *max-min* composition

$$y = x^0 \boldsymbol{R} \quad (3.19)$$

Let us suppose that an input fuzzy value $x = M^{\,i}$ which has the output value $N^{\,i}$ given by the relational composition:

$$\mu_{N^i}(y) = max\ [\mu_{M^i}(x) \wedge \mu_R(x, y)] \quad (3.20)$$

Substituting $\mu_{Ri}(x, y)$ from Equation (3.18), the above expression becomes

$$\mu_{N^i}(y) = \max_{x}\ (\mu_{M^i}(x) \wedge \max_{1 \le l \le K}\ [\mu_{Mi}(x) \wedge \mu_{Ni}(y)]) \quad (3.21)$$

The above equation can be rearranged as

$$\mu_{N^i}(y) = \max_{x}(\max_{1 \le i \le k}[\mu_{M^i}(x) \wedge \mu_{M_i}(x)] \wedge \mu_{Ni}(y)) \quad (3.22)$$

Assuming $\alpha_i = \max_X [\mu_{M^i}(x) \wedge \mu_{Mi}(x)]$ the degree of fulfillment of the i^{th} rule's antecedent. The output fuzzy set of the linguistic model is thus given by Equation 3.23.

$$\mu_{N'}(y) = \max_{1 \le i \le k} [\alpha_i \wedge \mu_{Ni}(y)], y \in Y \quad (3.23)$$

For defuzzification various techniques are available in the literature (Ross 1995, Zimmermann, 1996) but most commonly used are Chen's ranking (1985) and Yager's centroidal (1980). In the study, Yager's centroidal method is used for defuzzification due to its simplicity, which can be determined by

$$\text{Defuzzified value} = \int_m^n y\, \mu_{N'}{}^{i}(y)\, dy \Big/ \int_m^n \mu_{N'}{}^{i}(y)\, dy \quad (3.24)$$

Where, m and n are the lower and upper limits of the integral, which determines the validity domain of the membership function, and y is the centroidal distance from the origin. The above algorithm is called the mamdani inference. This algorithm is for single input and single output (SISO). It can be extended to multiple inputs and single Output (MISO) and multiple input - multiple output (MIMO) models.

Therefore, in the case of multi input and single output (MISO)

R_i: ***If*** x_1 is M_{1i} ***and*** x_2 is M_{2i} ***and...and*** x_p is M_{pi} ***then*** y is N_i, $i = 1, 2...K$ (3.25)

The above model is the special case of Equation 3.13, as the set M_i is obtained by the Cartesian product of fuzzy sets $M_{ij} = M_{i1}.M_{i2}.M_{i3}. \ldots . M_{ip}$

Hence the degree of fulfillment (α_i) becomes:

$$\alpha_i = \mu_{Mi1(x1)} \wedge \mu_{Mi2(x2)} \wedge \ldots \wedge \mu_{Mip(xp)}; \; 1 \le i \le k \quad (3.26)$$

The remaining process remains the same for MISO as that of SISO. The details of the above algorithm can be seen in Yager and Filev (1994).

In practical applications the fuzziness of the antecedents eliminates the need for precise match with the inputs. All the rules that have any truth in their antecedent will fire and contributes towards the fuzzy conclusion set. Each rule is fired to a degree that is function of the degree to which its antecedent matches the input. This imprecise matching provides a basis for interpolation between possible input states and serves to minimize the number of rules needed to describe the input-output relation.

3.2.5.2 Fuzzy measure and fuzzy integral

Information fusion is a process of combining objective evidence from different information sources in order to make a better judgment. The traditional weighted average method, which is commonly used, for information aggregation is based on the premise that the information sources are non-interactive/independent, i.e. each attribute must be independent of the others. However, this assumption is not realistic in real world applications because of inherent interaction/inter-dependencies among the information sources. To address such situations Choquet integral proposed by Sugeno provides an intuitive and effective way. Based on any fuzzy measure it can be applied to analyze human evaluation process and to specify decision-makers' preference structures. Typically, this fuzzy measure represents the importance or relevance of the sources when computing the aggregation. Briefly the computational procedure is described as below.

Let $y = \{y_1, y_2, y_3 \ldots\ldots y_n\}$ be a finite set of information sources and g: $P(Y) \rightarrow [0, 1]$ a set function satisfying following conditions

(i) $G(\Phi) = 0, g(Y) = 1$

(ii) $g(A) \leq g(B)$, if $A \subset B$ and $A, B \in P(Y)$

and g λ *is a* fuzzy measure, with an additional property ,$g(A \cup B) = g(A) + g(B) + \lambda g(A)g(B)$

For all $A, B \subset$ Y and $A \cap B = \Phi$, and for some $\lambda > -1$.

As per the boundary condition $g(Y) = 1$, λ is determined from following polynomial Equation 3.27.

$$\lambda + 1 = \prod_{i=1}^{n} (1 + \lambda g_i) \tag{3.27}$$

Where, g_i ($\in [0, 1]$ is the fuzzy density of the i^{th} information source and is interpreted as the degree of importance of it. λ value has three cases i.e.

If, $\sum_{i=1}^{n} g_i > g_\lambda(X)$, then $-1 < \lambda < 0$

$\sum_{i=1}^{n} g_i = g_\lambda(X)$, then $\lambda = 0$, and

$\sum_{i=1}^{n} g_i < g_\lambda(X)$, then $\lambda > 0$.

The objective evidence *h (y)* ($\in [0,1]$) of each information source is rearranged in a decreasing order i.e. is $\{h(y'_1) \geq, h(y'_2), ... h(y'_n)\}$

Let $Y = \{y'_1, y'_2, y'_3, ... y'_n\}$ be the new order and corresponding fuzzy densities are

$\{ g'_1, g'_2, g'_3, ... g'_n \}$.

Let $A_i = \{y'_1, y'_2, y'_3, ... y'_n\}$.Based on the new order, the fuzzy measure *g (A i)* can be determined using a recursive Equation 3.28

$$g(A_i) = g'_i + g(A_{i-1}) + \lambda g'_i g(A_{i-1}), \quad for\ 1 < i \leq n \tag{3.28}$$

Thus, g_λ a Fuzzy measure is completely determined by its densities (Grabisch 1995, Chiang 1999, Grabisch *et al.* 2000, Torra and Narukawa, 2005). Finally the so-called, Choquet fuzzy integral is computed using Equation 3.29.

$$\int_Y h(y) \circ g(\cdot) = \sum_{i=1}^{n} [h(y_i) - h(y_{i+1})] g(A_i), \text{ Where, } h(y'_{n+1}) = 0 \text{ and } g(A_0) = 0 \tag{3.29}$$

3.2.5.3 Fuzzy Ranking

There are various methods, which are commonly used for fuzzy ranking such as

(1) Weighted center of a fuzzy number (Tseng and Klein, 1992)

(2) The area center of a fuzzy number (Huang, 1989)

(3) The total integral value of a fuzzy number (Liou and Wang, 1992)

(4) The left and right assigned scores of a fuzzy number (Chen *et al.*, 1992)

The study makes use of Chen's method, which is briefly described as

Let $\widetilde{A}_1, \widetilde{A}_2, \ldots\ldots\ldots\ldots\ldots \widetilde{A}_n$, be n fuzzy numbers to be ranked with membership functions $\mu_{\widetilde{A}_i}(x), i = 1,2,\ldots\ldots\ldots\ldots\ldots n, x \in R$. As in the study the importance scale [0,1] so that, $x \in (0,1)$

Defining the maximizing set $\widetilde{M}$ and minimizing set as $\widetilde{G}$ the equations can be written as 3.30(a) &(b)

$$\mu_{\widetilde{M}} = \begin{cases} [(x - x_{min})/(x_{max} - x_{min})]^k, & x_{min} \le x \le x_{max} \\ 0 & , otherwise \end{cases} \quad 3.30(a)$$

$$\mu_{\widetilde{G}} = \begin{cases} [(x_{max} - x)/(x_{max} - x_{min})]^k, & x_{min} \le x \le x_{max} \\ 0 & , otherwise \end{cases} \quad 3.30(b)$$

Where, $x_{min} = \inf(U_{i=1}^{n} S(\widetilde{A}_i))$, $x_{max} = \sup(U_{i=1}^{n} S(\widetilde{A}_i))$, $S(\widetilde{A}_i)$ is the support of $\widetilde{A}_i$ defined as, $S(\widetilde{A}_i) = \{x / \mu_{A_i}(x) > 0\}$. The value of k is constant. For the study it is taken as 1.Then the right and left utility values of fuzzy number are calculated using Equation 3.31.

$$U_{\widetilde{M}}(i) = \sup_x(\min(\mu_{\widetilde{M}}(x), \mu_{\widetilde{A}_i}(x))) \text{ And } U_{\widetilde{G}}(i) = \sup_x(\min(\mu_{\widetilde{G}}(x), \mu_{\widetilde{A}_i}(x))) \quad (3.31)$$

Where, $i = 1,\ldots\ldots\ldots\ldots\ldots\ldots n$. Finally the total value for the ith fuzzy number is given by equation

$$U_{TOT}(i) = (U_{\widetilde{M}}(i) + 1 - U_{\widetilde{G}}(i))/2 \text{ , where } U_{TOT}(i) \in [0,1]$$

The above procedure is used to compute the fuzzy density values with respect to expert linguistic definitions of various cost items.

3.3.6 Grey Relation Analysis

Proposed and developed by Deng (1986), Grey theory like fuzzy set theory also deals with making decisions characterized by incomplete and partially known information. It explores system behavior using relation analysis and model construction (Liu and Lin, 1998). Grey system theory has been widely used in many fields, such as forecasting, Hsu and Chen (2003),Zhang *et al.* (2003), Industrial applications, Lin and Yang (2003), engineering applications, Wang *et al.* (2002), Lian *et al.* (2005). The main steps involved in Grey approach are

(i) Formulation of comparative series: The comparative series also known as information series, is used to represent various linguistic terms and decision factors in form of a Equation 3.32.

$$x=\begin{bmatrix} \\ x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}=\begin{bmatrix} x_1(1) & x_1(2)\ldots\ldots & x_1(k) \\ x_2(1) & x_2(2)\ldots\ldots & x_2(k) \\ . & . & . \\ . & . & . \\ x_n(1) & x_n(2)\ldots\ldots & x_n(k) \end{bmatrix} \tag{3.32}$$

The linguistic terms describing the decision factors may be remote, low, fairly low, moderate etc. For instance, If $x_i=\{x_1(1), x_1(2)\ldots x_1(k)\}, \{x_2(1), x_2(2)\ldots x_2(k)\}$, etc are the linguistic terms (decision factors), then $\{x_1, x_2\ldots x_n\}$ are the potential failure modes or failure causes of FMEA.

(ii) Formulation of standard series: The standard series is an objective series that reflects the ideal or desired level of all the decision factors and can be expressed as Equation 3.33.

$$x_0=[x_0(1), x_0(2), x_0(k)]. \tag{3.33}$$

(iii) Obtain difference between the two series: To determine the degree of grey relation, the difference between the two series, D_0, (comparative and standard series) is calculated and expressed in the form of matrix Equation 3.34 as

$$D_0=\begin{bmatrix} \Delta_{01}(1) & \Delta_{01}(2) & \Delta_{01}(3) & \Delta_{01}(k) \\ .\Delta_{02}(1) & .\Delta_{02}(2) & \Delta_{03}(3) & \Delta_{02}(k) \\ . & . & . & . \\ . & . & . & \Delta_{0j}(k) \\ \Delta_{0m}(1). & \Delta_{0m}(2) & \Delta_{0m}(3) & \Delta_{0m}(k) \end{bmatrix} \tag{3.34}$$

Where, $\Delta 0j(k)=\|x_0(k)-x_j(k)\|$

(iv) Compute grey relation coefficient: To compare the decision factors with standard series a relationship has to be established. This relationship is known as grey relation coefficient and is expressed as Equation 3.35.

$$\gamma(x_0(k), x_i(k)) = \frac{\min_i \min_k | x_0(k) - x_j(k) | + \zeta \max_i \max_k | x_0(k) - x_j(k) |}{| x_0(k) - x_j(k) | + \zeta \max_i \max_k | x_0(k) - x_j(k) |} \tag{3.35}$$

Where, x_0 (k): the min or max value from the standard series

x_j (k) : the min or max value from the comparative series, and

ζ : Identifier, $\zeta \in (0, 1)$ (affects the relative value of risk without changing the priority.

(v) Determine degree of relation: The degree of relation [Γ (x_i, xj)] denotes the relationship between the potential causes and the optimal value of the decision factors and is expressed as Equation 3.36.

$$\Gamma(x_i, x_j) = \sum_{k=1}^{n} \beta_k \gamma\{x_i(k).x_j(k)\} \tag{3.36}$$

$\sum_{k=1}^{n} \beta_k = 1$; Where (β_k), the weighting coefficient of the decision factors.

The weighting coefficients can be determined using Analytical Hierarchical Process (AHP). For the application of the grey theory to FMEA, (β_k) should be set equal to 1. The higher the value obtained from Equation 3.36, the smaller the effect of the identified events. Therefore, the increasing order of the degree of relation represents the risk priority of the identified areas that are to be improved.

CHAPTER 4

PERFORMANCE EVALUATION*

4.1 INTRODUCTION

The study is carried out in a process industry (paper mill) situated in northern part of India, producing 180 tons of paper per day. There are many functional units in a paper mill such as (i) Feeding (ii) Pulp Preparation (iii) Pulp Washing (iv) Screening (v) Bleaching, and (vi) Preparation of paper (forming, press and dryer units). For the production of the paper the raw material (soft+ hardwood and bamboo) is chopped into small pieces of approximately uniform in size and transported to the store for temporarily storage by the use of a compressed air. A chain conveyor carries the chips from the store to digesters whenever required, where these are cooked using $NaOH+Na_2S$ and steamed at $8.5 Kg/cm^2$ pressure and 180^0C temperature. The cooked chips are called pulp. The pulp is transported to the storage tanks from where it is further processed through fibrelizier and refiner. The pulp is then filtered and is washed (in three-four stages) with water to remove knots and chemicals. The washed pulp obtained in last stage of washing is stored in a surge tank. The next stages of processing are bleaching and screening. For the production of white paper, pulp is bleached (by passing chlorine gas through the pulp stored in the tank) and the brown pulp (used for packaging purpose) is screened directly. This pulp is then washed, cleaned and is send to

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the head box of paper machine consisting of three sections i.e. forming, press and dryer respectively. In the forming section of the paper machine, the suction box (having six pumps) dewaters the pulp through vacuum action. The paper pulp in the form of sheets produced by rolling presses is send to press and dryer section to reduce the moisture content by means of heat and vapor transfer and to smooth out any irregularities. Finally the rolled dried sheet of the paper (in the form of rolls) is sent for packaging. A schematic diagram of processes in paper mill is shown in Figure 4.1.

The aim of the present chapter is to evaluate the performance of various subsystems associated with paper production using both qualitative and quantitative techniques (discussed in Chapter 3). In the qualitative framework, Root Cause Analysis (RCA) is used to provide comprehensive classification of causes related to abnormal performance of the subsystems. Further, to list all potential failure modes, their causes and effect on system performance, Failure Mode and Effect Analysis (FMEA), for all the subsystems, is carried out. In the quantitative framework, quantification of system parameters (important for managerial decision making with respect to maintenance planning) in terms of fuzzy, crisp and defuzzified values is done. In this framework the Petrinet model of the system is obtained first from its equivalent fault tree model and then system failure and repair times are then computed based on the steps as discussed in Section 4.3.3. For the system components the fuzzification of failure and repair time data is done using Triangular Membership Function (TMF). After knowing the input fuzzy triangular numbers for all the components shown in Petri net model the corresponding fuzzy values of failure rate (λ) and repair time (τ) for the respective sub-system at different confidence levels (α) are determined using fuzzy transition expressions.

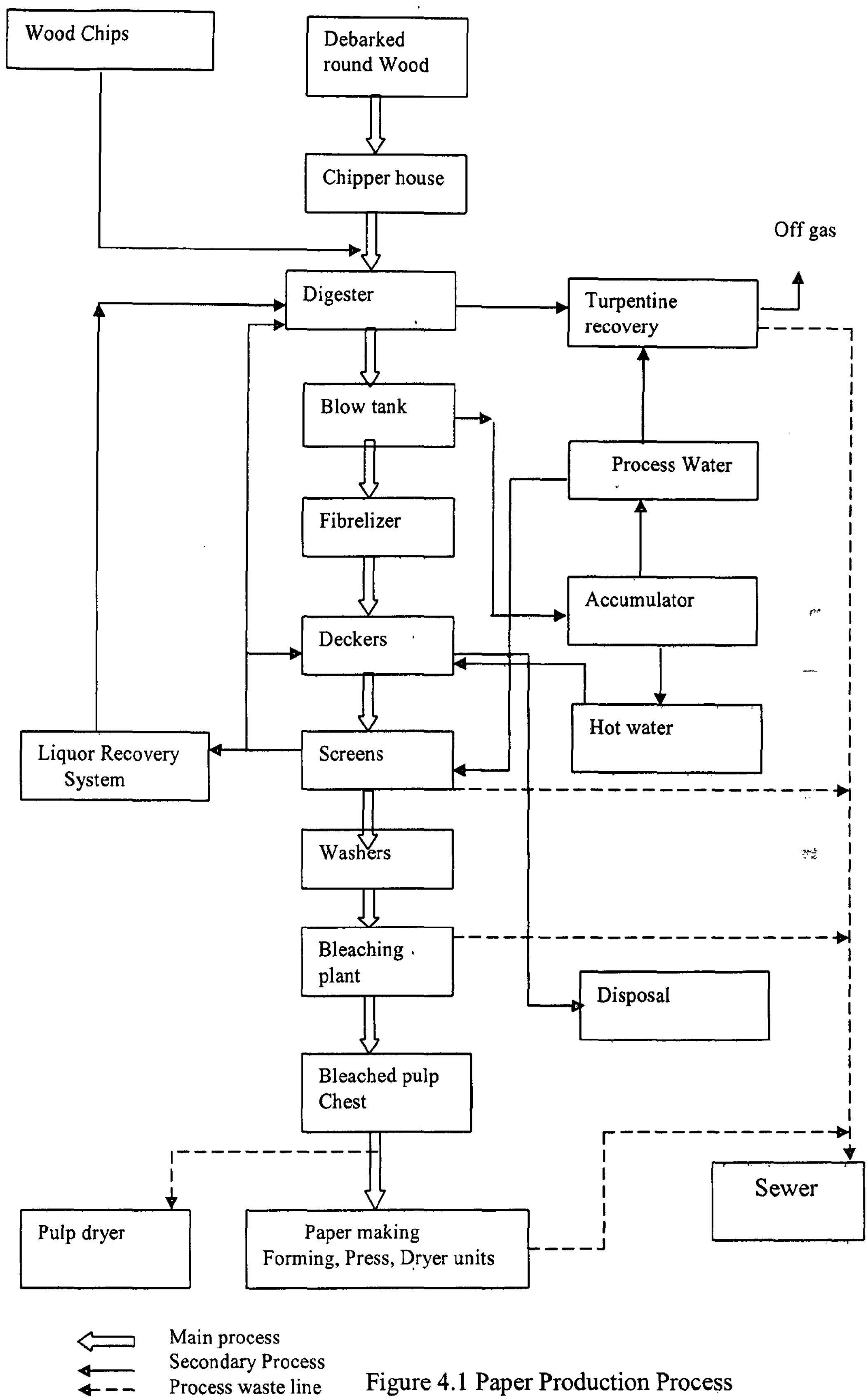


Figure 4.1 Paper Production Process

4.2 System Description

The paper production system consists of many functional sub-systems such as feeding, pulp preparation, pulp washing, screening etc. as discussed in the section 4.1. The following paragraphs discuss the details of the respective subsystems in brief.

4.2.1 Feeding

The main function of this sub-system is to continuously feed the broken wooden chips available from chipping house to the digester. Figure 4.2 shows the schematic diagram of the system. It comprises of various critical subsystems, defined as

(i) Sub System 1 [SS_1]: The Blower, for pushing the wood chips through pipe

(ii) Sub System 2 [SS_2]: The chain conveyor and bucket conveyor for carrying and lifting the chips to the height of digester

(iii) Sub System 3 [SS_3]: The stand by unit (for subsystem 2), when there is a failure in SS_2, Sub System 3 is switched on to feed the digester

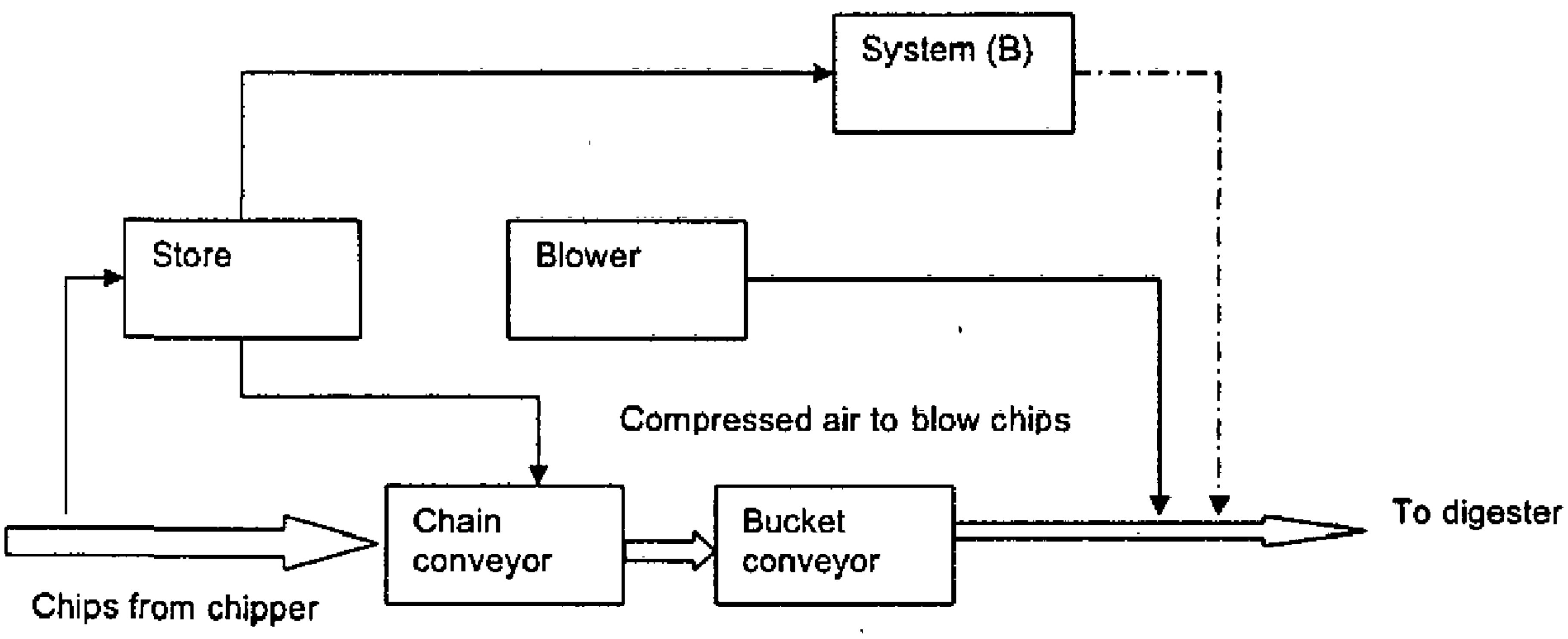


Figure 4.2 Feeding System

4.2.2 PULPING

In pulping the chips are first cooked using the chemicals ($NaOH$ and Na_2S) and fine fibers are then prepared by passing the pulp through knotter, openers and deckers. Figure 4.3 shows the schematic diagram of the pulping system.

The four major operations carried out in the unit are

(i) Cooking of chips

(ii) Separation of knots

(iii) Washing of pulp, and

(iv) Opening of fibers

The chips from storage are fed into the digester (through feeding system) where after mixing with $NaOH$ and Na_2S (called white liquor) cooking of chips is carried out for several (8-10) hours. The pulp is then passed through knotters (to remove the knots) and deckers (to remove the black liquor). The liquor and knot free pulp is then washed in two to three stages. Lastly, the washed pulp is passed through openers (rotating at high speed) to segregate fibers through combing action. The prepared pulp (called pulp with fine fibers) is then sent to screening subsystem for further treatment.

The pulping unit consists of four subsystems, namely

(i) Digester (SS_1): The mixture (chips + $NaOH$ + Na_2S) is heated with steam at 8.5Kg/cm^2 pressure and around 180^{0}C temperature.

(ii) Knotter (SS_2): To separate knots and lumps from the cooked pulp. It consists of two units arranged in parallel.

(iii) Deckers (SS_3): To wash the pulp. It consists of three units arranged in series.

(iv) Openers (SS_4): To segregate fibers from washed pulp through combing action. It consists of two units arranged in parallel.

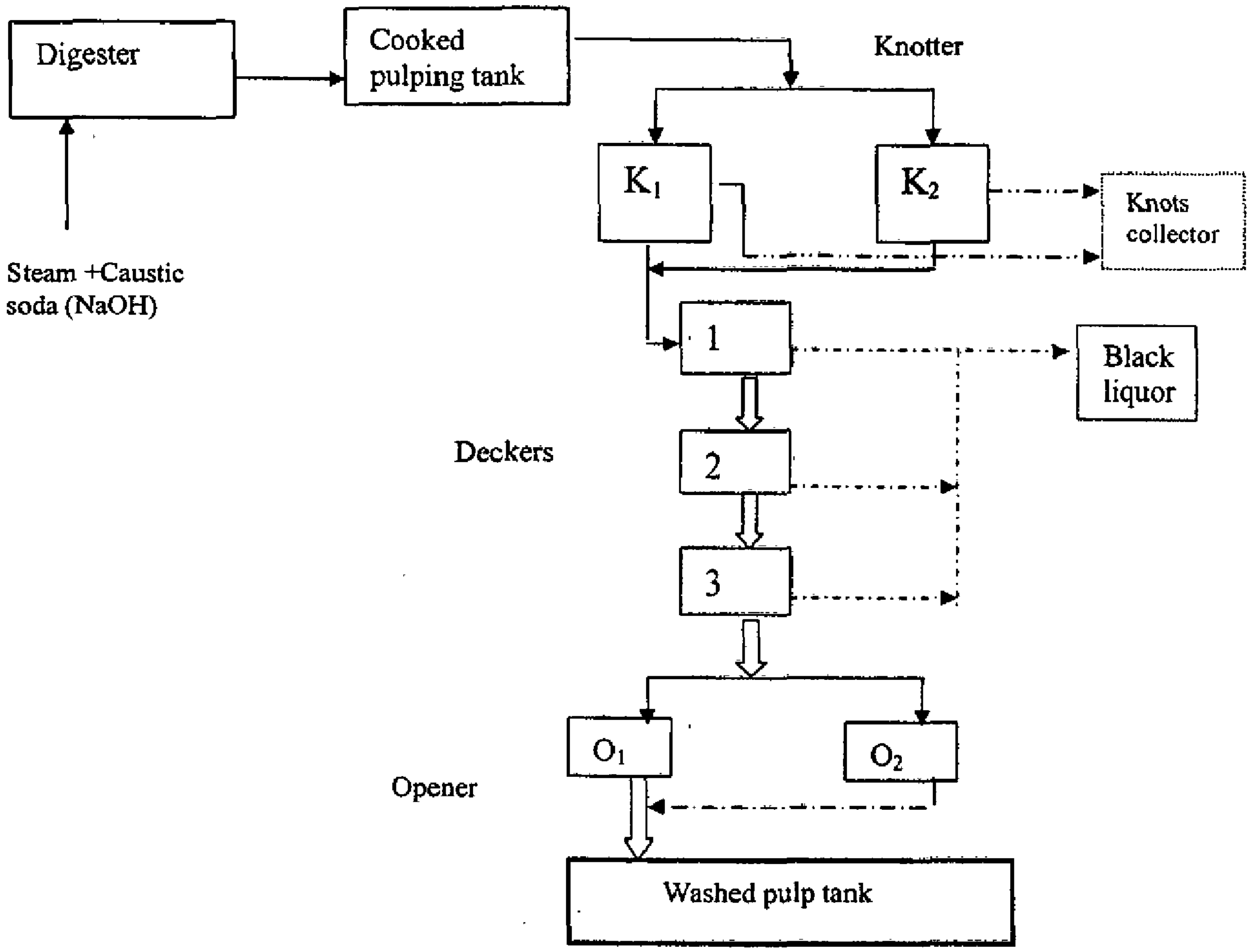


Figure 4.3 Pulping System

4.2.3 WASHING

The washing of the pulp is done in three to four stages to free it from blackness and to prepare the fine fibers of the pulp. Figure 4.4 shows the schematic representation of the system. The system consists of four main subsystems defined as:

(i) Filter [SS_1]: Filter is employed to drain black liquor from the cooked pulp.

(ii) Cleaners [SS_2]: Cleaners have three units in parallel. Here water is mixed with pulp to cleanse by centrifugal action. Failure of any one will reduce the efficiency of the system, which reduces the quality of paper.

(iii) Screen [SS_3]: Screen has two units in series. These are used to remove oversized, uncooked and odd shaped fibers from pulp through straining action. Failure of any one unit will cause system to fail.

(iv) Decker [SS_4]: Decker has two units in parallel. Complete failure of Decker occurs when both fail.

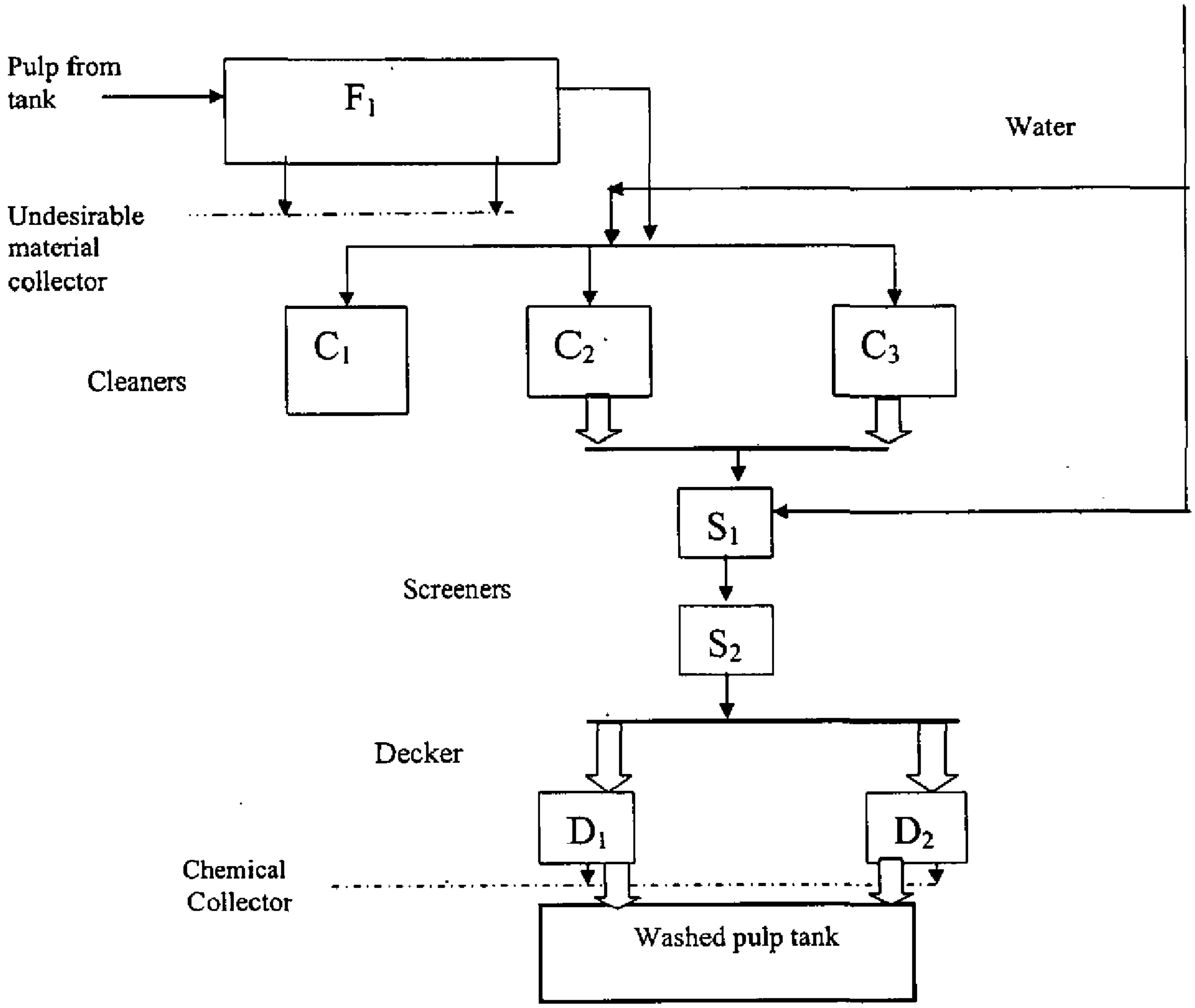


Figure 4.4 Washing System

4.2.4 BLEACHING

The bleaching system is used to bleach the pulp and further treat it to obtain bright white pulp. Figure 4.5 shows the schematic diagram of the system, it consists of bleaching tank along with two subsystems arranged in series defined as under:

Sub System 1 [SS_1] (The filters). Its primary function is to wash the bleached pulp and remove entrapped gases. The sub system consists of two units and is said to be failed when one of the two units have failed.

Sub System 2 [SS_2] (The washers). Its primary function is to wash the fibers and to remove chlorine from the pulp. It consists of two units in series and is said to be failed when one of the unit fails.

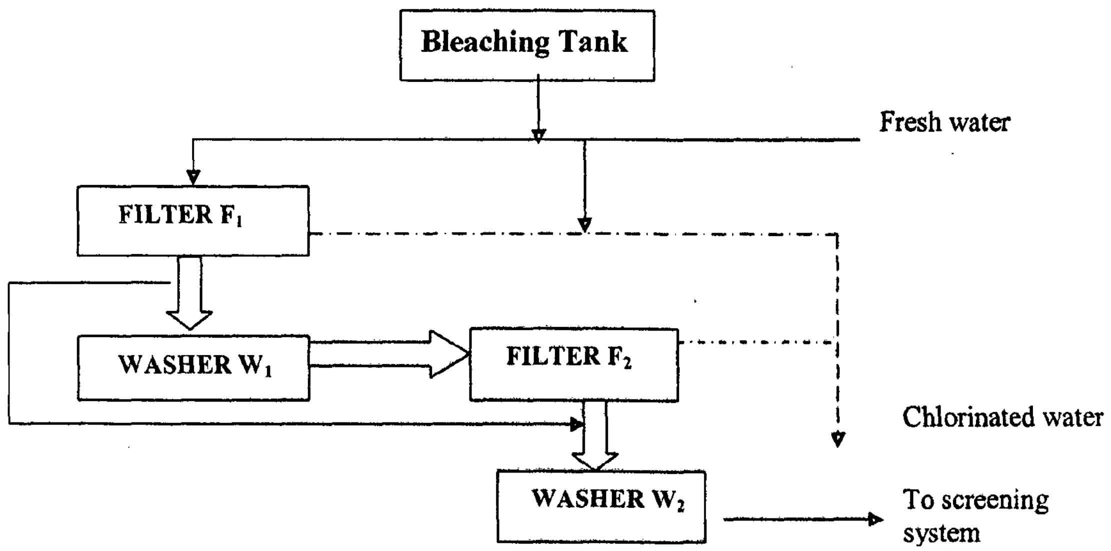


Figure 4.5 Bleaching System

4.2.5 SCREENING

The system is used to screen the pulp available from bleaching and/or pulping and to make it free from impurities. Figure 4.6 shows the schematic diagram of the system.

It consists of four main subsystems defined as

(i) Filter [SS_1]: Filter is employed to remove foreign material from the cooked pulp.

(ii) Screener [SS_3]: Screener has one unit which is used to remove oversized, uncooked and odd shaped fibers from pulp through straining action. Its failure will cause system to fail.

(iii) Cleaners [SS_2]: It has three units in parallel. Here water is mixed with pulp to cleanse by centrifugal action. Failure of any one will reduce the efficiency of the system, and hence, reduces the quality of paper.

(iv) Washer [SS_4]: It has also one unit. The main function is to wash the before delivering it to the head box of the paper machine.

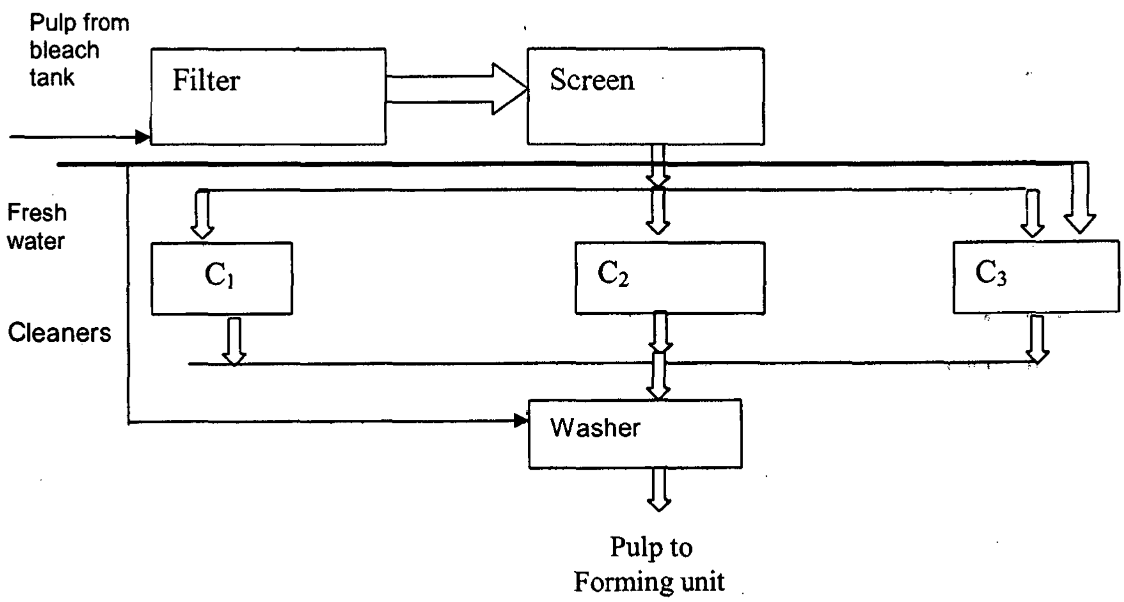


Figure 4.6 Screening System

.2.6 FORMING

The forming unit is the important functionary part of the paper machine. The unit is used › carry the metered quantity of the pulp for processing. It consists of head box, wire mat and ıction box (more failure occurrence units) and large number of rollers. Cooked pulp after :ocessing through number of stages is fed to head box of paper machine from where (in ›ntrolled proportion) it is made to run over the wire mat, running over the rollers. Head box ›livers stock (pulp +water) in controlled quantity to moving wire mat, supported by series of table ıd wire rolls. The suction box (having six pumps) dewaters the pulp through vacuum action.

2.7 Press

The main function of the system is to reduce the moisture content of the paper (received om forming section) by pressing the pulp under the rolls. The system consists of felt, upper and ›ttom rolls as three main components. The system receives wet paper sheet from forming unit on the felt, which is further passed through press rolls, thereby reducing the moisture content to most 50-60 %.

2.8 Dryer

The main function of the system is to dry the pulp (available from press section) by heating d vaporizing the moisture content to zero level. The system consists of felt, steam-heated rolls ryers), in stages, associated with steam handling systems. The rolls are heated with superheated ›am and they carry the paper along with the felt and thus, vaporize the moisture content mpletely. Figure 4.7 shows the schematic diagram consisting of all the three units.

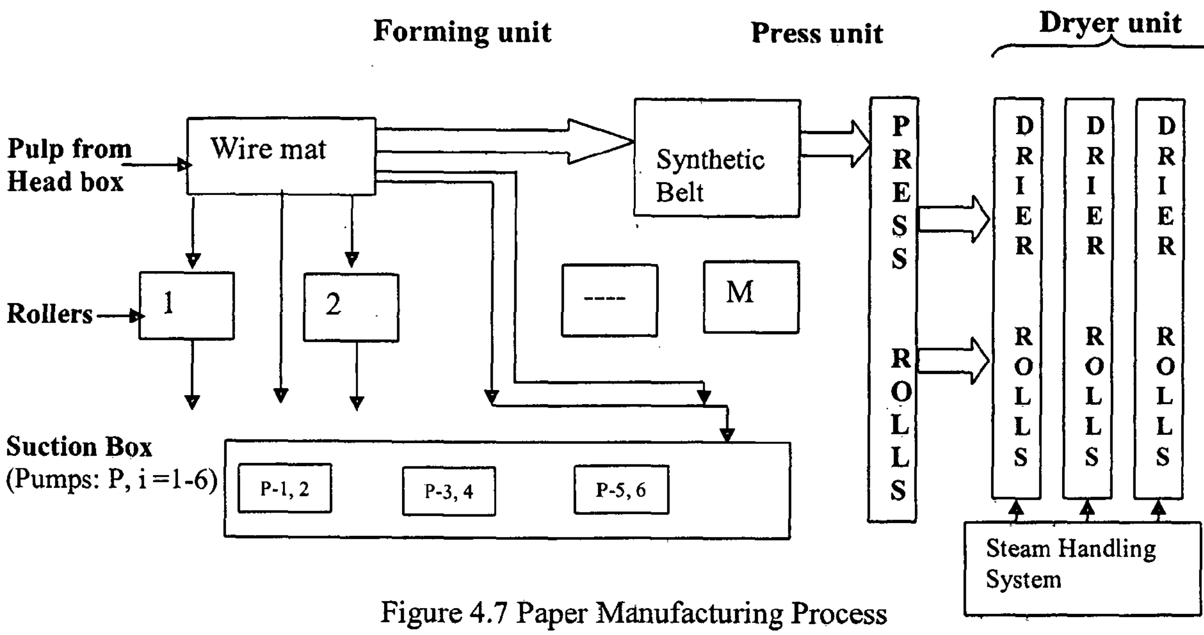


Figure 4.7 Paper Manufacturing Process

4.3 FRAMEWORK FOR PERFORMANCE EVALUATION

4.3.1 Introduction As discussed in section 4.1 that framework based upon qualitative and quantitative techniques is used to analyze and evaluate the system performance. Root cause analysis and failure mode effect analysis has been used to analyze the qualitative aspects related to the system. In order to determine various causes related to abnormal performance of the subsystems, the root cause analysis of all the sub-systems is carried out. The RCA diagrams of all the subsystems are shown in Figure 4 (viii) to 4 (xv) (Appendix A-4). Further, to list out all potential failure modes, their causes and effect on system performance FMEA for all the subsystems is carried out. In brief the methodology used to compute the scores (related to failure of occurrence (O_f), likelihood of non-detection of failure (O_d), and severity (S) of failure of various components) and to address the limitations associated with the traditional method of obtaining RPN is given below (Sharma *et al.*, 2005) :

Probability of occurrence of failure [O_f] Probability of occurrence of failure is evaluated as a function of mean time between failures. The data related to mean time between failures of omponents is obtained from previous historical records, maintenance log-books and is then tegrated with the experience of maintenance personnel. For instance, if MTBF of component is etween 2 to 4 months then probability of occurrence of failure is high (occurrence rate 0.5-1%) ith the score ranging between 7 to 8. Table 4.1 presents the linguistic assessment of probability of ilure occurrence with corresponding MTBF and scores assigned.

robability of Non-detection of failures [O_d] The chance of detecting a failure cause or echanism depends on various factors such as ability of operator, maintenance personnel to detect ilure through naked eye, by periodical inspection or with the use of machine diagnostic aids such automatic controls, alarms and sensors. For instance, if non-detection probability of failure of a mponent (through naked eye) is 0-5%, then it is ranked 1 with non-detectability 'remote'. The lues of O_d for various failure causes reported in the study are evaluated as per the score reported Table 4.1.

Table 4.1 Scale for Measuring FMEA Inputs

nguistic rms	Symbol	Score /Rank no.	MTBF	Occurrence Rate% [O_f]	Severity Effect [S]	Likelihood Of Non-detection (%)[O_d]
emote	--	1	>3 years	< 0.01	Not noticed	0-5
w	-	2 3	1-3 years	0.01-0.1	Slight annoyance to operator	6-15 16-25
oderate	+	4 5 6	0.4-1 year	0.1-0.5	Slight deterioration in system performance	26-35 36-45 46-55
gh	++	7 8	2-4months	0.5-1	Significant deterioration in system performance	56-65 66-75
ry high	+++	9 10	< 2 months	>1	Production loss & non- conforming products	76-85 86-100

Severity of failure [S] Severity of failure is assessed by the possible outcome of failure effect on the system performance. The severity of effect may be regarded as remote, moderate or very high. In the study the data related to Mean Time to Repair (MTTR), effect on the quality of the product are used to obtain score for severity. For instance, if MTTR of facility/component is less, say less than 1 hour, the effect may be regarded as 'remote'. If external intervention is required for repairs or MTTR exceeds 1/2 days and there is appreciable deterioration in the quality of the paper, effect may be regarded as 'high'. If system degrades resulting process shut down i.e. stoppage of production, the severity may be regarded as 'very high'.

The main discrepancies associated with the traditional procedure of risk ranking (such as discussed in chapter 3 under section) were modeled using Fuzzy Decision Making System (FDMS) shown in Figure 4.16, based on fuzzy methodology and Grey Relation Analysis (GRA) approach as shown in Figure 4.17. The FDMS makes use of well-defined membership functions for three inputs O_f, S and O_d and one output [Figure 4.18(a) and (b)] to capture the element of uncertainty and subjectivity related to FMEA information. The interpretation of descriptive terms *Remote(R), Low (L), Moderate (M), High (H) and Very High (VH)* are used to describe occurrence, the severity and the non-detectability is presented in Table 4.2. The inputs are evaluated for various failure causes in Fuzzy Inference System (FIS), which makes use of well defined rule base as shown in Figure 4.19. All the parameters adopted in Mamdani model to generate FIS systems are presented in Table 4.3. As discussed in the literature review that like fuzzy set theory, Grey theory also deals with making decisions characterized by incomplete and partially known information by using relation analysis and model construction. Figure 4.17 illustrates the grey theory approach used in the study to prioritize the causes, identified in the FMEA process. The membership function for each linguistic term associated with (O_f), (S) and (O_d) are defined (which are same as that used in used in FDSS). Then, using Chen's (1985) ranking method, defuzzification is carried out (Table 4.4). The obtained defuzzified values are used to generate the comparative series.

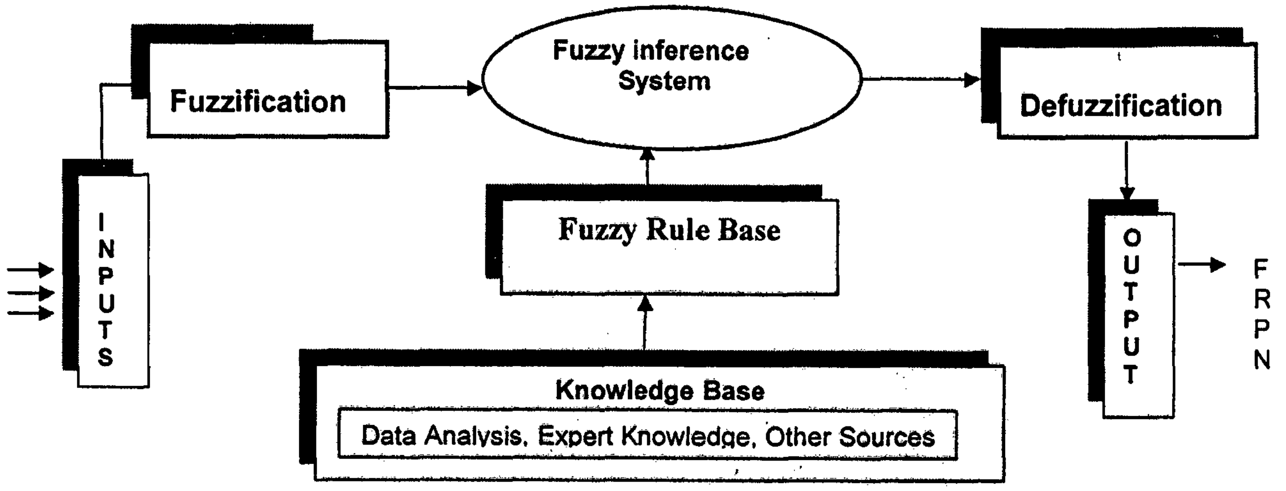


Figure 4.16 Fuzzy Decision Making System (FDMS)

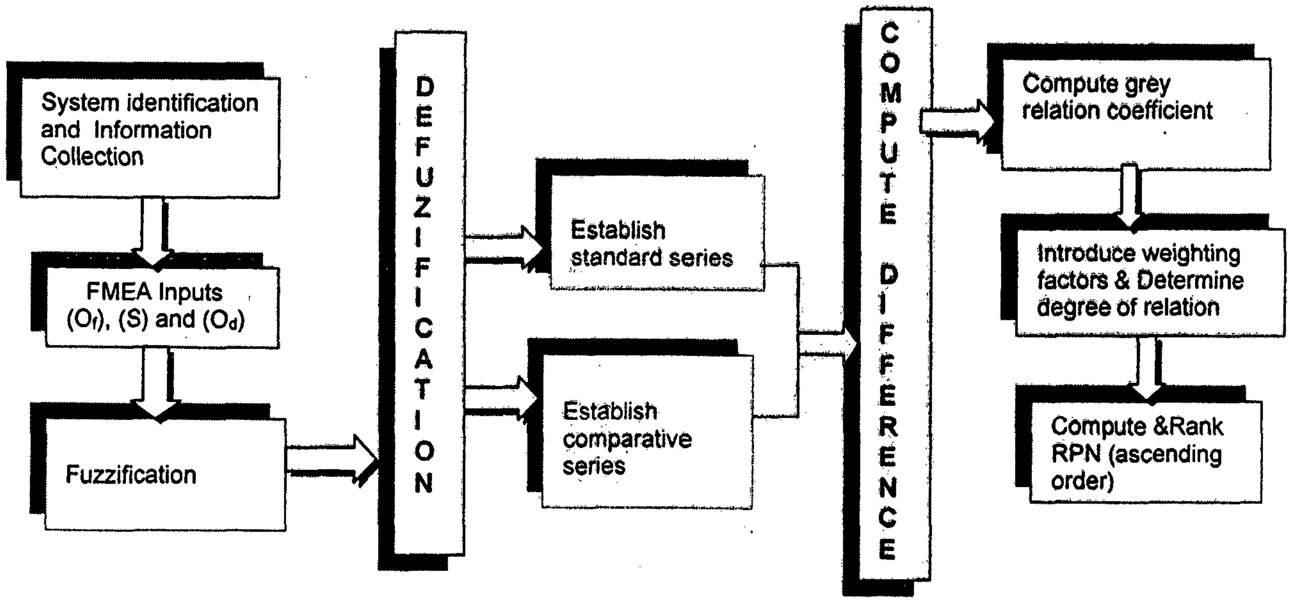


Figure 4.17 Grey Relation Analysis (GRA) Approach

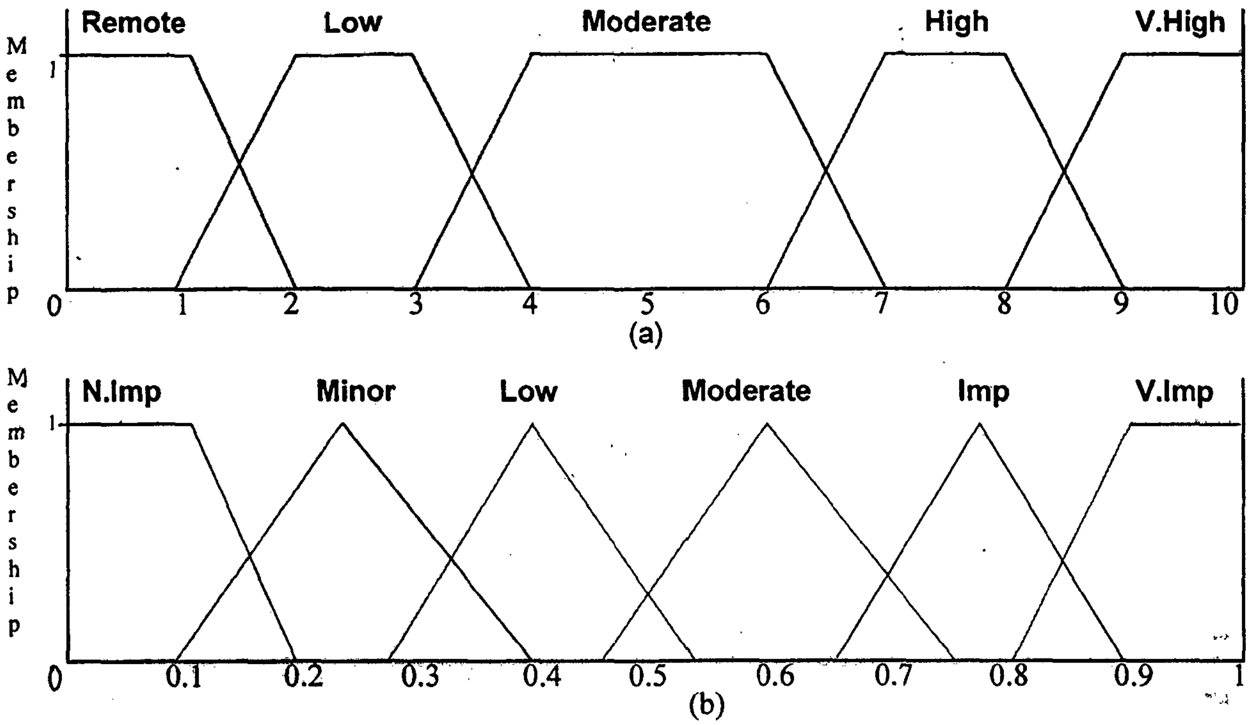


Figure 4.18 Representation of Fuzzy Membership function (a) O_s, S& O_d (b) risk priority

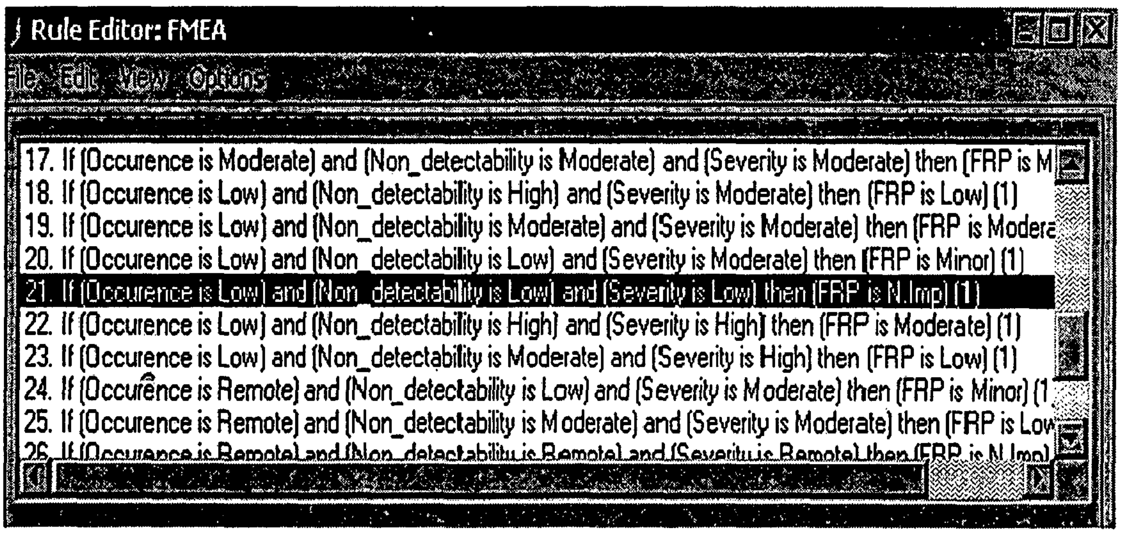


Figure 4.19 Format of Rules on Fuzzy Inference System

Table 4.2 Interpretation of Descriptive Terms used for Graphical Representation of Fuzzy MF

escriptive Term	Probability of occurrence (O_f)	Severity (S)	Non-Detectability (O_d)
Remote	It would be very unlikely for these failures to be observed once	A failure that has no effect on the system performance, the operator probably will not notice.	Defect remains undetected until the system performance degrades to the extent that the task will not be completed.
Low	Likely to occur once but un likely to occur more frequently	A failure that would cause slight annoyance to the operator, but that would cause no deterioration to the system	Defect remains undetected until the system performance is severely reduced
loderate	Likely to occur more than once	A failure that would cause high degree of operator dissatisfaction, or that causes noticeable but slight deterioration in system performance.	Defect remains undetected until the system performance is affected.
High	Near certain to occur at least once	A failure that causes deterioration in system performance and or leads to minor injuries.	Defect remains undetected until inspection or test is carried out.
'ery High	Near certain to occur several times	A failure that would seriously affect the ability to complete the task or cause damage, serious injuries or death.	Failure remains undetected such a defect would almost certainly be detected during inspection or test.

Table 4.3 Listing of Information on Fuzzy Inference System

[System] Name='FMEA Type='mamdani' Version=2.0 NumInputs=3 NumOutputs=1 NumRules=27 And Method='min' Or Method='max' Imp Method='min' AggMethod='max' DefuzzMethod='centroid' [Input1] Name='Occurrence' Range= [0 10] NumMFs=5 MF1='Remote':'trapmf', 0 0 1.0 2.0] MF2='Low':'trapmf', [1.0 2.0 3.0 4.0] MF3='Moderate':'trapmf', [3.0 4.0 6.0 7.0] MF4='High':'trapmf', [6.0 7.0 8 9.0] MF5='V.High':'trapmf', [8.0 9.0 10.010.0] [Input2] Name='Non Detectability' Range= [0 10] NumMFs=5 MF1='Remote':'trapmf', [0 0 1.0 2.0] MF2='Low':'trapmf', [1.0 2.0 3.0 4.0] MF3='Moderate':'trapmf', [3.0 4.0 6.0 7.0] MF4='High':'trapmf', [6.0 7.0 8.0 9.0] MF5='V.High':'trapmf', [8.0 9.0 10.0 10.0] [Input3] Name='Severity' Range= [0 10] NumMFs=5 MF1='Remote':'trapmf', 0 0 1.0 2.0] MF2='Low':'trapmf', [1.0 2.0 3.0 4.0] MF3='Moderate':'trapmf', [3.0 4.0 6.0 7.0] MF4='High':'trapmf', [6.0 7.0 8.0 9.0] MF5='V.High':'trapmf', [8.0 9.0 10.0 10.0] [Output1] Name='FRP' Range= [0 1]	Num MFs=6 MF1='N.Imp':'trapmf', 0 0 0.10.2] MF2='Minor':'trimf', [0.1 0.22 0.40] MF3='Low':'trimf', [0.258 0.39 0.544] MF4='Moderate':'trimf',[0.433 0.591 0.77] MF5='Imp':'trimf',[0.647 0.758 0.898] MF6='V.Imp':'trapmf',[0.80 0.90 1.0 1.0] [Rules] 4 5 5, 6 (1): 1 4 4 5, 4 (1): 1 4 5 4, 5 (1): 1 4 4 3, 5 (1): 1 4 5 3, 5 (1): 1 5 5 5, 6 (1) : 1 5 4 4, 5 (1): 1 5 3 5, 5 (1) : 1 5 2 5, 5 (1): 1 5 1 4, 3 (1): 1 3 4 4, 5 (1): 1 3 5 5, 5 (1): 1 3 4 4, 4 (1): 1 3 4 5, 4 (1): 1 3 3 4, 4 (1): 1 3 4 3, 3 (1): 1 3 3 3, 2 (1): 1 2 4 3, 2 (1): 1 2 3 3, 2 (1): 1 2 2 3, 1 (1): 1 2 2 2, 1 (1): 1 2 4 4, 4 (1): 1 2 3 4, 2 (1): 1 1 2 3, 1 (1):1 1 3 3, 1 (1):1 1 1 1, 1 (1):1 1 2 2, 1 (1):1

Table 4.4 Defuzzified Values of Linguistic Terms

Linguistic Term	**Defuzzified Value**
Remote	0.1409
Low	0.2920
Moderate	0.6240
High	0.7272
Very High	0.9090

The standard series for the variables are then generated by determining the optimal level of all three variables. To obtain the grey relation coefficient using Equation 3.35 (in section 3.3.6), the difference between the standard and comparative series is computed. Using the value of the grey relation coefficient and introducing a weighting factor for all three linguistic variables, the degree of grey relation for each failure cause is calculated. The degree represents the ranking order of each failure cause. The-weighting coefficient (β_k), for the linguistic variables, O_f, S and O_d is determined using AHP analysis. The experts were asked to make comparisons between occurrence (O_{w1}), severity (S_{w2}) and non-detectability (O_{w3}) and the values provided by them are:

(O_{w1}) vs. (S_{w2}) =60:40; (S_{w2}) vs. (O_{w3}) =30:70 and (O_{w3}) vs. (O_{w1}) =60:40 respectively.

Using the AHP analysis the weighting coefficients are determined and are given as below:

$$\beta_f = 0.21, \beta_s = 0.48, \text{ and } \beta_d = 0.31$$

The degree of grey relation is calculated by using Equation 3.36. Finally, the results so obtained from traditional, fuzzy and grey approach for each subsystem are prioritized.

4.3.2 Qualitative Analysis

4.3.2.1. Root cause analysis: First of all, RCA of all the sub-systems is carried out. Figure 4.8 presents RCA of the feeding system and for all other subsystems (pulping, washing, screening, bleaching, forming, press and dryer) RCA diagrams are shown in Appendix A.4 (Figures 4.9 - 4.15).

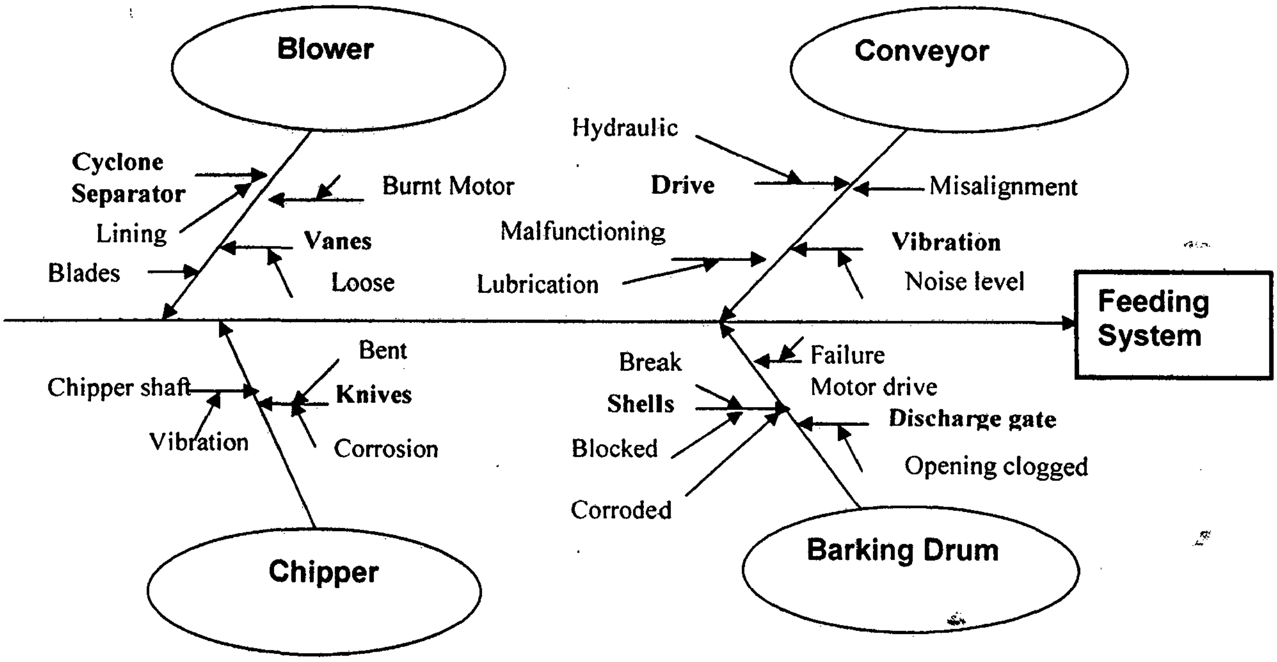


Figure 4.8 Root Cause Analysis of Feeding System

4.3.2.2 Failure Mode and Effect Analysis

Feeding system: Based upon the discussed methodology, FMEA for the sub-system is performed by listing all potential failure modes their causes and their effect on system functioning. The results (showing the respective RPN scores for each failure cause) for feeding system are presented in Table 4.5. From the table it is observed that causes PC_{11} and PC_{14} represented by different sets of linguistic terms *High, Moderate, High and Moderate, Moderate, High* produce an identical RPN i.e.245, however, the risk implication for both the causes may be totally different.

The causes PC_{14} and PC_{15} represented by same linguistic terms *Moderate, High, High and Moderate, High, High* produce different RPN and are ranked 2nd and 4th respectively, causing misleading effect on decision makers. These limitations of traditional FMEA are addressed by using both fuzzy and grey decision theory.

Table 4.5 FMEA for Feeding System

Components	**Function**	**Potential failure mode**	**Potential effect of failure**	**Potential cause of failure**	**(O_f)**	**(S)**	**(O_d)**	**RPN**
Solenoid Valve	Act as Energizer i.e. To Control piston stroke	Breaking	Piston fails to execute the movement	Burning of magnet (PC_{11})	7	5	7	245
Pressure Regulator	Control or regulate pressure	Breaking	Pressure out of range	Mechanical stresses (PC_{12})	5	6	8	240
Pneumatic pistons	To carry out movements	Blow by	Loss of air	Breaking of seal (PC_{13})	8	7	7	392
		Breaking	Piston fails to execute the movement	Breaking of piston rod (PC_{14})	5	7	7	245
Pneumatic gear case	Maintain the pressure	Breaking Clogging	Lack of adequate pressure for movement	Pump wear (PC_{15})	6	7	8	336
		Leakage	Loss of air	Blow-by (PC_{16})	5	6	9	270
Pressure tubes		Breaking	Lack of adequate pressure	Corrosion (PC_{17})	3	7	8	168

Based on the steps discussed in Chapter 3 and presented in Figure 4.17, grey theory approach is applied to prioritize the causes, identified in the FMEA process. The membership function for each linguistic term associated with O_f, S and O_d are defined (which are same as that used in used in FDMS). Using Chen's ranking, defuzzification is carried out. The defuzzified values so obtained, are shown in Table 4.4. These values are used to generate the comparative series. For instance, for the feeding system, the series obtained are represented using matrix Equation 4.1. The left hand side of matrix represents the linguistic terms assigned to failure causes (See, Table 4.1) and right hand side represents the corresponding defuzzified values (Table 4.4).

$$\begin{bmatrix} ++ & + & ++ \\ + & + & ++ \\ ++ & ++ & ++ \\ + & ++ & ++ \\ + & ++ & ++ \\ + & + & +++ \\ - & + & ++ \end{bmatrix} = \begin{bmatrix} 0.7272 & 0.4999 & 0.7272 \\ 0.4999 & 0.4999 & 0.7272 \\ 0.7272 & 0.7272 & 0.7272 \\ 0.4999 & 0.7272 & 0.7272 \\ 0.4999 & 0.7272 & 0.7272 \\ 0.4999 & 0.4999 & 0.9090 \\ 0.2920 & 0.4999 & 0.7272. \end{bmatrix} \quad (4.1)$$

Then, the standard series for the variables are generated by determining the optimal level of all three variables O_f, S and O_d. As in FMEA, smaller the RPN number, the lesser the risk, therefore standard series should consists of the lowest level of linguistic terms describing the three variables, i.e. *'Remote'* in the study. The defuzzified value obtained for remote is 0.1409, which represents the average value; as such the value 0 (lowest possible value) is used to represent the term remote. For instance, the series are represented in the form of a matrix Equation 4.2, as

$$\begin{bmatrix} - - & - - & - - \\ - - & - - & - - \\ - - & - - & - - \\ - - & - - & - - \\ - - & - - & - - \\ - - & - - & - - \\ - - & - - & - - \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{4.2}$$

To obtain the grey relation coefficient using Equation 3.35 (section 3.3.6), the difference between the standard and comparative series is computed. Using the value of the grey relation coefficient and introducing a weighting factor for all three linguistic variables, the degree of grey relation for each failure cause is calculated. The degree represents the ranking order of each failure cause. The weighting coefficient β_k for the linguistic variables, O_f, S and O_d is determined using AHP analysis as discussed in section 4.3.1. The degree of grey relation is then calculated by using Equation 3.36. For instance, for failure cause PC_{12} the grey output obtained as:

$$0.21\times 0.624+0.48\times 0.624+ 0.31\times 0.503 = 0.5864$$

The grey output values for failure causes associated with the system components are presented in Table 4.6. The comparison of the results obtained through traditional, fuzzy and grey approach is presented in Table 4.7 respectively.

Table 4.6 Grey Output Values

Failure Cause	O_f	γ_f	S	(γ_s)	O_d	(γ_d)	Grey Output
PC_{11}	++	0.503	+	0.624	++	0.503	0.5610
PC_{12}	+	0.624	+	0.624	++	0.503	0.5864
PC_{13}	++	0.503	++	0.503	++	0.503	0.5030
PC_{14}	+	0.624	++	0.503	++	0.503	0.5284
PC_{15}	+	0.624	++	0.503	++	0.503	0.5284
PC_{16}	+	0.624	++	0.503	+++	0.436	0.5657
PC_{17}	-	0.819	+	0.624	++	0.503	0.6274

Table 4.7 Comparison of Traditional, Fuzzy and Grey Results

Potential Failure Causes	Traditional FMEA Output	Ranking (Traditional)	Fuzzy RPN	Ranking (Fuzzy)	Grey Output	Ranking (Grey)
PC_{11}	245	4	0.660	3	0.5610	3
PC_{12}	240	5	0.617	5	0.5864	5
PC_{13}	392	1	0.677	1	0.5030	1
PC_{14}	245	4	0.664	2	0.5284	2
PC_{15}	336	2	0.664	2	0.5284	2
PC_{16}	270	3	0.619	4	0.5657	4
PC_{17}	168	6	0.579	6	0.6274	6

4.3.2.3 Results and Discussions:

From Table 4.7, it is observed that in traditional FMEA, events with same linguistic terms produce different RPN but both fuzzy and grey approaches produce same results and hence identical ranking. For instance, causes PC_{14}, PC_{15} where O_f, S and O_d are described by linguistic terms *Moderate, High and High* respectively, the defuzzified and grey output is 0.664 and 0.5284. This entails that these two causes should be given the same priority for attention. The RPN method, however, produces an output of 245 and 336 for these causes and ranks them at 2nd and 4th place respectively. This means that PC_{15} has the highest priority than PC_{14}, which could be misleading for decision makers. Also, we can observe that the causes PC_{11} and PC_{14} described with different linguistic terms i.e. *High, Moderate and High,* and *Moderate, High and High* produce same RPN and are assigned same priority i.e. 4th but fuzzy and grey approach entails different output and different priorities for both of them. The comparison of results presented in Table 4.9 shows that the priority ranking of failure causes associated with the system is altered i.e. as evident from traditional FMEA [PC_{13}> PC_{15}> PC_{16}> $PC_{11}$and PC_{14}> PC_{12}> PC_{17}] and with fuzzy and grey methodologies [PC_{13}> PC_{14} and PC_{15}> PC_{11}> PC_{16}> PC_{12}> PC_{17}].

PULPING

Table 4.8 presents details of FMEA (showing the respective RPN scores for each failure cause) analysis for the pulping system. From the table it is observed that a failure cause OC_{41} with high severity, low rate of occurrence, and moderate detectability (7, 3, and 4 respectively) has lower RPN (84) than DC_{31} where all the parameters are moderate (4, 5, and 5 yielding an RPN of 100) even though it OC_{41} should have a higher priority for corrective action. Also, it is observed that DC_{16} and DC_{18} produce an identical RPN i.e.288; however, the risk implication (on the basis of severity) for both of them is totally different. The grey relation results are tabulated in Table 4.9

and the comparison of traditional, fuzzy and grey approach results so obtained is presented in Table 4.10 respectively. From the Table 4.10, for digester, it is evident that in traditional FMEA, causes with same linguistic terms produce different RPN but the fuzzy and grey methods produce identical ranking. For instance, causes DC_{12}, DC_{13} and DC_{19} where O_f, S and O_d are described by *Moderate, High and, Moderate* respectively, the defuzzified output is 0.627 and the grey relation output is 0.565, for all the three events. This entails that these three causes should be given the same priority for attention. The RPN method, however, produces an output of 288, 252 and 210 for them and ranks them at 3rd, 4th and 5th place respectively. This means that DC_{11} has the highest priority followed by DC_{13} and DC_{19} which could be misleading. The effect of the weighting coefficient (decided with the help of expert opinions by performing AHP analysis) in the grey theory is visible in the results. For example, for causes DC_{16} and DC_{17} Where O_f, S and O_d are described by *Moderate, Moderate* and *High; Moderate*, *High and Moderate* respectively. The traditional approach ranks DC_{16} higher than DC_{17} but both fuzzy and grey approach ranks DC_{17} higher thanDC_{16}. This shows that DC_{17} should be given a higher priority (when severity is considered) as compared to [DC_{16}]. Similarly, for knotter, causes KC_{23} and KC_{24} produce identical RPN (though represented by different linguistic terms), which could be misleading. But both grey and fuzzy approach produces different rankings. Also, the effect of weighting coefficient can be seen which ranks KC_{24} higher than KC_{23}. For openers and deckers, the causes OC_{42} and OC_{44}; DC_{31} and DC_{32} and DC_{36} and DC_{39} described with same linguistic terms (Moderate, *High, Moderate and Moderate, Moderate, Moderate and* Moderate, *High, High)* produce different RPN and hence assigned different priorities but fuzzy and grey method produce identical ranking. We can also see the effect of weighting coefficient for causes DC_{38} and DC_{39}. Here even both causes produce identical RPN and same priority but after introducing a weighting coefficient, DC_{39} is ranked higher than DC_{38} i.e. because of high severity.

Table 4.8 Failure Mode Effect Analysis [Pulping System]

omponent	Function	Potential failure mode	Potential effect of failure	Potential cause of failure	O_f	S	O_d	RPN
igester								
'hip feeder alve	*To feed the chips to digester*	Fails to open properly	Reduced let down flow	Valve operator malfunction [DC_{11}]	6	8	8	384
				Broken internals [DC_{12}]	6	8	6	288
emote valve perator	To adjust air supply to vessel	Fails open Fails close	Combustion loss Loss in operation	Valve operator malfunction [DC_{13}]	6	7	6	252
'emperature ontroller valve	To control bed temperature	Fails open Fails close	Possible damage to cooking	Mechanical binding. [DC_{14}]	4	9	5	180
'ressure time ycle controller alve	To control steam pressure (100-135psi)	Fails open	Loss in cooking /digestion of chips	Broken internals [DC_{15}]	5	9	9	405
		Fails close		Valve operator failure [DC_{16}]	6	6	8	288
team flow and ontroller valve	To control steam flow	Fails to open completely	Failure to regulate steam flow	Valve operator malfunction [DC_{17}]	6	7	6	252
'op relief valve	To relieve non condensable gases from digester	Fails to operate	Increase in temperature	Valve operator malfunction [DC_{18}]	4	9	8	288
'low line valve	To blow the charge	Fails open	Loss in operation	Clogging [DC_{19}]	6	7	5	210
				Mechanical binding [DC_{110}]	4	7	7	196
notter	To remove knots or lumps							
'ibrating screen	To screen coarse fibers	Wear	Incomplete screening	Corrosion [KC_{21}]	3	3	6	54
		Plugging		Abrasion [KC_{22}]	4	4	5	80
			Loss in operational efficiency	Mat build up [KC_{23}]	6	5	7	210
				Contaminants[KC_{24}]	7	5	6	210

Table 4.8 Contd-

Deckers	To remove black liquor from pulp. (4% A.D) air dry							
Wire mesh	Drainage of water and black liquor	Buildup	Improper screening of pulp	Abrasion of mesh [DC_{31}]	4	5	5	100
				Corrosion [DC_{32}]	5	6	5	150
				Foreign material [DC_{33}]	7	8	8	448
Vacuum pumps	To create vacuum	Leakage rotor jamming	Loss in operational efficiency	Lack of lubrication in moving parts. [DC_{34}]	4	7	5	140
				Bearing failure [DC_{35}]	6	7	5	210
				Inclusion of solid particles [DC_{36}]	5	7	7	245
				Seal failure [DC_{37}]	7	6	5	210
Let down relief valve	To remove contaminants	Fails open Fails closed	Loss in operation	Mechanical failure [DC_{38}]	7	6	8	336
				Blockage. [DC_{39}]	6	8	7	336
Openers	To separate oversized fibers							
Combing Blades	To bundle out big fibers through combing action	Buildup Wear	Improper separation of fibers	Abrasion [OC_{41}]	3	4	7	84
				Corrosion [OC_{42}]	5	7	5	175
				Foreign material [OC_{43}]	7	8	8	448
Pump		Rotor jamming	Complete failure of system	Lack of lubrication in moving parts. [OC_{44}]	6	8	5	240
				Impeller failure[OC_{45}]	3	7	5	105
			Loss in operation	Seal failure [OC_{46}]	7	6	5	210

Table 4.9 Grey Output Values for Pulping System

Failure cause	O_f	γ_f	S	(γ_s)	O_d	(γ_d)	**Grey output**
DC_{11}	+	0.624	++	0.503	++	0.503	0.5284
DC_{12}	+	0.624	++	0.503	+	0.624	0.5650
DC_{13}	+	0.624	+	0.624	+	0.624	0.5864
DC_{14}	+	0.624	+++	0.436	+	0.624	0.53376
DC_{15}	+	0.624	+++	0.436	+	0.436	0.47548
DC_{16}	+	0.624	+	0.624	++	0.503	0.5864
DC_{17}	+	0.624	++	0.503	+	0.624	0.5650
DC_{18}	+	0.624	+++	0.436	++	0.503	0.4962
DC_{19}	+	0.624	++	0.503	+	0.624	0.5650
DC_{110}	+	0.624	++	0.503	++	0.503	0.5284
KC_{21}	- -	0.819	+++	0.436	+++	0.436	0.7585
KC_{22}	+	0.503	+	0.624	+	0.624	0.624
KC_{23}	+	0.624	+	0.624	++	0.503	0.5864
KC_{24}	++	0.503	+	0.624	+	0.624	0.5405
DC_{31}	+	0.624	+	0.624	+	0.624	0.624
DC_{32}	+	0.624	+	0.624	+	0.624	0.624
DC_{33}	+	0.624	++	0.503	++	0.503	0.503
DC_{34}	+	0.624	++	0.503	+	0.624	0.665
DC_{35}	+	0.624	++	0.503	+	0.624	0.665
DC_{36}	+	0.624	++	0.503	++	0.503	0.5284
DC_{37}	++	0.503	+	0.624	+	0.624	0.6195
DC_{38}	++	0.503	+	0.624	++	0.503	0.5610
DC_{39}	+	0.624	++	0.503	++	0.503	0.5284
OC_{41}	+	0.624	+	0.436	+	0.624	0.624
OC_{42}	+	0.503	++	0.503	+	0.624	0.565
OC_{43}	+	0.624	++	0.503	++	0.503	0.5284
OC_{44}	+	0.624	++	0.503	+	0.624	0.565
OC_{45}	- -	0.819	++	0.503	+	0.624	0.606
OC_{46}	++	0.503	+	0.624	+	0.624	0.5405

Table 4.10 Comparative Results [Traditional, Fuzzy and Grey] for Pulping System

Potential cause of failure	Traditional RPN output	Traditional Ranking	Fuzzy RPN Output	Fuzzy Ranking	Grey Output	Grey Ranking
DC_{11}	384	2	0.667	3	0.5284	3
DC_{12}	288	3	0.627	5	0.5650	5
DC_{13}	252	4	0.627	5	0.5650	5
DC_{14}	180	7	0.659	4	0.5337	4
DC_{15}	405	1	0.679	1	0.4754	1
DC_{16}	288	3	0.617	6	0.5864	6
DC_{17}	252	4	0.627	5	0.5650	5
DC_{18}	288	3	0.677	2	0.4962	2
DC_{19}	210	5	0.627	5	0.5650	5
DC_{110}	196	6	0.667	3	0.5284	3
KC_{21}	54	3	0.301	4	0.7585	4
KC_{22}	80	2	0.511	3	0.6240	3
KC_{23}	210	1	0.617	2	0.5864	2
KC_{24}	210	1	0.660	1	0.5405	1
DC_{31}	100	7	0.511	7	0.6240	6
DC_{32}	150	5	0.511	7	0.6240	6
DC_{33}	448	1	0.667	1	0.5030	1
DC_{34}	140	6	0.627	5	0.6650	7
DC_{35}	210	4	0.627	5	0.6650	7
DC_{36}	245	3	0.644	3	0.5284	3
DC_{37}	210	4	0.546	6	0.6195	5
DC_{38}	336	2	0.636	4	0.5610	4
DC_{39}	336	2	0.644	2	0.5284	2
OC_{41}	84	6	0.5110	5	0.6240	5
OC_{42}	175	4	0.6270	3	0.5650	3
OC_{43}	448	1	0.6670	1	0.5284	1
OC_{44}	240	2	0.6270	3	0.5650	3
OC_{45}	105	5	0.5330	4	0.6060	4
OC_{46}	210	3	0.6600	2	0.5405	2

WASHING

Table 4.11 presents the details of traditional FMEA analysis for the washing unit. The numerical values of FMEA parameters i.e. O_f, S and O_d were obtained by using the methodology discussed in section 4.1. Then *RPN* number for each failure cause is evaluated by multiplying the factor scores i.e. [$O_f \times S \times O_d$]. From Table 4.11 it is observed that for deckers, WC_{48} and WC_{49} represented by different sets of linguistic terms produce an identical RPN (336), however, the risk implication for both the causes may be totally different. For pumps, the causes WC_{54} and WC_{57} represented by same linguistic terms produce different RPN and are ranked 2nd and 1st respectively, which could be misleading and so on. These limitations of traditional FMEA are addressed by using both fuzzy and grey decision theory. The grey output values for failure causes associated with the system components are presented in Table 4.12 and the comparison of the results is presented in Table 4.13 respectively.

From Table 4.13 (for Cleaners), it is evident that in traditional FMEA, events with same linguistic terms produce different RPN but the fuzzy and grey methods produce identical ranking .For instance, causes WC_{22} and WC_{24}, where O_f, *S* and O_d are described by same linguistic terms i.e. *Moderate, Moderate and High* respectively, the defuzzified output is 0.617 and the grey relation output is 0.5864. This entails that these two causes should be given the same priority for attention. The RPN method, however, produces an output of 288 and 240 for these causes and ranks them at 3rd and 4th place respectively. This means that WC_{22} has the highest priority than WC_{24}, which could be misleading. For screeners, the effect of the weighting coefficient (introduced by taking expert opinions by performing AHP analysis) in the grey theory is visible in the results obtained. For example, for causes $WC_{33}$and WC_{34} (where O_f, *S* and O_d are described by *High, Moderate, Moderate; Moderate, High, Moderate* respectively) the traditional approach ranks WC_{33} higher than WC_{34} but both fuzzy and grey approach ranks WC_{34} higher than WC_{33}. This shows that WC_{34} should be given a higher priority when severity is considered as deciding factor.

For deckers, the causes WC_{41} and WC_{42} (described with same linguistic terms i.e. *Moderate, Moderate, Moderate*) produce different RPN and are assigned different priorities but fuzzy and grey method entails same output and same priorities for them. We can also see the effect of weighting coefficient for causes WC_{48} and WC_{49}. Though both causes produce identical RPN and same priority but by introducing a weighting coefficient WC_{49} is ranked higher than WC_{48} because of high severity. For pumps, the causes WC_{54} and WC_{57} (with same linguistic terms) produce different RPN using traditional FMEA and are ranked 3rd and 1st respectively, which could be misleading. On the other hand both grey and fuzzy approaches produce same output/rank.

Table 4.11 Failure Mode Effect Analysis [Washing System]

Component	Function	Potential failure mode	Potential effect of failure	Potential cause of failure	O_f	S	O_d	RPN
Filters	To filter the contaminants	Blockage Rupture	Loss in operational efficiency	Presence of Foreign materials. (Sand, grit, nails, staples, rocks etc.) [WC_{11}]	8	8	8	512
Cleaners	To remove high specific. gravity debris from pulp.	Mat scale build up Pressure drop loss	Impairs cleaning	Presence of contaminants [WC_{21}]	8	8	8	512
				Blade wear [WC_{22}]	6	6	8	288
				Faulty installation [WC_{23}]	3	6	6	108
				Mat build up [WC_{24}]	5	6	8	240
Contaminant isolation valve	To extract contaminants	Fails to open properly	Loss in extraction	Mechanical binding [WC_{25}]	6	7	8	336
				Valve operator malfunction [WC_{26}]	4	6	5	120
Screeners	To wash the pulp to remove blackness.	Wear of blades	Loss in operation	Corrosion [WC_{31}]	3	6	5	90
				Abrasion [WC_{32}]	4	6	5	120
Screens		Plugging	Flow obstructed	Mat build up [WC_{33}]	7	6	5	210
				Presence of contaminants [WC_{34}]	4	8	6	192
Deckers								
Wire mesh	Drainage of water and black liquor	Buildup	Improper screening of pulp	Abrasion of mesh [WC_{41}]	4	5	5	100
				Corrosion [WC_{42}]	5	6	5	150
				Foreign material [WC_{43}]	7	8	8	448
Vacuum pumps	To create vacuum	Leakage rotor jamming	Loss in operational efficiency	Lack of lubrication in moving parts. [WC_{44}]	4	7	5	140
				Bearing failure [WC_{45}]	6	7	5	210
				Inclusion of solid particles[WC_{46}]	5	7	7	245
				Seal failure [WC_{47}]	7	6	5	210
Let down relief valve	To remove contaminants	Fails open Fails closed	Loss in operation	Mechanical failure [WC_{48}]	7	6	8	336
				Blockage. [WC_{49}]	6	8	7	336
Pump	To pump water from reservoir	Leakage	Loss of water	Seal failure [WC_{51}]	7	6	5	210
				Packing improperly installed [WC_{52}]	3	6	5	90
		Rotor jamming	Motor overloaded /pressure loss	Lack of lubrication in moving parts. [WC_{53}]	6	6	6	216
				Bearing failure [WC_{54}]	6	8	5	240
		Noisy and vibrations	Reduction in efficiency of pump.	Cavitation [WC_{55}]	4	6	5	120
				Foreign material in impeller [WC_{56}]	5	7	5	175
				Worn-out bearings. [WC_{57}]	6	7	6	252

Table 4.12 Computation of Grey Output Values

Failure cause	O_f	γ_f	S	(γ_s)	O_d	(γ_d)	Grey output
WC_{11}	++	0.503	++	0.503	++	0.503	0.5030
WC_{21}	++	0.503	++	0.503	++	0.503	0.5030
WC_{22}	+	0.624	+	0.624	++	0.503	0.5864
WC_{23}	-	0.819	+	0.624	+	0.624	0.6649
WC_{24}	+	0.624	+	0.624	++	0.503	0.5864
WC_{25}	+	0.624	++	0.503	++	0.503	0.5284
WC_{26}	+	0.624	+	0.624	+	0.624	0.6240
WC_{31}	-	0.819	+	0.624	+	0.624	0.6649
WC_{32}	+	0.624	+	0.624	+	0.624	0.6240
WC_{33}	++	0.503	+	0.624	+	0.624	0.5985
WC_{34}	+	0.624	++	0.503	+	0.624	0.5650
WC_{41}	+	0.624	+	0.624	+	0.624	0.6240
WC_{42}	+	0.624	+	0.624	+	0.624	0.6240
WC_{43}	++	0.503	++	0.503	++	0.503	0.5030
WC_{44}	+	0.624	++	0.503	+	0.624	0.6650
WC_{45}	+	0.624	++	0.503	+	0.624	0.6650
WC_{46}	+	0.624	++	0.503	++	0.503	0.5284
WC_{47}	++	0.503	+	0.624	+	0.624	0.6195
WC_{48}	++	0.503	+	0.624	++	0.503	0.5610
WC_{49}	+	0.624	++	0.503	++	0.503	0.5284
WC_{51}	++	0.503	+	0.624	+	0.624	0.5985
WC_{52}	-	0.503	+	0.624	+	0.624	0.6649
WC_{53}	+	0.624	+	0.624	-	0.819	0.6844
WC_{54}	+	0.624	++	0.503	+	0.624	0.5650
WC_{55}	+	0.624	+	0.624	+	0.624	0.6240
WC_{56}	++	0.503	++	0.503	+	0.624	0.54051
WC_{57}	+	0.624	++	0.503	+	0.624	0.5650

Table 4.13 Comparison of Traditional, Fuzzy and Grey Output

Potential cause of failure	Traditional RPN output	Traditional Ranking	Fuzzy Output	Fuzzy Ranking	Grey output	Grey Ranking
WC_{11}	512	1	0.667	1	0.503	1
WC_{21}	512	1	0.667	1	0.5030	1
WC_{22}	288	3	0.617	3	0.5864	3
WC_{23}	108	6	0.579	5	0.6649	5
WC_{24}	240	4	0.617	3	0.5864	3
WC_{25}	336	2	0.664	2	0.5284	2
WC_{26}	120	5	0.597	4	0.6240	4
WC_{31}	90	4	0.579	4	0.6649	4
WC_{32}	120	3	0.597	3	0.6240	3
WC_{33}	210	1	0.601	2	0.5985	2
WC_{34}	192	2	0.627	1	0.5650	1
WC_{41}	100	7	0.597	6	0.6240	5
WC_{42}	150	5	0.597	6	0.6240	5
WC_{43}	448	1	0.667	1	0.5030	1
WC_{44}	140	6	0.627	4	0.6650	6
WC_{45}	210	4	0.627	4	0.6650	6
WC_{46}	245	3	0.644	2	0.5284	2
WC_{47}	210	4	0.601	5	0.6195	4
WC_{48}	336	2	0.636	3	0.5610	3
WC_{49}	336	2	0.644	2	0.5284	2
WC_{51}	210	5	0.601	3	0.5985	3
WC_{52}	90	7	0.579	5	0.6649	5
WC_{53}	216	4	0.551	6	0.6844	6
WC_{54}	240	3	0.627	2	0.5650	2
WC_{55}	120	6	0.597	4	0.6240	4
WC_{56}	245	2	0.646	1	0.54051	1
WC_{57}	252	1	0.627	2	0.5650	2

BLEACHING

Table 4.14 presents the FMEA analysis along with the numerical values assigned to the parameters i.e. O_f, S and O_d, obtained using the discussed methodology in section 4.1. From the table it is observed that causes BC_1 and BC_3 represented by different sets of linguistic terms i.e. *low, high, moderate and low, moderate, high* produce an identical RPN i.e.120, however, the risk implication for both the causes may be totally different. The causes BC_1 and BC_6 represented by same linguistic terms i.e. low, high, moderate produce different RPN and are ranked 8^{th} and 7^{th} respectively, which could be misleading for arriving at decisions. The above listed limitations of traditional FMEA were addressed by using both fuzzy and grey decision theory as discussed in section 4.1. The grey relation results are tabulated in Table 4.15 and the comparative results (traditional, fuzzy and grey approach) so obtained are presented in Table 4.16.

From the Table 4.16, it is observed that in traditional FMEA, causes with same linguistic terms produce different RPN but both fuzzy and grey approaches produce same results and hence identical ranking. For instance, causes BC_1 and BC_6 ; BC_8 and BC_{13} where O_f, S and O_d are described by linguistic terms *Low, High, Moderate and Moderate, Moderate, High* respectively, the defuzzified and grey output are same for the respective sets. This entails that these causes should be given the same priority for attention. The RPN method, however, produces an output of 120 for BC_1, 126 for BC_6, 192 for BC_8 and 240 for BC_{13} and ranks them at 8^{th}, 7^{th}, 5th, and 3^{rd} place respectively, which could be misleading. Also, we can observe that causes BC_1 and BC_3 ; BC_6 and BC_{12} (represented with different sets of linguistic terms i.e. *Low, High, Moderate* and *Low, Moderate, High*) produce an identical RPN i.e.120, 126 however, the risk implication for both the may be totally different. But fuzzy and grey approach entails different output and different priorities for both of them. We can also visualize the effect of weighting coefficient.

Cause BC_1 is ranked higher than BC_3 when severity is considered as criterion. The comparison of results presented in Table 4.16 shows that the priority ranking of failure causes associated with the system, obtained from the traditional FMEA and approximate reasoning methodologies are altered.

Table 4.14 Failure Mode Effect Analysis [Bleaching System]

Component	**Function**	**Potential failure mode**	**Potential effect of failure**	**Potential cause of failure**	**O_f**	**S**	**O_d**	**RPN**
Bleaching tank	*Mixing of Cl_2 and pulp*	Rupture wall	Leakage	Aging [BC_1]	3	8	5	120
		External leakages		Lining Erosion [BC_2]	4	7	5	140
			Solution spills	Corrosion [BC_3]	3	5	8	120
Pulp regulator valve	To regulate flow of pulp	Fails to open Completely	Failure to control metered flow.	Mechanical binding [BC_4]	4	9	6	216
				Broken internals [BC_5]	7	8	8	448
		Degraded operation	Failure to provide desired quantity of pulp	Valve operator failure. [BC_6]	3	7	6	126
Relief valve	To relieve gasses	Fails to close	Unable to provide emergency exit	Mechanical failure [BC_7]	4	9	8	288
		Fails to open Properly.		Broken internals [BC_8]	4	6	8	192
Chlorine flow controller valve	To control the flow of Cl_2 gas	Fails to operate continuously.	Over chlorination	Mechanical binding [BC_9]	2	6	7	84
				Broken internals [BC_{10}]	3	6	6	108
Pulp blender	Stirring or mixing the pulp	Shaft bending	Loss of steering action	Foreign material in slurry. [BC_{11}]	8	8	7	448
				Bearing failure [BC_{12}]	7	6	3	126
System piping	To carry the fluids	Leakage Rupture	Loss of fluid	Corrosion [BC_{13}]	5	6	8	240

Table 4.15 Grey Output Values

Failure Cause	O_f	γ_f	S	(γ_s)	O_d	(γ_d)	Grey Output
BC_1	-	0.819	++	0.503	++	0.503	0.606
BC_2	+	0.624	++	0.503	+	0.624	0.565
BC_3	-	0.819	+	0.624	++	0.503	0.6274
BC_4	+	0.624	+++	0.436	+	0.624	0.5337
BC_5	++	0.503	++	0.503	++	0.503	0.503
BC_6	-	0.819	++	0.503	+	0.624	0.6060
BC_7	+	0.624	+++	0.436	++	0.503	0.4962
BC_8	+	0.624	+	0.624	++	0.503	0.5864
BC_9	--	1	+	0.624	++	0.503	0.6654
BC_{10}	-	0.819	+	0.624	+	0.624	0.6649
BC_{11}	++	0.503	++	0.503	++	0.503	0.5030
BC_{12}	++	0.503	+	0.624	-	0.819	0.6590
BC_{13}	+	0.624	+	0.624	++	0.503	0.5864

Table 4.16 Comparison of Traditional, Fuzzy and Grey Output

Potential Cause	Traditional RPN output	Traditional Ranking	Fuzzy Output	Fuzzy Rank	Grey Output	Grey Ranking
BC_1	120	8	0.333	7	0.606	6
BC_2	140	6	0.431	5	0.565	4
BC_3	120	8	0.321	8	0.6274	7
BC_4	216	4	0.659	3	0.5337	3
BC_5	448	1	0.667	2	0.5030	2
BC_6	126	7	0.333	7	0.6060	6
BC_7	288	2	0.679	1	0.4962	1
BC_8	192	5	0.617	4	0.5864	5
BC_9	84	10	0.319	9	0.6654	10
BC_{10}	108	9	0.313	10	0.6649	8
BC_{11}	448	1	0.667	2	0.5030	2
BC_{12}	126	7	0.411	6	0.6590	9
BC_{13}	240	3	0.617	4	0.5864	5

SCREENING

Table 4.17 presents the details of traditional FMEA analysis for the screening unit. The numerical values of FMEA parameters i.e. O_f, S and O_d are obtained by using the discussed methodology. Then *RPN* number for each failure cause is evaluated by multiplying the factor scores i.e. [$O_f \times S \times O_d$]. From the table it is observed that for deckers, WC_{48} and WC_{49} represented by different sets of linguistic terms produce an identical RPN i.e.336, however, the risk implication for both the causes may be totally different. These limitations are addressed by using both fuzzy and grey decision theory (discussed in section 4.1). The grey output values for failure causes associated with the system components are presented in Table 4.18 and the comparison of the results (obtained through traditional, fuzzy and grey approach) is presented in 4.19 respectively.

From the Table 4.19, for Cleaners, it is observed that in traditional FMEA, events with same linguistic terms produce different RPN but the fuzzy and grey methods produce identical ranking. For instance, in case of cleaners causes WC_{22} and WC_{24}, where O_f, S and O_d are described by same linguistic terms i.e. *Moderate, Moderate and High* respectively, the defuzzified output is 0.617 and the grey relation output is 0.5864. This entails that these two causes should be given the same priority for attention. The RPN method, however, produces an output of 288 and 240 for these causes and ranks them at 3rd and 4th place respectively. This means that WC_{22} has the highest priority than WC_{24}, which could be misleading.

For screeners, the effect of the weighting coefficient (introduced with the help of expert opinions by performing AHP analysis) in the grey theory can be clearly seen in the results obtained .For example for causes WC_{33} and WC_{34}Where O_f, S and O_d are described by *High, Moderate,*

Moderate; Moderate, High, Moderate respectively. The traditional approach ranks WC_{33} higher than WC_{34} but both fuzzy and grey approach ranks WC_{34} higher than WC_{33}. This shows that higher attention should be given to WC_{34} when severity is considered as deciding factor.

Table 4.17 Failure Mode Effect Analysis [Screening System]

Component	Function	Potential failure mode	Potential effect of failure	Potential cause of failure	O_f	S	O_d	RPN
Filters	To filter the contaminants	Blockage Rupture	Loss in operational efficiency	Presence of Foreign materials. (Sand, grit, nails, staples, rocks etc.) [WC_{11}]	8	8	8	512
Cleaners	To remove high specific. gravity debris from pulp.	Mat scale build up Pressure drop loss	Impairs cleaning	Presence of contaminants [WC_{21}]	8	8	8	512
				Blade wear [WC_{22}]	6	6	8	288
				Faulty installation [WC_{23}]	3	6	6	108
				Mat build up [WC_{24}]	5	6	8	240
Contaminant isolation valve	To extract contaminants	Fails to open properly	Loss in extraction	Mechanical binding [WC_{25}]	6	7	8	336
				Valve operator malfunction [WC_{26}]	4	6	5	120
Screeners Screens	To wash the pulp to remove blackness.	Wear of blades	Loss in operation	Corrosion [WC_{31}]	3	6	5	90
				Abrasion [WC_{32}]	4	6	5	120
		Plugging	Flow obstructed	Mat build up [WC_{33}]	7	6	5	210
				Presence of contaminants [WC_{34}]	4	8	6	192

Table 4.18 Computation of Grey Output Values

Failure cause	O_f	γ_f	S	(γ_s)	O_d	(γ_d)	Grey output
WC_{11}	++	0.503	++	0.503	++	0.503	0.5030
WC_{21}	++	0.503	++	0.503	++	0.503	0.5030
WC_{22}	+	0.624	+	0.624	++	0.503	0.5864
WC_{23}	-	0.819	+	0.624	+	0.624	0.6649
WC_{24}	+	0.624	+	0.624	++	0.503	0.5864
WC_{25}	+	0.624	++	0.503	++	0.503	0.5284
WC_{26}	+	0.624	+	0.624	+	0.624	0.6240
WC_{31}	-	0.819	+	0.624	+	0.624	0.6649
WC_{32}	+	0.624	+	0.624	+	0.624	0.6240
WC_{33}	++	0.503	+	0.624	+	0.624	0.5985
WC_{34}	+	0.624	++	0.503	+	0.624	0.5650

Table 4.19 Comparison of Traditional, Fuzzy and Grey Output

Potential cause of failure	Traditional RPN output	Traditional Ranking	Fuzzy RPN Output	Fuzzy Ranking	Grey Output	Grey Ranking
WC_{11}	512	1	0.667	1	0.503	1
WC_{21}	512	1	0.667	1	0.5030	1
WC_{22}	288	3	0.617	3	0.5864	3
WC_{23}	108	6	0.579	5	0.6649	5
WC_{24}	240	4	0.617	3	0.5864	3
WC_{25}	336	2	0.664	2	0.5284	2
WC_{26}	120	5	0.597	4	0.6240	4
WC_{31}	90	4	0.579	4	0.6649	4
WC_{32}	120	3	0.597	3	0.6240	3
WC_{33}	210	1	0.601	2	0.5985	2
WC_{34}	192	2	0.627	1	0.5650	1

FORMING

Table 4.20 presents the traditional FMEA analysis for the forming unit. The *RPN* for each failure cause is evaluated by multiplying the factor scores i.e. $O_f \times S \times O_d$ obtained by using the methodology (discussed in section 4.1). From the table it is observed that a failure cause FC_{11} with *high severity*, *low rate of occurrence*, and *moderate detectability* (7, 3, and 4 respectively) have lower RPN (84) than FC_{12} where all the parameters are *moderate* (4, 5, and 5 yielding an RPN of 100) even though FC_{11} should have a higher priority for corrective action. In case of fourdinier wire table, the causes FC_{12} and FC_{13} though represented by different linguistic *(Moderate, Very High, High, and Moderate, High, Very High)* produce identical RPN i.e. 288 and are ranked at same position. Similarly, for causes FC_{35} and FC_{36} the linguistic definition are different (i.e. *Moderate, High, Moderate and Moderate, Moderate, High*) but the RPN scores are same i.e.252 for each.

The grey output values for failure causes associated with the system components are presented in Table 4.21. The comparison of the results obtained through traditional, fuzzy and grey approach is presented in Table 4.22 respectively. The analysis of the tabulated results shows that in traditional FMEA, events with same linguistic terms produce different RPN but the fuzzy and grey methods produce identical ranking. For instance, the causes FC_{24}, FC_{29} and FC_{210}, where O_f, S and O_d are described by *Moderate, High and High,* respectively, the defuzzified output is 0.664 and the grey relation output is 0.5284, which is same for all the three causes. This entails that these three should be given the same priority for attention. The RPN method, however, produces an output of 280, 384 and 320 for them and ranks 6^{th}, 3^{rd}, and 4^{th} place respectively. This means that FC_{29} has the highest priority followed by F_{210} and F_{24}, which could be misleading. Also the causes FC_{28} and FC_{211} with same linguistic terms produce different RPN but fuzzy and grey method produce identical ranking. The effect of the weighting coefficient (introduced with the help of expert opinions by performing AHP analysis) in the grey theory can be clearly seen in the results obtained. For example, for events FC_{212} and FC_{213} where, O_f, S and O_d are described by *Moderate, V.High, High* and *Moderate, High, V.High* respectively. The traditional approach produces identical RPN number and identical rankings but both fuzzy and grey approach produces different outputs and different ranking as observed from the Table 4.34.The fuzzy output for FC_{212} is 0.677 and for F_{213} the fuzzy output is 0.674. However, when using the grey theory (incorporating the weighted coefficient), the grey relation produces an output of 0.4962 for F_{212} and 0.5076 for FC_{213} respectively. This shows that FC_{212} should be given a higher priority (when severity is considered) as compared to FC_{213}.

Table 4.20 Failure Mode Effect Analysis [Forming unit]

Component	***Function***	***Potential failure mode***	***Potential effect of failure***	***Potential cause of failure***	O_f	S	O_d	***RPN***
Head box *-Baffles* *-Perforated plates/bars* *-Slice jet/nozzle*	To discharge pulp on to wire.	Breaking Jamming	Non-uniform interrupted flow	Broken internals [FC_{11}]	3	7	4	84
				Corrosion [FC_{12}]	4	5	5	100
				Scale buildup [FC_{13}]	6	5	8	240
		Blockage Fails to open	Unable to provide required conc. (pulp+ water)	Particulate contamination [FC_{14}]	7	7	8	392
-Level control valve.	To regulate the level	Fails to open fully	Failure to provide full-metered flow.	Mechanical binding [FC_{15}]	4	7	6	168
				Scale building [FC_{16}]	5	8	7	280
		Fails to close	Loss of flow	Broken internals. [FC_{17}]	3	6	7	126
Fourdinier wire Table	Carry the pulp	Abrasion	Holes /marks on the sheet.	Foreign materials. [FC_{21}] (sand, grit, nails etc.)	8	10	9	720
	Support the wire.	Building of fiber mat	Rapid wear and shorten the life.	Lumps/pimples etc. [FC_{22}]	7	9	8	504
-Wire mat				Roll wear [FC_{23}]	4	9	8	288
	Drainage of water	Misalignment	Variation in wire tension	Vibrations. [FC_{24}]	5	7	8	280
-Table rolls				Out of balance [FC_{25}]	6	6	5	180
	Run freely on the surface	Buckling/deformation	Loss in operation	Improper maintenance [FC_{26}]	3	7	5	105
-Suction rolls	Dewatering the pulp	Looseness Sagging	Stock jumps and creates disturbance on wire	Mechanical stresses [FC_{27}]	7	8	5	280
-Dandy rolls				Bearing seizure [FC_{28}]	6	7	6	252
	Transfer sheet to pickup felt	Breaks Bearing seizure	Sheet formation interrupted (crush and curl)	Jammed shafts [FC_{29}]	6	8	8	384
				High temperature [FC_{210}]	5	8	8	320
-Cough rolls				Nip pressure [FC_{211}]	6	8	4	192
		Breaks Bearing seizure	Fails to transfer sheet to pickup felt	Vibrations [FC_{212}]	4	9	8	288
				High temperature [FC_{213}]	4	8	9	288
-Pickup rolls								
Suction Box *Vacuum pumps*	*Complete dewatering/ drainage.*	Fails to operate continuously	Piston fails to execute the movement	Breaking of piston rod [FC_{31}]	4	9	9	324
				Seal failure [FC_{32}]	7	6	8	336
		Leakage from casing	Air may enter the system	Excessive radial thrust [FC_{33}]	6	7	4	168
				Lack of lubrication in moving parts. [FC_{34}]	4	8	6	192
		Rotor jamming	Pump motor overloaded	Bearing failure [FC_{35}]	6	7	6	252
			Pressure loss.	Incursion of solid particles into clearances [FC_{36}]	6	6	7	252

Table 4.21 Grey Output Values

Failure cause	O_f	γ_f	S	(γ_s)	O_d	(γ_d)	Grey output
FC_{11}	-	0.819	++	0.503	+	0.624	0.606
FC_{12}	+	0.624	+	0.624	+	0.624	0.624
FC_{13}	+	0.624	+	0.624	++	0.503	0.5864
FC_{14}	++	0.503	++	0.503	++	0.503	0.503
FC_{15}	+	0.624	++	0.503	+	0.624	0.565
FC_{16}	+	0.624	++	0.503	++	0.503	0.5284
FC_{17}	-	0.819	+	0.624	++	0.503	0.6274
FC_{21}	++	0.503	+++	0.436	+++	0.436	0.4500
FC_{22}	++	0.503	+++	0.436	++	0.503	0.4708
FC_{23}	+	0.624	+++	0.436	++	0.503	0.4962
FC_{24}	+	0.624	++	0.503	++	0.503	0.5284
FC_{25}	+	0.624	+	0.624	+	0.624	0.624
FC_{26}	-	0.819	++	0.503	+	0.624	0.606
FC_{27}	++	0.503	++	0.503	+	0.624	0.606
FC_{28}	+	0.624	++	0.503	+	0.624	0.565
FC_{29}	+	0.624	++	0.503	++	0.503	0.5284
FC_{210}	+	0.624	++	0.503	++	0.503	0.5284
FC_{211}	+	0.624	++	0.503	+	0.624	0.565
FC_{212}	+	0.624	+++	0.436	++	0.503	0.4962
FC_{213}	+	0.624	++	0.503	+++	0.436	0.5076
FC_{31}	+	0.624	+++	0.436	+++	0.436	0.4754
FC_{32}	++	0.503	+	0.624	++	0.503	0.5610
FC_{33}	+	0.624	++	0.503	-	0.819	0.6263
FC_{34}	+	0.624	++	0.503	+	0.624	0.565
FC_{35}	+	0.624	++	0.503	+	0.624	0.565
FC_{36}	+	0.624	+	0.624	++	0.503	0.5864

Table 4.22 Comparison of Traditional, Fuzzy and Grey Output

Potential Cause Of Failure	Traditional Output	Traditional Ranking	Fuzzy Output	Fuzzy Ranking	Grey Output	Grey Ranking
FC_{11}	84	7	0.533	5	0.6060	5
FC_{12}	100	6	0.511	7	0.6240	6
FC_{13}	240	3	0.617	4	0.5864	4
FC_{14}	392	1	0.667	1	0.5030	1
FC_{15}	168	4	0.627	3	0.5650	3
FC_{16}	280	2	0.664	2	0.5284	2
FC_{17}	126	5	0.521	6	0.6274	7
FC_{21}	720	1	0.699	1	0.4500	1
FC_{22}	504	2	0.679	2	0.4708	2
FC_{23}	288	5	0.677	3	0.4962	3
FC_{24}	280	6	0.664	5	0.5284	5
FC_{25}	180	9	0.511	9	0.6240	9
FC_{26}	105	10	0.533	8	0.6060	8
FC_{27}	280	6	0.646	6	0.5405	6
FC_{28}	252	7	0.627	7	0.5650	7
FC_{29}	384	3	0.664	5	0.5284	5
FC_{210}	320	4	0.664	5	0.5284	5
FC_{211}	192	8	0.627	6	0.5650	7
FC_{212}	288	5	0.677	3	0.4962	3
FC_{213}	288	5	0.674	4	0.5076	4
FC_{31}	324	2	0.681	1	0.4754	1
FC_{32}	336	1	0.636	2	0.5610	2
FC_{33}	168	5	0.611	5	0.6263	5
FC_{34}	192	4	0.627	3	0.5650	3
FC_{35}	252	3	0.627	3	0.5650	3
FC_{36}	252	3	0.617	4	0.5864	4

PRESS

The FMEA along with resulting RPN score for the unit is presented in Table 4.23. From the table it is observed that in case of press rolls, the causes PC_{26} and PC_{28} produce an identical RPN i.e. 280, however, the occurrence rate and detectability for both the causes are totally different. Also, PC_{14} and PC_{24} though represented by different sets of linguistic terms but they produce identical RPN i.e.180, which could be misleading. The above listed limitations of traditional FMEA are addressed by using both fuzzy and grey decision theory. The grey relation results are tabulated in Table 4.24 and the comparison of traditional, fuzzy and grey approach results so obtained is presented in Table 4.25

From Table 4.25 it is observed that for causes PC_{26} and PC_{28} where O_f, S and O_d are described by *Moderate, High, High,* and *High, High, Moderate* respectively, the traditional FMEA output is 280 for both, this means that both the events are prioritized at same rank i.e. 5th. But the defuzzified outputs for them are 0.664 and 0.660 respectively which shows that PC_{26} should be ranked higher than PC_{28}. Also, the causes PC_{14} and PC_{24} which are represented by different sets of linguistic terms (*Moderate, Very high, Moderate, and Moderate, Moderate, Moderate*) produce identical RPN i.e.180. But FDMS output so obtained is different for both of them. The causes PC_{12} and PC_{28} though represented by same linguistic terms (i.e. *High, High, Moderate*) but produce different RPN as 294 and 280. But the fuzzy and grey output results are same for both of them. We can also visualize the effect of introducing a weighting coefficient introduced with the help of a grey relation approach. The cause PC_{21} based on RPN score is ranked high to that of PC_{22}. But, if severity is considered as an important factor than PC_{22} is ranked higher than PC_{21}.

Table 4.23 Failure Mode Effect Analysis [Press Unit]

Component	Function	Potential failure mode	Potential effect of failure	Potential cause of failure	O_f	S	O_d	RPN
Press section *Press felts*	*To carry the sheet*	Excessive tension/ Slippage	Web-breaks/ Loss in operation	Vibrations [PC_{11}]	5	8	8	320
				Inadequate tension [PC_{12}]	7	7	6	294
				Broken internals [PC_{13}]	4	6	7	168
		Abrasion/ Worn-out (prematurely)	(i) Deteriorate/degrade the sheet	Abrasive materials. [PC_{14}]	4	9	5	180
				Corrosion. [PC_{15}]	6	6	6	216
			(ii) Loss of flow	Scale buildup [PC_{16}]	5	8	8	320
				Insufficient cleaning /maintenance. [PC_{17}]	3	6	8	144
Press rolls	To apply mechanical pressure when felt and sheet sandwich passes through loaded press rolls.	(i) Sagging	Loss in operation	Non uniform loading of stock [PC_{21}]	8	8	8	512
		(ii) Deflection	Loss in operation	Pull of felts [PC_{22}]	7	9	7	441
		(iii) Bearing seizure/failure	Overheating with noise Rolls fails to move	Scanty lubrication [PC_{23}]	6	5	5	150
				High temperature [PC_{24}]	5	6	6	180
		(iv) Buckling/ deformation	Stock jumps and creates disturbance on wire	Misalignment [PC_{25}]	8	9	9	648
				Vibrations. [PC_{26}]	5	8	7	280
		(v) Improper alignment	Felt failure (crush and curl the paper)	Out of balance [PC_{27}]	5	9	6	270
				Improper maintenance [PC_{28}]	8	7	5	280
		(vi) Rubber wear	Degrade quality of sheet	Vibrations [PC_{29}]	5	6	8	240
				Loss in Heat resistance [PC_{210}]	8	7	9	504

Table 4.24 Grey Output Values

Failure cause	O_f	γ_f	S	(γ_s)	O_d	(γ_d)	**Grey output**
PC_{11}	+	0.624	++	0.503	++	0.503	0.5284
PC_{12}	++	0.503	++	0.503	+	0.624	0.606
PC_{13}	+	0.624	+	0.624	++	0.503	0.5864
PC_{14}	+	0.624	+++	0.436	++	0.503	0.4962
PC_{15}	+	0.624	+	0.624	+	0.624	0.624
PC_{16}	+	0.624	++	0.503	++	0.503	0.5284
PC_{17}	-	0.819	+	0.624	++	0.503	0.6274
PC_{21}	++	0.503	++	0.503	++	0.503	0.503
PC_{22}	++	0.503	+++	0.436	++	0.503	0.4708
PC_{23}	+	0.624	+	0.624	+	0.624	0.624
PC_{24}	+	0.624	+	0.624	+	0.624	0.624
PC_{25}	++	0.503	+++	0.436	+++	0.436	0.4500
PC_{26}	+	0.624	++	0.503	++	0.503	0.5284
PC_{27}	+	0.624	+++	0.436	++	0.503	0.4962
PC_{28}	++	0.503	++	0.503	+	0.624	0.606
PC_{29}	+	0.624	+	0.624	++	0.503	0.5864
PC_{210}	++	0.503	++	0.503	+++	0.436	0.5020

Table 4.25 Comparative Results [Traditional, Fuzzy and Grey] for Press System

Potential Cause of Failure	Traditional RPN output	Traditional Ranking	Fuzzy RPN Output	Fuzzy Ranking	Grey Output	Grey Ranking
PC_{11}	320	1	0.664	2	0.5284	2
PC_{12}	294	2	0.646	3	0.606	4
PC_{13}	168	5	0.617	4	0.5864	3
PC_{14}	180	4	0.667	1	0.4962	1
PC_{15}	216	3	0.511	6	0.624	5
PC_{16}	320	1	0. 664	2	0.5284	2
PC_{17}	144	6	0.521	5	0.6274	6
PC_{21}	512	2	0.667	4	0.503	5
PC_{22}	441	4	0.679	2	0.4708	2
PC_{23}	150	9	0.511	8	0.624	9
PC_{24}	180	8	0.511	8	0.624	9
PC_{25}	648	1	0.699	1	0.4500	1
PC_{26}	280	5	0.664	5	0.5284	6
PC_{27}	270	6	0.667	4	0.4962	3
PC_{28}	280	5	0.646	6	0.606	8
PC_{29}	240	7	0.617	7	0.5864	7
PC_{210}	504	3	0.669	3	0.5020	4

Dryer

Table 4.26 presents the details of traditional FMEA analysis by listing possible failure modes, their causes and effect on system functioning along with RPN scores for the dryer unit. From Table 4.26 it is observed that a failure cause DC_{25} with high severity, low rate of occurrence, and moderate detectability (8, 3, and 5) have same RPN (120) to that of DC_{22} where, all the parameters are moderate, (O_f = 5, S = 6 ,and O_d = 4) yielding an RPN of 120 and are ranked same at 4 th position. These limitations of FMEA are addressed by using both fuzzy and grey decision theory. The grey relation results are tabulated in Table 4.27 and the comparison of (traditional, fuzzy and grey approach) results is presented in Table 4.28.

From the Table 4.28, for dryer rollers, it is evident that in traditional FMEA, events with different linguistic terms produce same RPN but the fuzzy and grey methods produce different ranking. For instance, as discussed earlier that a failure cause DC_{25} with different linguistic definitions (high severity = 8, low rate of occurrence = 3, and moderate detectability = 5) produce same RPN (120) to that of DC_{22} (where all the parameters are moderate). But the approach based on fuzzy and grey methods produce different results and ranks them differently. The effect of the weighting coefficient considered is visualized in grey output results. The grey theory ranks cause DC_{25} higher than to that of DC_{22} if severity is considered as an important factor. Also, in case steam handling system causes DC_{33} and DC_{35} produces same RPN score and are ranked at 4th place according to the resulting score. But after fuzzy and grey treatment the ranking has changed and now the cause DC_{33} is ranked at 2 nd place, higher to that of DC_{35}. The effect of weighting coefficient can be seen if severity is considered as an important factor then ranking obtained through grey relation analysis places DC_{13} higher to that of DC_{17} instead of traditional ranking which places DC_{17} higher to that of DC_{13}.

Table 4.26 FMEA for Dryer Unit

Component	Function	Potential failure mode	Potential effect of failure	Potential cause of failure	O_f	S	O_d	RPN
Dryer section -dryer felts	To carry the sheet	Excessive tension	Web-breaks	Vibrations [DC_{11}]	5	9	7	315
			Loss in operation	Inadequate tension [DC_{12}]	4	8	6	192
		Slippage		Broken internals [DC_{13}]	3	8	5	120
		Abrasion Worn-out (prematurely)	Deteriorate/degrade the sheet	Abrasive materials. [DC_{14}] (sand, grit, nails etc.)	5	9	8	360
				Corrosion. [DC_{15}]	3	5	7	105
			Loss of flow	Scale buildup [DC_{16}]	6	6	8	288
				Insufficient cleaning /maintenance. [DC_{17}]	5	5	6	150
Dryer rolls /Cylinders	To remove vapor from felt and sheet.	Roller wear	Increase in vibration	Misalignment [DC_{21}]	3	8	9	216
				Scanty lubrication [DC_{22}]	5	6	4	120
				Bearing failure [DC_{23}]	6	8	7	336
		Buildup	Reduction in Heat transfer	Irregular cleaning of dryers [DC_{24}]	4	6	7	168
		Bending	Loss in operation	Vibrations [DC_{25}]	3	8	5	120
Steam handling system								
Flow restrictor valve	To control the flow of steam	Fails to open Completely	Failure to provide full-metered flow.	Broken internals [DC_{31}]	5	8	3	120
				Vibrations [DC_{32}]	5	7	5	175
Pressure controller recorder valve	To record steam pressure	Fails open / Fails close	Loss in operation	Loss of power, spurious signal [DC_{33}]	3	7	5	105
				Mechanical binding [DC_{34}]	5	5	5	125
Temperature controller recorder valve	To give desired temperature gradient	Fails open / Fails close	Loss in operation	Valve operator malfunction [DC_{35}]	3	5	7	105

Table 4.27Grey Output Values

Failure Cause	O_f	γ_f	S	(γ_s)	O_d	(γ_d)	Grey Output
DC_{11}	+	0.624	+++	0.436	++	0.503	0.4962
DC_{12}	+	0.624	++	0.503	+	0.624	0.5650
DC_{13}	-	0.819	++	0.503	+	0.624	0.6060
DC_{14}	+	0.624	+++	0.436	++	0.503	0.4962
DC_{15}	-	0.819	+	0.624	++	0.503	0.6274
DC_{16}	+	0.624	+	0.624	++	0.503	0.5864
DC_{17}	+	0.624	+	0.624	+	0.624	0.6240
DC_{21}	-	0.819	++	0.503	+++	0.436	0.5485
DC_{22}	+	0.624	++	0.503	+	0.624	0.6240
DC_{23}	+	0.624	++	0.503	++	0.503	0.5284
DC_{24}	+	0.624	+	0.624	++	0.503	0.5864
DC_{25}	-	0.819	++	0.503	+	0.624	0.6060
DC_{31}	++	0.503	+	0.624	+	0.624	0.6263
DC_{32}	++	0.503	+	0.624	+	0.624	0.5650
DC_{33}	+	0.624	+	0.624	-	0.819	0.6060
DC_{34}	+	0.624	++	0.503	+	0.624	0.6240
DC_{35}	+	0.624	+	0.624	+	0.624	0.6274

Table 4.28 Comparative Results [Traditional, Fuzzy and Grey] for Dryer System

Potential Cause of Failure	Traditional Output	Traditional Ranking	Fuzzy Output	Fuzzy Ranking	Grey Output	Grey Ranking
DC_{11}	315	2	0.667	1	0.4962	1
DC_{12}	192	4	0.627	2	0.5650	2
DC_{13}	120	6	0.601	4	0.6060	4
DC_{14}	360	1	0.667	1	0.4962	1
DC_{15}	105	7	0.579	6	0.6274	6
DC_{16}	288	3	0.617	3	0.5864	3
DC_{17}	150	5	0.597	5	0.6240	5
DC_{21}	216	2	0.711	1	0.5485	2
DC_{22}	120	4	0.597	5	0.6240	5
DC_{23}	336	1	0.664	2	0.5284	1
DC_{24}	168	3	0.617	3	0.5864	3
DC_{25}	120	4	0.601	4	0.6060	4
DC_{31}	120	2	0.577	5	0.6263	4
DC_{32}	175	1	0.627	1	0.5650	1
DC_{33}	105	4	0.601	2	0.6060	2
DC_{34}	125	3	0.597	3	0.6240	3
DC_{35}	105	4	0.579	4	0.6274	5

4.3.3 Quantitative Analysis

4.3.3.1 Introduction

In order to measure and analyze the behavior of system quantification of various syster parameters [such as Repair time (τ), Failure rate (λ), Mean Time between Failures (MTBF Availability (Av.) and Expected Number of Failures (ENOF)] is essential for managerial decisio making (with respect to maintenance and manpower planning). In this framework, the Petrin model of the system is first obtained from its equivalent fault tree model and then system failu and repair times are computed and the fuzzy, crisp and defuzzified results are derived based on th steps presented in Figure 4.20.

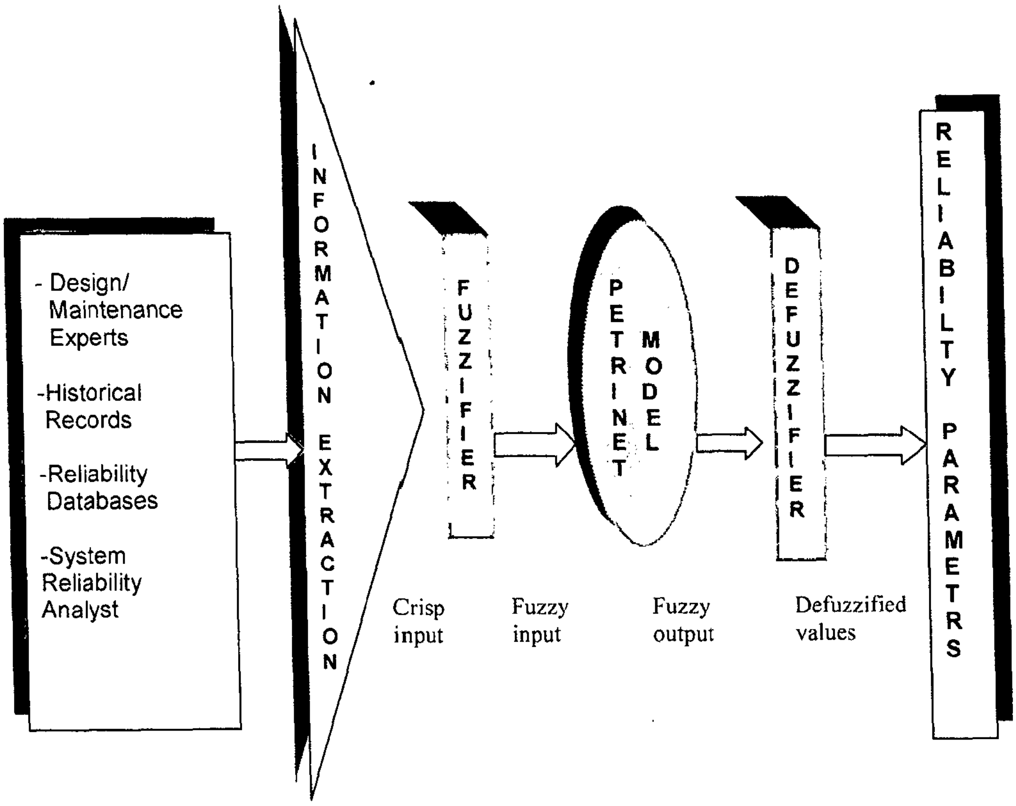


Figure 4.20 Framework of Quantitative Analysis

In brief the steps are discussed as

Step1. Under the information extraction phase, the data related to failure rate [λ_i] and repair time [τ_i] of the components related to various subsystems is collected from present/ historical records of a paper mill and is integrated with expertise of maintenance personnel [shown in Table 4.29]

Step 2. In this step, for the sub-system components the fuzzification of failure and repair time data is done using Triangular Membership Function (TMF). For instance Figure 4.21 shows the representation for the first component i.e. blower in case of feeding system.

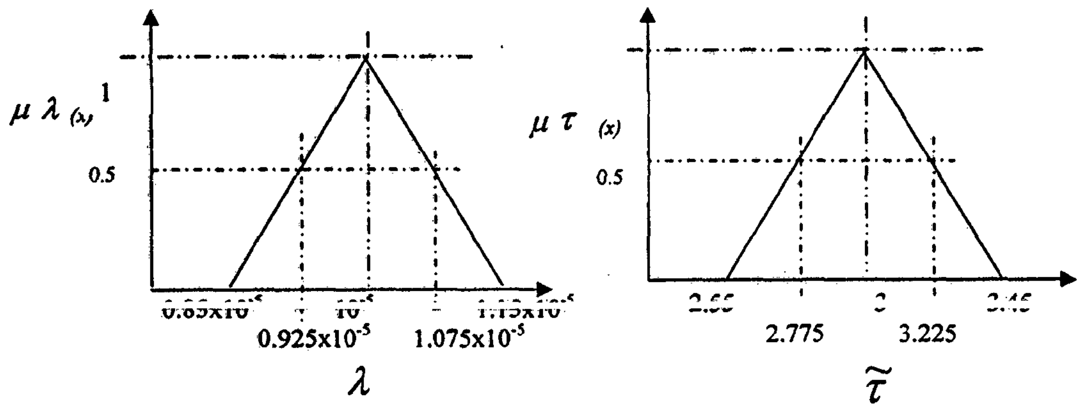


Figure 4.21 Input Fuzzy Triangular Number Representation

Step 3. After knowing the input fuzzy triangular numbers for all the components shown in Petrinet model, the corresponding fuzzy values of failure rate (λ) and repair time (τ) for the system at different confidence levels (α) are determined using fuzzy transition expressions [Table 4.30(b)] derived from traditional expressions [Table 4.30 (a)]. For instance, the lower limit and upper limit calculations for failure rate at confidence level, $\alpha = 0.4$ for feeding system are shown in Table 4.31 .Similarly, the lambda and tau values for the sub-system, at confidence factor, ranging from 0 to 1 with increments of 0.1 are computed (Table 4.32).

Table 4.29 Subsystems Failure Rate and Repair Time

S.No	Subsystem	Failure rate (failures/hr)	Repair time (hr)	Description
1	Feeding	$\lambda_1 = 10^{-5}$, λ_i(i=2 to5) = 10^{-3}	$\tau_1 = 2$, λ_i(i=2 to5) = 6	*i*=1[blower]; *i*=2,3 [chain and bucket conveyor]; *i*=4,5 [stand by unit of chain and bucket conveyor]
2	Pulping	$\lambda_1 = 4\times10^{-5}$, $\lambda_2 = \lambda_3 = 5\times10^{-3}$, λ_i(i=4 to6) = 2×10^{-3}, $\lambda_7 = \lambda_8 = 5\times10^{-3}$	$\tau_1 = 18$, $\tau_2 = \tau_3 = 6$, τ_i(i=3 to 6) =3, $\tau_7 = \tau_8 = 6$	*i*=1[Digester]; *i*=2,3 [Knotters]; *i*=4,5,6 [deckers]; *i*=7,8[openers] respectively.
3.	Washing	$\lambda_1 = 1\times10^{-3}$, λ_i(i=2 to4)= 3×10^{-3}, $\lambda_5 = \lambda_6 = \lambda_7 = \lambda_8 = 5\times10^{-3}$	$\tau_1 = 3$, τ_i(i=2 to4)=2, τ_i(i=5 to8) = 3	*i*=1[filter]; *i*=2,3,4 [cleaners]; *i*=5,6 [screener]; *i*=7,8[deckers] respectively.
4	Bleaching	$\lambda_1 = 0.8320\times10^{-4}$ $\lambda_2 = \lambda_3 = 5\times10^{-3}$, $\lambda_4 = \lambda_5 = 6\times10^{-4}$	$\tau_1 = 2.5$, $\tau_2 = \tau_3 = 2$, $\tau_4 = \tau_5 = 3$	*i*=1 Bleaching tank i=2,3 Filters and i= 4,5 Washers
5	Screening	$\lambda_1 = 5\times10^{-3}$, $\lambda_2 = \lambda_3 = 1\times10^{-2}$, λ_i(i=4 to 6)= 6×10^{-3}	$\tau_1 = 2$, $\tau_2 = \tau_3 = 5$, τ_4,(i= 4 to 6)= 2	*i*=1[filter]; *i*=2 [screener]; *i*=3[decker] *i*=4,5,6 [cleaners].
6	Forming	$\lambda_1 = 1\times10^{-4}$, $\lambda_2 = 3\times10^{-3}$, $\lambda_3 = \lambda_4 = 1\times10^{-3}$, $\lambda_5 = 1.5\times10^{-3}$, $\lambda_6 = 2\times10^{-3}$	$\tau_1 = 10$, $\tau_2 = 10$, $\tau_3 = \tau_4 = 2$, $\tau_5 = 3$, $\tau_6 = 4$	*i*=1[Head box]; *i*=2 [wire mat], *i*=3 [suction box]; *i*=4,5,6[roller bearing, roller bending *and* roller rubber wear]
8	Press	$\lambda_1 = 1\times10^{-4}$, $\lambda_2 = \lambda_5 = 1\times10^{-3}$, $\lambda_3 = \lambda_6 = 1.5\times10^{-3}$, $\lambda_4 = \lambda_7 = 2\times10^{-3}$	$\tau_1 = 5$, $\tau_2 = \tau_5 = 2$, $\tau_3 = \tau_6 = 3$, $\tau_4 = \tau_7 = 4$	*i*=1[Felt]; *i*=2,5[top, bottom roller bearing]; *i*=3,6[top, bottom roller bending]; *and i*=4,7[top, bottom roller rubber wear]
9	Dryer	$\lambda_1 = 1\times10^{-4}$, $\lambda_2 = \lambda_4 = 1\times10^{-3}$, $\lambda_3 = \lambda_5 = 2\times10^{-3}$	$\tau_1 = 10$, $\tau_2 = \tau_4 = 2$, $\tau_3 = \tau_5 = 4$	*i*=1[Felt]; *i*=2,4[top, bottom roller bearing]; *i*=3,5[top, bottom roller bending]

Table 4.30 Expressions Used

(a) Conventional *lambda -tau* expressions

Type of Gate	λ_{AND}	τ_{AND}	λ_{OR}	τ_{OR}
Expressions	$\prod_{i=1}^{n}\lambda_i\left[\sum_{j=1}^{n}\prod_{\substack{i=1\\ i\neq j}}^{n}\tau_i\right]$	$\prod_{i=1}^{n}\tau_i \Big/ \sum_{j=1}^{n}\left[\prod_{\substack{i=1,\\ i\neq j}}^{n}\tau_i\right]$	$\sum_{j=1}^{n}\lambda_j$	$\sum_{j=1}^{n}\lambda_j\tau_j \Big/ \sum_{j=1}^{n}\lambda_j$

(b) Fuzzy *lambda -tau* expressions

$$\lambda(\alpha)=\left[\prod_{i=1}^{n}\{(\lambda_{i2}-\lambda_{i1})\alpha+\lambda_{i1}\}.\sum_{j=1}^{n}\left[\prod_{i=1,i\neq j}^{n}\{(\tau_{i2}-\tau_{i1})\alpha+\lambda_{i1}\}.\right]\right.$$

$$\left.\prod_{i=1}^{n}\{-(\lambda_{i3}-\lambda_{i2})\alpha+\lambda_{i3}\}.\sum_{j=1}^{n}\left[\prod_{i=1,i\neq j}^{n}\{-(\tau_{i3}-\tau_{i2})\alpha+\tau_{i3}\}\right]\right] \quad \forall\alpha\in[0,1] \tag{4.1}$$

$$\tau(\alpha)=\left[\frac{\prod_{i=1}^{n}\{(\tau_{i2}-\tau_{i1})\alpha+\tau_{i1}\}}{\sum_{j=1}^{n}\left[\prod_{\substack{i=1\\ ,i\neq j}}^{n}\{-(\tau_{i3}-\tau_{i2})\alpha+\tau_{i3}\}\right]},\ \frac{\prod_{i=1}^{n}\{(\tau_{i3}-\tau_{i2})\alpha+\tau_{i3}\}}{\sum_{j=1}^{n}\left[\prod_{i=1,i\neq j}^{n}\{(\tau_{i2}-\tau_{i1})\alpha+\tau_{i1}\}\right]}\right] \tag{4.2}$$

$$\lambda(\alpha)=\left[\sum_{i=1}^{n}\{(\lambda_{i2}-\lambda_{i1})\alpha+\lambda_{i1}\},\sum_{i=1}^{n}\{-(\lambda_{i3}-\lambda_{i2})\alpha+\lambda_{i3}\}\right] \tag{4.3}$$

$$\tau(\alpha)=\frac{\sum_{i=1}^{n}[\{(\lambda_{i2}-\lambda_{i1})\alpha+\lambda_{i1}\}.\{(\tau_{i2}-\tau_{i1})\alpha+\tau_{i1}\}]}{\sum_{i=1}^{n}\{-(\lambda_{i3}-\lambda_{i2})\alpha+\lambda_{i3}\}},\ \frac{\sum_{i=1}^{n}[\{-(\lambda_{i3}-\lambda_{i2})\alpha+\lambda_{i3}\}.\{(\tau_{i3}-\tau_{i2})\alpha+\tau_{i3}\}]}{\sum_{i=1}^{n}\{(\lambda_{i2}-\lambda_{i1})\alpha+\lambda_{i1}\}} \tag{4.4}$$

(c) Performance Expressions

Availability $=\dfrac{\mu}{\lambda+\mu}+\dfrac{\lambda}{\lambda+\mu}e^{-(\lambda+\mu)t}$; Reliability $=e^{-\lambda t}$; ENOF $=\dfrac{\lambda\mu}{\lambda+\mu}t+\dfrac{\lambda^2}{(\lambda+\mu)^2}[1-e^{-(\lambda+\mu)t}]$

MTBF = MTTR+ MTTF [MTTR $=\int_0^\infty t\lambda e^{-\lambda t}dt=\dfrac{1}{\lambda}$, MTTF $=\int_0^\infty t\mu e^{-\mu t}dt=\dfrac{1}{\mu}$]

Table 4.31 Calculations for Upper and Lower limit

[Lower Limit calculations]

$\lambda_{i1}^{(0.4)}$(AND) = $0.91\times10^{-3}+0.91\times10^{-3}(5.46+5.46)=0.9042\times10^{-5}$

$\lambda_{1}^{(0.4)}$ (OR) $=0.9042\times10^{-5}+0.9042\times10^{-5}+0.91\times10^{-5})=2.7185\times10^{-5}$ (Top place)

[Upper Limit calculations]

$\lambda_{i3}^{(0.4)}$(AND) = $1.09\times10^{-3}+1.09\times10^{-3}(6.54+6.54)=1.5540\times10^{-5}$

$\lambda_{3}^{(0.4)}$ (OR) $=1.5540\times10^{-5}+1.5540\times10^{-5}+1.09\times10^{-5}=4.19806\times10^{-5}$(Top place)

Table 4.32 Fuzzy Failure Rate and Repair Time Values

D.O.MF	**λ (hr^{-1})**		**τ (hr)**	
	L.S	**R.S**	**L.S**	**R.S**
1.0	3.400000×10^{-5}	3.400000×10^{-5}	2.7000	2.7000
0.9	3.278604×10^{-5}	3.524000×10^{-5}	2.4169	3.0302
0.8	3.160465×10^{-5}	3.652555×10^{-5}	2.1563	3.3938
0.7	3.045455×10^{-5}	3.783777×10^{-5}	1.9285	3.8021
0.60	2.933434×10^{-5}	3.911833×10^{-5}	1.7229	4.2603
0.50	2.824454×10^{-5}	4.056111×10^{-5}	1.5391	4.7734
0.40	2.718561×10^{-5}	4.198066×10^{-5}	1.3762	5.3522
0.30	2.615666×10^{-5}	4.343111×10^{-5}	1.2302	6.0000
0.20	2.515596×10^{-5}	4.491144×10^{-5}	1.1004	6.7290
0.10	2.418335×10^{-5}	4.644001×10^{-5}	0.9666	7.5470
0.0	2.320001×10^{-5}	4.800111×10^{-5}	0.8788	8.4710

Further, to analyze the behavior of system in quantitative terms, various parameters of system interest such as availability, system reliability, expected number of failures and mean time between failures are computed from respective λ and τ values using the expressions listed in Table 4.30(c: performance expressions).

Step 4. In order to make decisions with respect to maintenance actions it is necessary to convert fuzzy output into a crisp value. In fuzzy environment the defuzzification of fuzzy numbers is important in order to incorporate inherent fuzziness (by converting fuzzy output into a crisp value), associated with the data, to deal with the element of uncertainty. Among the various techniques for defuzzification such as centroid, bisector, middle of the max, weighted average available in literature the centroid method is used in the study because of its plausibility (lie approximately in the middle of the area) and computational simplicity. Mathematically represented as

$$\text{Defuzzified value} = \frac{\int_y \mu_{B'}(y)y.dy}{\int_y \mu_{B'}(y)dy.}.$$

Where, B' is the output fuzzy set, and $\mu_{B'}$ is the membership function.

4.3.3.2 Analysis of Systems

Based on the steps shown in Figure 4.20 and as discussed in previous section for feeding system, the analysis for all other subsystems is carried out in similar manner. The following paragraphs sums up the results and discussions for the respective systems one by one.

4.3.3.3 Results/Discussions

Feeding System

Figure 4.22 (a) and (b) shows the fault tree model and its equivalent Petrinet model of the system. Following the basic steps used in computing algorithm (Figure 4.20) as discussed under introduction section 4.4.1 the fuzzy, crisp and defuzzified results for the system were obtained. The fuzzy results with left and right spread values are shown in Table 4.33 and graphically presented in Figure 4.23. In order to incorporate inherent fuzziness (by converting fuzzy output into a crisp value), defuzzification is carried out to deal with the element of uncertainty associated with the data. The crisp result is evaluated at different spreads i.e. at ±15%, ±30% and ±60%. According to the crisp value (as depicted in Table 4.34), the system failure rate is 3.4×10^{-5} but if uncertainty in information regarding the input data is introduced then the results so obtained at different spreads are more pragmatic in nature. For instance, as shown in Figure 4.24 that with increase in spread, as the failure rate of system increases, the repair time also increases which results in decrease of both availability and reliability of the system. The results are helpful for the managers to understand the behavior of system performance. It is evident from the results presented in Table 4.34 that defuzzified value changes with change in percentage-spread. For instance, failure rate increases by 0.675% (i.e. when going from 3.4079998×10^{-5} to 3.431106×10^{-5}) with increase in spread from ±15% to ±30% and further by 2.09 % (i.e. from 3.431106×10^{-5} to 3.502966×10^{-5}) when spread changes from ±30% to ±60%. Similarly, for repair time and expected number of failures, with increase in spread, increase in defuzzified values, is observed.

other hand, at the same time for mean time between failures a decrease by 0.667% with increase in spread from ±15% to ±30% and further by 2.05% when spread changes from ±30% to ±60% is observed.

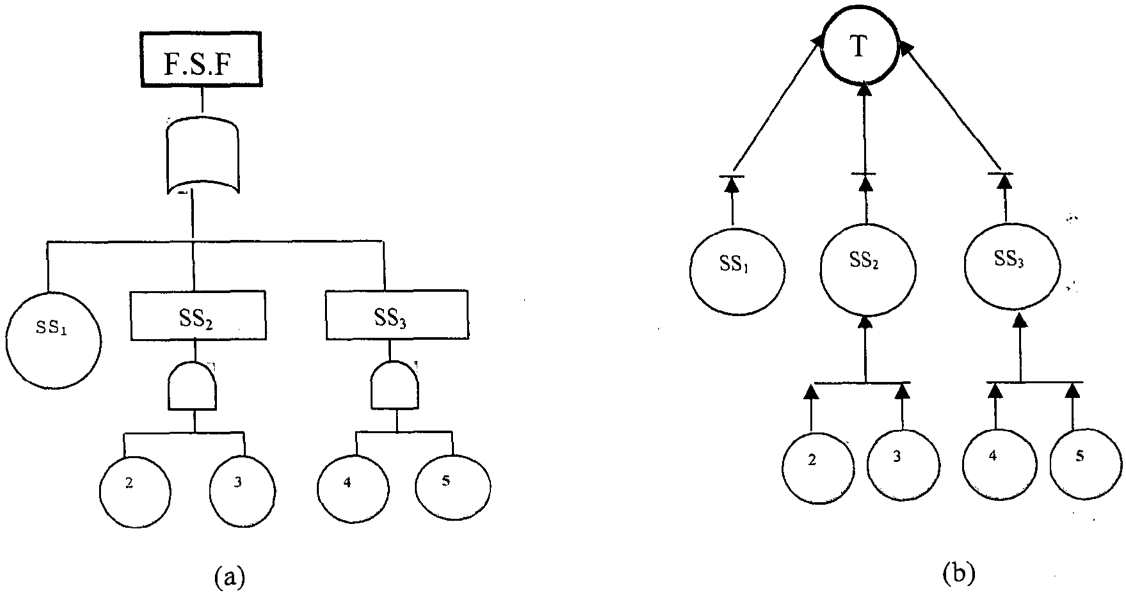


Figure 4.22 Feeding System (a) Fault tree Model (b) Petrinet Model

F.S.F: Feeding System Failure, T =Top Event Failure
SS_1= (Subsystem-1) SS_2= (Subsystem-2) SS_3= (Subsystem-3)
i=1[blower]; i=2,3 [chain and bucket conveyor]; i=4,5 [stand by unit of chain and bucket conveyor]

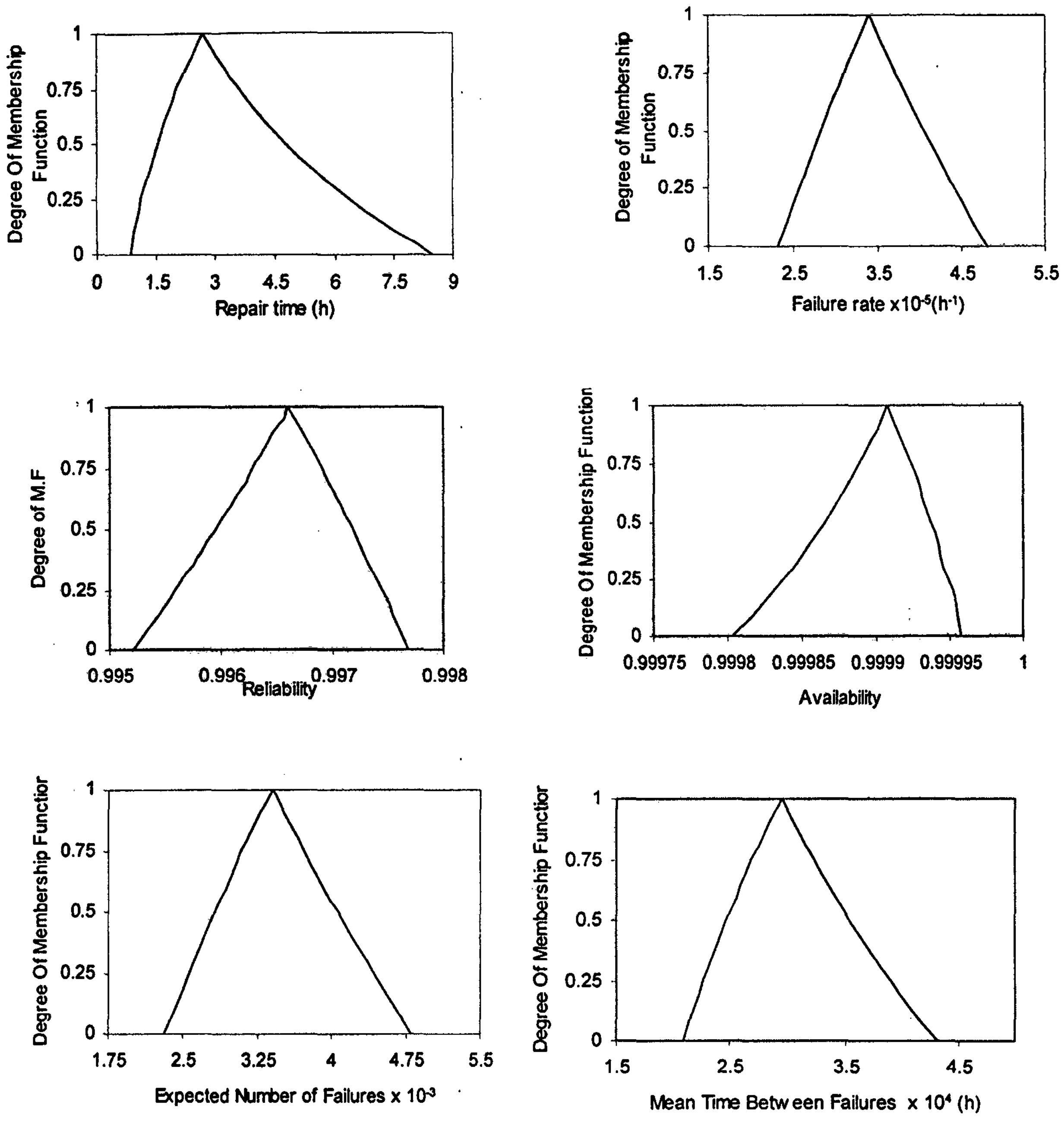


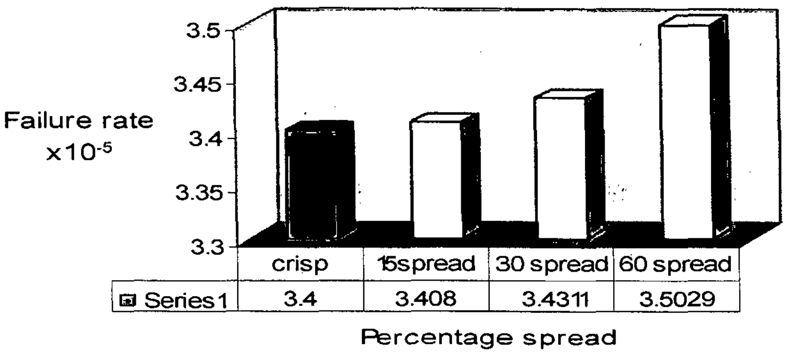
Figure 4.23 Fuzzy Representations of System Parameters (Feeding)

Table 4.33 System Parameters (Feeding)

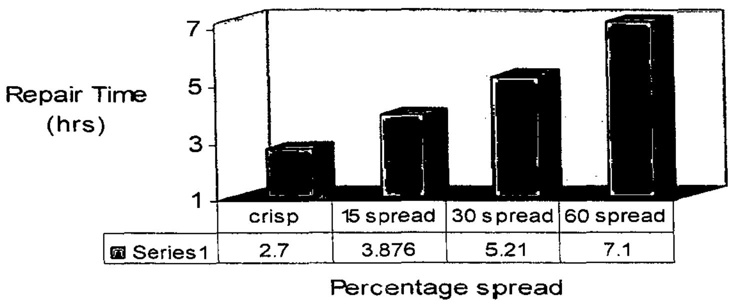
DOMF	Repair hr		Failure $X\ 10^{-4} hr^{-1}$		Availability $X\ 10^{-1}$		Reliability $X\ 10^{-1}$		MTBF $X\ 10^{4} hr$		ENOF $X\ 10^{-3}$ hr	
	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S
1	2.7000	2.7000	3.4000	3.4000	9.99908	9.99908	9.9660	9.9660	2.94144	2.9414	3.3999	3.3999
0.9	2.4169	3.0302	3.2740	3.5240	9.99900	9.99914	9.96482	9.9672	2.83794	3.0544	3.269	3.523952
0.8	2.1563	3.3938	3.1605	3.6525	9.99895	9.999212	9.96356	9.9684	2.73800	3.16434	3.160	3.652463
0.7	1.9285	3.8021	3.0453	3.7834	9.99884	9.99920	9.96226	9.9695	2.64329	3.28424	3.04494	3.783664
0.6	1.7229	4.2603	2.9318	3.9118	9.99874	9.99932	9.96006	9.9707	2.55279	3.40914	2.93334	3.917963
0.5	1.5391	4.7734	2.8244	4.0564	9.99865	9.99937	9.95956	9.9717	2.46586	3.54076	2.82434	4.056065
0.4	1.3762	5.3522	2.7188	4.1980	9.99855	9.99942	9.95866	9.9727	2.38251	3.67866	2.71844	4.198022
0.3	1.2302	6.0000	2.6156	4.3431	9.99843	9.99946	9.95656	9.9738	2.30311	3.82336	2.61553	4.343062
0.2	1.1004	6.7290	2.5155	4.4911	9.9983	9.99949	9.95516	9.9750	2.22731	3.97538	2.51542	4.490975
0.1	0.9666	7.5470	2.4183	4.6440	9.99817	9.99555	9.95364	9.9758	2.15381	4.13528	2.41821	4.643900
0	0.8788	8.4710	2.3200	4.800	9.99803	9.99957	9.95215	9.9769	2.08411	4.31046	2.31991	4.800001

Table 4.34 Crisp and Defuzzified Results

System Parameters	Defuzzified Value [±15% spread]	Defuzzified value [±30% spread]	Defuzzified value [±60% spread]	Crisp values
Failure rate (hr^{-1})	3.4079998×10^{-5}	3.431106×10^{-5}	3.502966×10^{-5}	3.40000×10^{-5}
Repair time (hr)	3.8761299	5.210021	7.100000	2.70000
Availability	9.998676×10^{-1}	9.9982124×10^{-1}	9.9974832×10^{-1}	9.99908×10^{-1}
MTBF (hr)	2.934661×10^{4}	2.9150392×10^{4}	2.8549901×10^{4}	2.941446×10^{4}
ENOF	3.4079680×10^{-3}	3.4309712×10^{-3}	3.502835×10^{-3}	3.39995×10^{-3}
Reliability	9.965978×10^{-1}	9.9657410×10^{-1}	9.9650301×10^{-1}	9.966057×10^{-1}



(a) Failure rate

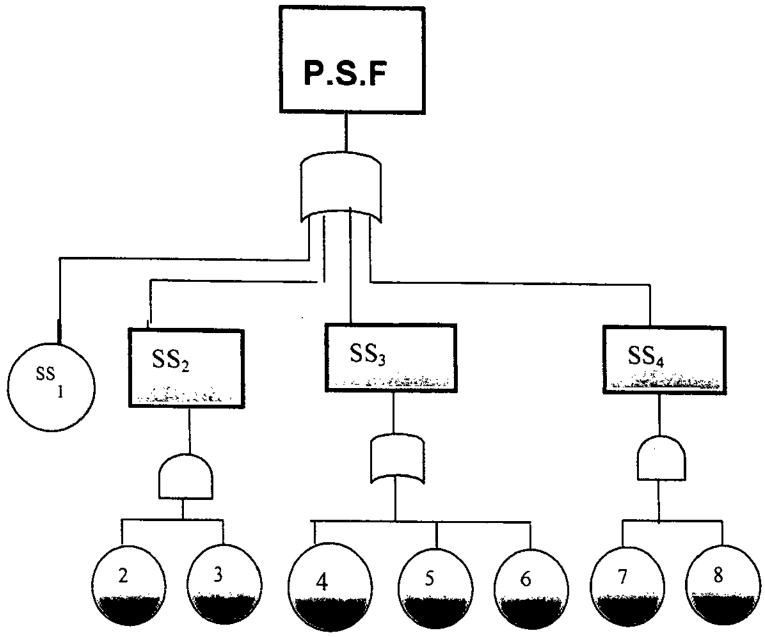


(b) Repair time

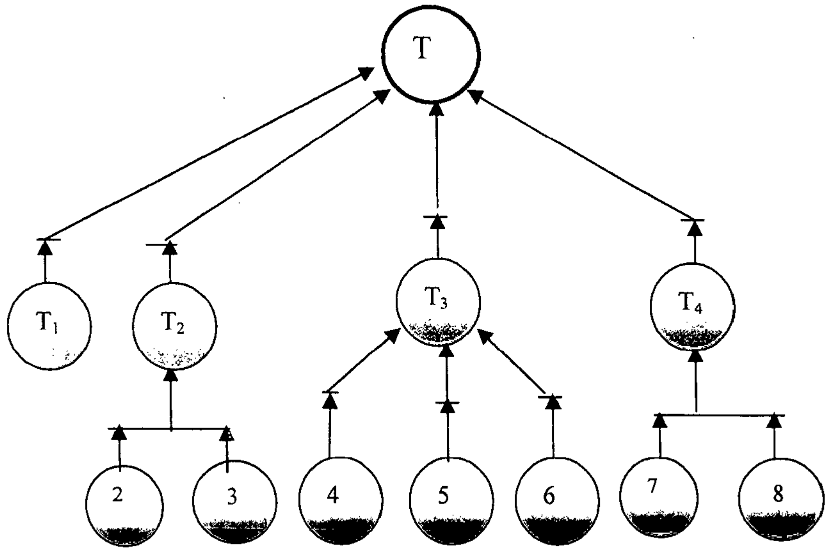
Figure 4.24 Trend of Failure Rate and Repair Time with Percentage Spread

Pulping System

Figure 4.25 (a) and (b) shows the fault tree model and equivalent Petrinet model of the system. Following the basic steps used in computing algorithm, the fuzzy, crisp and defuzzified results for the system were obtained. The fuzzy results with left and right spread values are shown in Table 4.35 and graphically presented in Figure 4.26. From the results in Table 4.36, it is evident that defuzzified value changes with change in percentage-spread. For instance, repair time first increases by 13.30% when spread changes from ±15% to ±25% and further by 19.50% when spread changes from ± 25% to ±60%. Similarly, for failure rate and expected number of failures, with increase in spread, increase in defuzzified values is observed. On the other hand, at the same time for mean time between failures a decrease of 0.31% when spread changes from ±15% to ±25% and further to 0.84% when spread from changes from ±25% to ±60% is observed. Similarly, for availability and reliability decrease in defuzzified values with increase in spread is observed. Thus, from above discussions it is inferred that the maintenance action for the system should be based on defuzzified MTBF rather than on crisp value because with the reduced MTBF values, a safe interval between maintenance actions can be established and inspections (continuous or periodic) can be conducted to monitor the condition or status of various equipments constituting the system before it reaches the crisp value. It can also be observed that with increase in repair time the availability of the unit goes on decreasing.



(a)



(b)

P.S.F = Pulping System Failure, T = Top Event Failure
SS_1= (Subsystem-1), SS_2= (Subsystem-2), SS_3= (Subsystem-3), SS_4= (Subsystem-4)
i=1[Digester]; i=2,3 [Knotters]; i=4,5,6 [deckers]; i=7,8[openers].

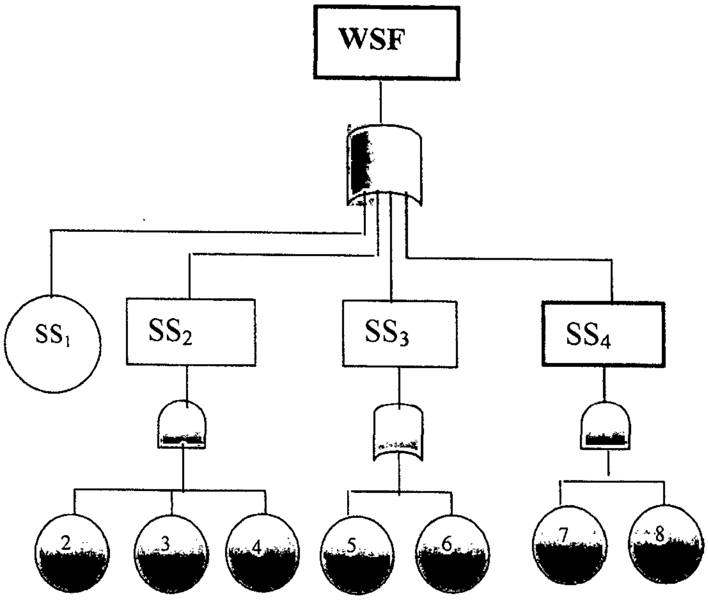
Figure 4.25 Pulping (a) Fault Tree Model (b) Petrinet Model

Table 4.35 System Parameters (Pulping)

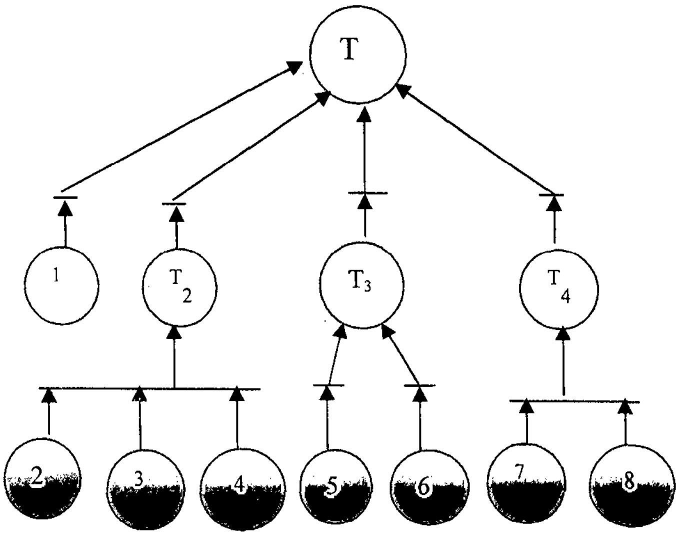
	LEFT SPREAD VALUES						RIGHT SPREAD VALUES					
DOMF	Repair (hr)	Failure X10^{-3} (hr)$^{-1}$	MTBF X10^{2} (hr)	Avail.	ENOF	Reliab	Repair (hr)	Failure X10^{-3} hr^{-1}	MTBF X10^{2} (hr)	Avail.	ENOF	Reliab
1	3.090	6.6400	1.5369	0.98029	0.66200	0.93550	3.090	6.6400	1.5369	0.98029	0.66200	0.93550
0.9	2.9242	6.5202	1.5131	0.97884	0.65025	0.93420	3.265	6.7650	1.5634	0.98179	0.67481	0.93620
0.8	2.7584	6.4010	1.4857	0.97739	0.63850	0.93340	3.435	6.8910	1.5900	0.98339	0.68761	0.93741
0.7	2.6237	6.2850	1.4612	0.97574	0.62697	0.93215	3.6275	7.0231	1.6178	0.98422	0.70036	0.93840
0.6	2.488	6.1701	1.4368	0.97410	0.61547	0.93090	3.8204	7.1502	1.6456	0.98515	0.71366	0.93951
0.5	2.383	6.0690	1.4135	0.97225	0.60470	0.92980	4.025	7.2850	1.6738	0.98597	0.72718	0.94070
0.4	2.277	5.9550	1.3900	0.97046	0.59394	0.92841	4.230	7.4216	1.7020	0.98679	0.74010	0.94193
0.3	2.1815	5.8510	1.3673	0.96805	0.58340	0.92760	4.5100	7.5651	1.7308	0.98753	0.75525	0.94300
0.2	2.096	5.7511	1.3447	0.96573	0.57351	0.92671	4.7721	7.7101	1.7596	0.98827	0.76975	0.94411
0.1	1.9976	5.6501	1.3245	0.96213	0.56251	0.92545	5.0955	7.8600	1.7902	0.98895	0.78477	0.94554
0	1.9093	5.5512	1.3033	0.95856	0.55350	0.92412	5.4910	8.0101	1.8209	0.98969	0.79980	0.94681

Table 4.36 Crisp and Defuzzified Values at different Spread

System Parameters	Crisp Value	Defuzzified Value [±15% spread]	Defuzzified Value [±25% spread]	Defuzzified Value [±60% spread]
Failure rate (h^{-1})	6.6400×10^{-3}	6.6510×10^{-3}	6.6920×10^{-3}	6.7830×10^{-3}
Repair time (h)	3.090	3.210	3.640	4.356
Availability	9.8029×10^{-1}	9.7950×10^{-1}	9.7670×10^{-1}	9.72088×10^{-1}
MTBF (h)	1.5369×10^{2}	1.5356×10^{2}	1.5307×10^{2}	1.5178×10^{2}
ENOF	6.6200×10^{-1}	6.6372×10^{-1}	6.6790×10^{-1}	6.77245×10^{-1}
Reliability	9.3500×10^{-1}	9.3560×10^{-1}	9.3520×10^{-1}	9.3440×10^{-1}



(a)



(b)

W.S.F = Washing System Failure, T = Top Event Failure
SS_1= (Subsystem-1), SS_2= (Subsystem-2), SS_3= (Subsystem-3), SS_4= (Subsystem-4)
i=1[filter]; i=2, 3, 4 [cleaners]; i=5, 6 [screener]; i=7, 8 [deckers]

Figure 4.27 Washing (a) Fault Tree Model (b) Petrinet Model

Table 4.37 System Parameters (Washing)

	LEFT SPREAD VALUES						RIGHT SPREAD VALUES					
DO MF	Repair hrs	Failure X10^{-3} hr-1	MTBF X10^{2} hrs	Avail.	ENOF	Reliability	Repair hrs	Failure X10^{-3} hr-1	MTBF X10^{2} hrs	Avail.	ENOF	Reliab.
1	2.1970	4.3000	2.3475	0.99071	0.42900	0.95790	2.1970	4.3000	2.3475	0.99071	0.42900	0.95790
0.9	2.0925	4.2250	2.3102	0.99006	0.42150	0.95710	2.3130	4.3933	2.3885	0.99126	0.43641	0.95860
0.8	1.9988	4.1554	2.2730	0.98941	0.41412	0.95640	2.4321	4.4470	2.4296	0.99180	0.44381	0.95934
0.7	1.9044	4.0798	2.2378	0.98866	0.40721	0.95571	2.5610	4.5210	2.4708	0.99231	0.45126	0.95981
0.6	1.8100	4.0096	2.2027	0.98792	0.40015	0.95500	2.6910	4.5960	2.5121	0.99284	0.45864	0.96070
0.5	1.7261	3.9420	2.1678	0.98697	0.39339	0.95425	2.8551	4.6750	2.5540	0.99327	0.46665	0.96128
0.4	1.6421	3.8766	2.1332	0.98603	0.38672	0.95356	3.0223	4.7550	2.5960	0.99371	0.47471	0.96180
0.3	1.5666	3.8133	2.0992	0.98481	0.38037	0.95234	3.2315	4.8391	2.6387	0.99409	0.48319	0.96250
0.2	1.4980	3.7500	2.0653	0.98359	0.37405	0.95195	3.4431	4.9240	2.6815	0.99447	0.49169	0.96319
0.1	1.4352	3.6944	2.0325	0.98241	0.36841	0.95110	3.6715	5.0122	2.7217	0.99480	0.50051	0.96375
0	1.3580	3.6384	1.9984	0.98070	0.36281	0.95037	3.9210	5.1001	2.7619	0.99513	0.50933	0.96426

Table 4.38 Crisp and Defuzzified Values at Different Spreads

System parameters	Crisp values	Defuzzified value [±15% spread]	Defuzzified value [±30% spread]	Defuzzified value [±60% spread]
Failure rate (hr^{-1})	4.300×10^{-3}	4.308×10^{-3}	4.326×10^{-3}	4.462×10^{-3}
Repair time (hr)	2.197	2.460	2.590	2.960
Availability	9.9072×10^{-1}	9.8960×10^{-1}	9.8800×10^{-1}	9.8713×10^{-1}
MTBF (hr)	2.3475×10^{2}	2.3458×10^{2}	2.3370×10^{2}	2.2707×10^{2}
ENOF	4.2900×10^{-1}	4.3004×10^{-1}	4.3187×10^{-1}	4.4550×10^{-1}
Reliability	9.5790×10^{-1}	9.5780×10^{-1}	9.5760×10^{-1}	9.5485×10^{-1}

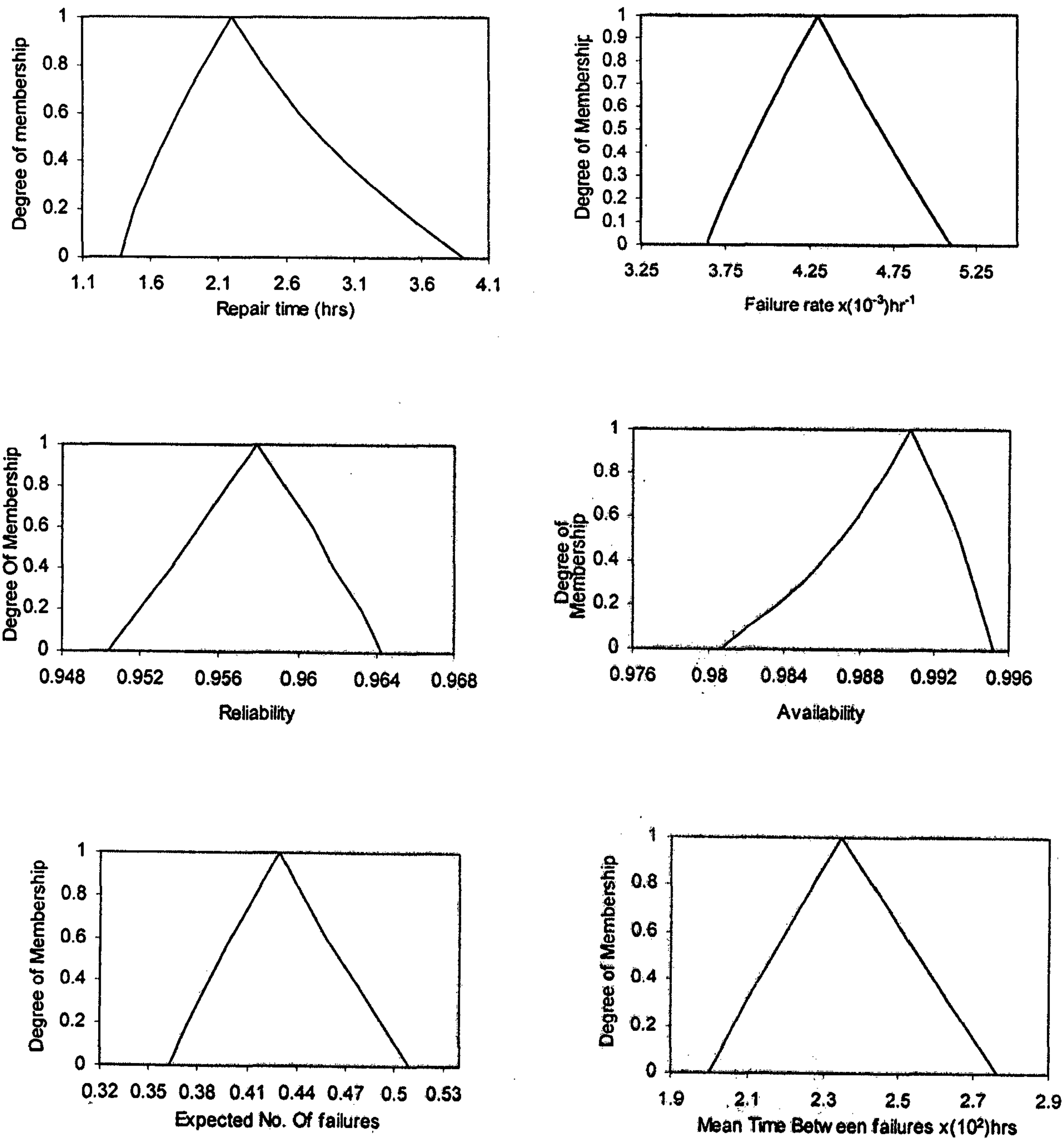
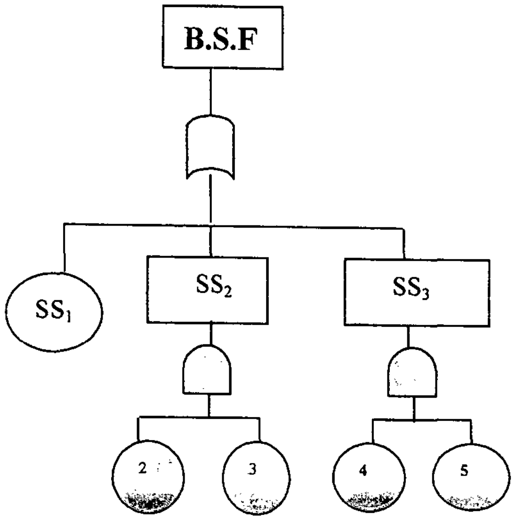


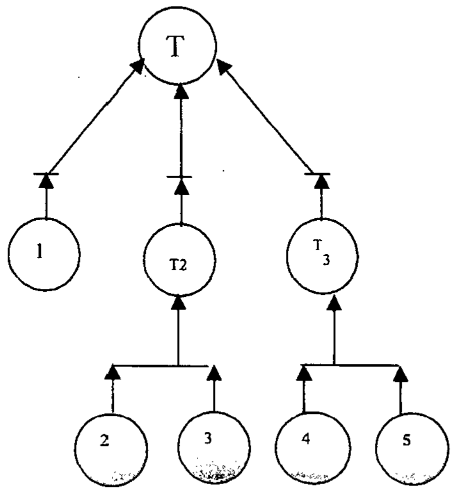
Figure 4.28 Fuzzy Representations of System Parameters (Washing)

Bleaching System

Figure 4.29 (a) and (b) shows the fault tree model and equivalent Petrinet model of the system. Following the basic steps shown in Figure 4.20, the fuzzy, crisp and defuzzified results for the system were obtained. The fuzzy results with left and right spread values are shown in Table 4.39 and graphically presented in Figure 4.30.The crisp and defuzzified values for the system at different spread are given in Table 4.40. From the Table 4.40, it is evident that defuzzified value changes with change in percentage-spread .For instance, repair time first increases by 1.21% when spread changes from ±15% to ±30% and further by 9.61% when spread changes from ±30% to ±60%. Similarly, for failure rate and expected number of failures, with increase in spread, increase in defuzzified values, is observed. On the other hand, at the same time for mean time between failures a decrease of 1.14% when spread changes from ±15% to ±30% and further by 4.19% when spread from changes from ±30% to ±60% is observed. Similarly, for availability and. reliability decrease in defuzzified values with increase in spread is observed. Thus from above discussions it is inferred that the maintenance action for the system should be based on defuzzified MTBF rather than on crisp value because with the reduced MTBF values a safe interval between maintenance actions can be established and inspections (continuous or periodic) can be conducted to monitor the condition or status of various equipments constituting the system before it reaches the crisp value.



(a)



(b)

B.S.F = Bleaching System Failure, T = Top Event Failure
SS_1= (Subsystem-1), SS_2= (Subsystem-2), SS_3= (Subsystem-3),
i = 1 Bleaching tank, i =2, 3 filters, and i= 4,5 Washers.

Figure 4.29 Bleaching (a) Fault Tree Model (b) Petrinet Model

Table 4.39 System Parameters (Bleaching)

DOMF	Repair (hrs)		Failure X10^{-4} (hr^{-1})		M.T.B.F X10^{3} (hrs)		E.N.O.F X10^{-2} (hrs)		Availability		Reliability	
	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S
1	1.5390	1.5390	7.8320	7.8320	1.278130	1.278130	7.827300	7.827300	0.99879	0.998790	0.92466	0.92466
0.9	1.3870	1.7402	7.4880	8.1685	1.227500	1.339351	7.483900	8.164050	0.99871	0.999087	0.92158	0.92784
0.8	1.2372	1.9404	7.1456	8.5050	1.177300	1.400401	7.140590	8.500800	0.99858	0.999214	0.91852	0.93103
0.7	1.1195	2.1364	6.9208	8.8619	1.131901	1.447355	6.916001	8.857840	0.99829	0.999327	0.91522	0.93189
0.6	1.0010	2.4030	6.5860	9.2189	1.086801	1.494200	6.600360	9.214880	0.99801	0.999440	0.91193	0.93775
0.5	0.9110	2.7145	6.3438	9.5954	1.046201	1.588531	6.357920	9.591200	0.99758	0.999538	0.90849	0.94112
0.4	0.8200	3.0805	6.0316	9.9719	1.005680	1.658301	6.025550	9.968432	0.99714	0.999636	0.90509	0.94444
0.3	0.7509	3.5110	5.7669	10.362	0.969130	1.737651	5.760620	10.36562	0.99658	0.999690	0.90151	0.94623
0.2	0.6808	3.9280	5.5023	10.766	0.933256	1.817420	5.495750	10.76288	0.99602	0.999744	0.89793	0.95201
0.1	0.6258	4.4880	5.2497	11.184	0.899601	1.909400	5.242920	11.18134	0.99523	0.999770	0.89419	0.95616
0	0.5736	5.0480	4.9972	11.602	0.866670	2.001420	4.990141	11.59980	0.99444	0.999796	0.89045	0.96002

Table 4.40 Crisp and Defuzzified Values at Different Spreads

System Parameters	Defuzzified value [±15% spread]	Defuzzified value [±30% spread]	Defuzzified value [±60% spread]	Crisp value
Failure rate (hr^{-1})	0.0007832	0.0007901	0.0007997	0.0008772
Repair time (hr)	1.53921	1.963911	3.186223	5.0412120
Availability	0.998790	0.998430	0.997180	0.9956140
MTBF (hr)	127.8111	126.7611	125.3311	145.03110
ENOF	0.078273	0.078940	0.079940	0.0877041
Reliability	0.92466	0.924030	0.923140	0.9160351

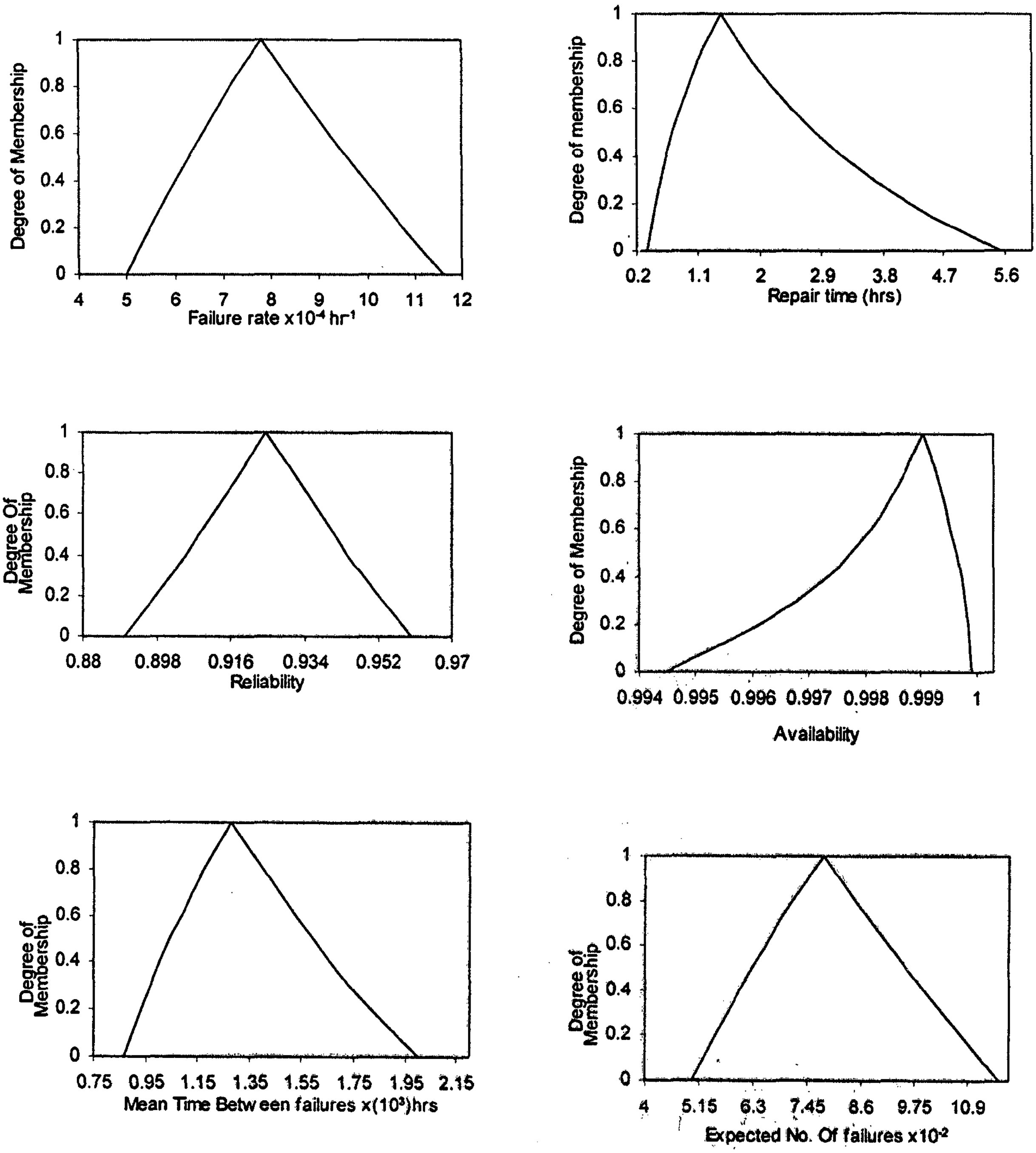
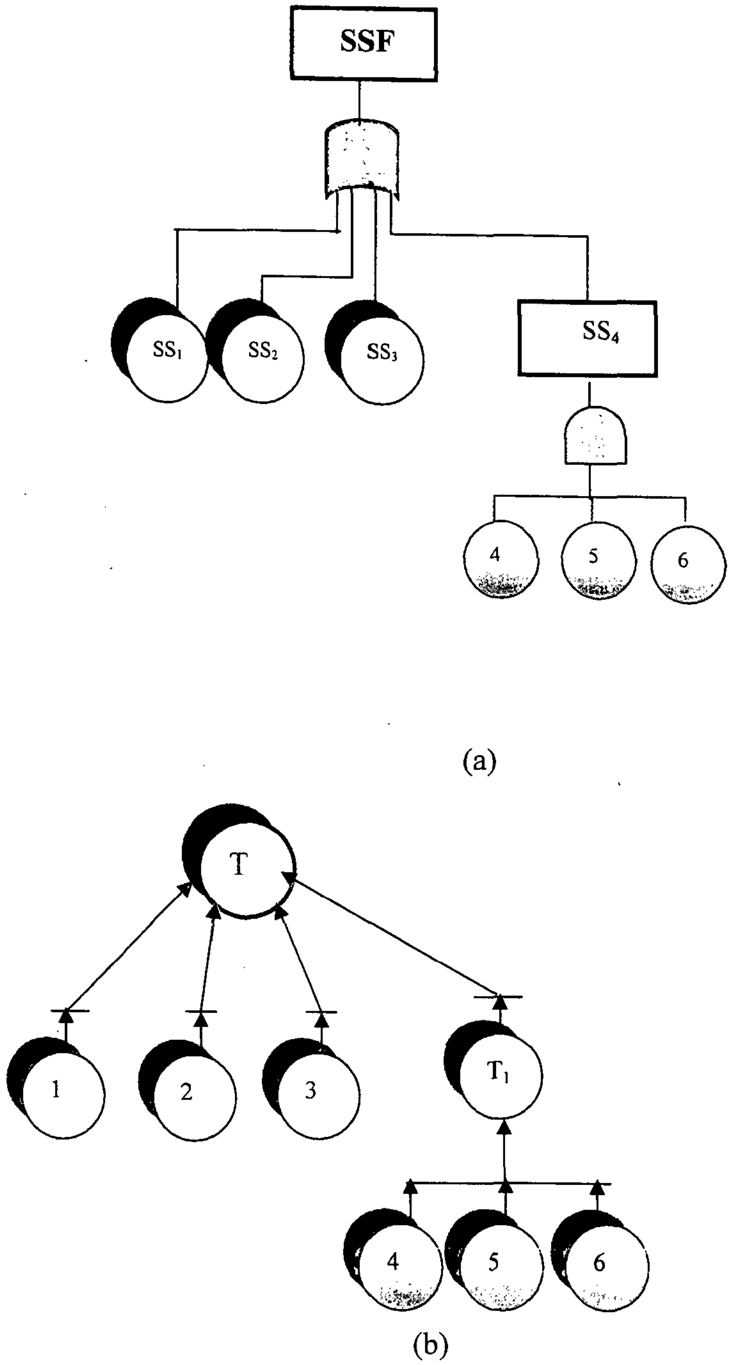


Figure 4.30 Fuzzy Representations of System Parameters (Bleaching)

Screening System

Figure 4.31 (a) and (b) shows the Fault tree Model and equivalent Petrinet Model of the system. Following the basic steps used in computing algorithm given in Figure 4.5 the fuzzy, crisp and defuzzified results for the system were obtained. The fuzzy results with left and right spread values are shown in Table 4.41 and graphically presented in Figure 4.32. From the Table 4.42, it is evident that defuzzified value changes with change in percentage-spread. For instance, repair time first increases by 1.89% when spread changes from ±15% to ±30% and further by 3.70% when spread changes from ±30% to ±60%. Similarly, for failure rate and expected number of failures, with increase in spread, increase in defuzzified values, is observed. On the other hand, at the same time for mean time between failures a decrease of 1.862% when spread changes from ±15% to ±30% and further to 1.59% when spread changes from ±30% to ±60% is observed. Similarly, for availability and. reliability decrease in defuzzified values with increase in spread is observed. Thus from above discussions it is inferred that the maintenance action for the system should be based on defuzzified MTBF rather than on crisp value because with the reduced MTBF values a safe interval between maintenance actions can be established and inspections (continuous or periodic) can be conducted to monitor the condition or status of various equipments constituting the system before it reaches the crisp value.



S.S.F = Screening System Failure, T = Top Event Failure
SS_1= (Subsystem-1), SS_2= (Subsystem-2), SS_3= (Subsystem-3), SS_4= (Subsystem-4, Cleaners)
i=1[filter]; i=2 [screener]; i=3[decker] i=4, 5, 6 [cleaners]

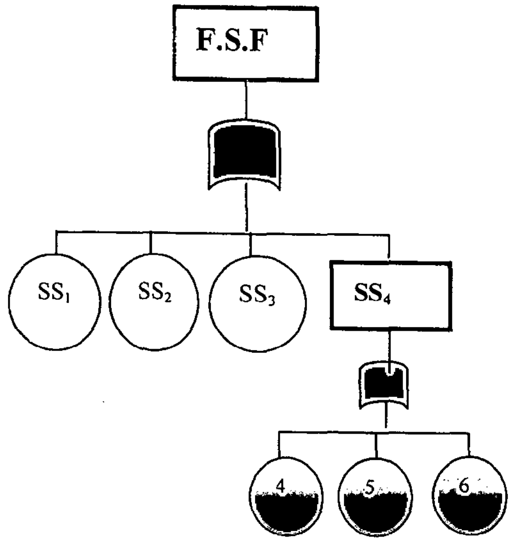
Figure 4.31 Screening (a) Fault Tree Model (b) Petrinet Model

Table 4.41 System Parameters (Screening)

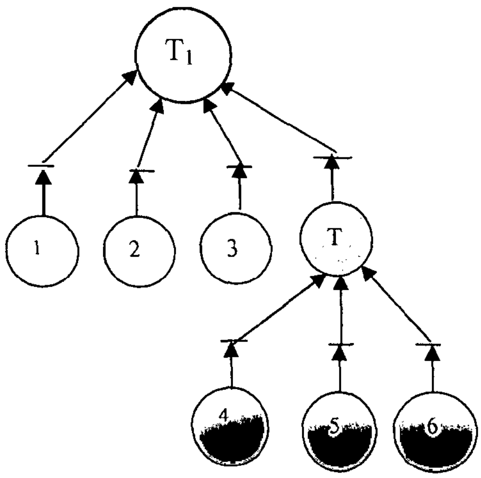
DOMF	Repair hr		Failure $X\ 10^{-3}$hr		Availability		Reliability		MTBF $X\ 10^{2}$hr		ENOF $X\ 10^{-2}$ hr	
	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S
1	2.1146	2.1146	5.2025	5.2025	0.98920	0.98920	0.949305	0.949305	1.94329	1.94329	5.1897	5.18970
0.9	2.0230	2.2138	5.1242	5.2807	0.98856	0.989835	0.948510	0.950048	1.916215	1.972186	5.1112	5.26150
0.8	1.9315	2.3130	5.046	5.3590	0.98800	0.990440	0.947820	0.950791	1.889147	2.001082	5.0321	5.34660
0.7	1.8469	2.4205	4.9670	5.4271	0.98719	0.990980	0.947170	0.951470	1.86656	2.032050	4.9540	5.41504
0.6	1.7624	2.5280	4.8890	5.4954	0.98658	0.991520	0.946528	0.952285	1.844984	2.063032	4.8750	5.48348
0.5	1.6865	2.6413	4.8110	5.5771	0.98568	0.991996	0.945755	0.953001	1.819825	2.095965	4.7972	5.59538
0.4	1.6146	2.7546	4.7330	5.6589	0.98488	0.992472	0.944982	0.953772	1.794673	2.128970	4.7191	5.64729
0.3	1.5381	2.9061	4.6550	5.7434	0.98383	0.992930	0.944182	0.954516	1.770550	2.164210	4.6411	5.732104
0.2	1.4616	3.0576	4.5770	5.8280	0.98279	0.993397	0.943380	0.955261	1.746430	2.199450	4.5627	5.816910
0.1	1.3948	3.2394	4.4990	5.9064	0.98155	0.993793	0.942642	0.956001	1.725240	2.237305	4.4849	5.895720
0	1.3280	3.4213	4.4211	5.9851	0.98082	0.994196	0.941905	0.95600	1.705056	2.275160	4.4071	5.974540

Table 4.42 Crisp and Defuzzified Values at Different Spreads

System Parameters	Crisp values	Defuzzified value [±15% spread]	Defuzzified value [±30% spread]	Defuzzified value [±60% spread]
Failure rate (h^{-1})	5.2025×10^{-3}	5.2205×10^{-3}	5.3260×10^{-3}	5.5350×10^{-3}
Repair time (h)	2.11460	2.21601	2.46001	3.2000
MTBF (h)	1.9432×10^{2}	1.9376×10^{2}	1.90218×10^{2}	1.8719×10^{2}
ENOF	5.19870×10^{-2}	5.20820×10^{-2}	5.31400×10^{-2}	5.42570×10^{-2}
Availability	9.89230×10^{-1}	9.88640×10^{-1}	9.87230×10^{-1}	9.83170×10^{-1}
Reliability	9.49300×10^{-1}	9.49100×10^{-1}	9.481300×10^{-1}	9.47100×10^{-1}



(a)



(b)

F.S.F = Forming System Failure, T = Top Event Failure

SS_1 – (Subsystem-1), SS_2 – (Subsystem-2), SS_3 – (Subsystem-3), SS_4 – (Subsystem-4, Roller wear)

i=1[Head box]; i=2 [wire mat], i=3 [suction box]; i=4, 5, 6 [roller bearing, roller bending *and* roller rubber wear]

Figure 4.33 Forming (a) Fault Tree Model (b) Petrinet Model

Table 4.43 System Parameters (Forming)

DO MF	Repair (hrs)		Failure X10^{-3} (hr^{-1})		M.T.B.F X10^{2} (hrs)		E.N.O.F		Avail.		Reliability	
	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S
1	5.5116	5.5116	8.6000	8.60000	1.2179	1.2179	0.42930	0.429334	0.9567	0.95670	0.91759	0.917594
0.9	5.4436	5.5978	8.4790	8.72500	1.2023	1.2340	0.42317	0.435587	0.9554	0.95783	0.91650	0.918655
0.8	5.3762	5.6841	8.3580	8.85111	1.1867	1.2502	0.41704	0.441839	0.9542	0.95890	0.91542	0.919817
0.7	5.3228	5.7926	8.2430	8.98301	1.1713	1.2651	0.41139	0.448465	0.9528	0.95983	0.94140	0.920874
0.6	5.2694	5.9011	8.1280	9.11623	1.1559	1.2801	0.40574	0.455097	0.9514	0.96076	0.91277	0.921936
0.5	5.2262	6.0375	7.5205	9.25655	10140	1.2978	0.40039	0.462091	0.9497	0.96143	0.91154	0.922920
0.4	5.1831	6.1741	7.9130	9.39666	1.1260	1.3155	0.39504	0.469086	0.9480	0.96209	0.91031	0.923919
0.3	5.1515	6.3460	7.8115	9.54233	1.1115	1.3318	0.38997	0.476375	0.9459	0.96278	0.90899	0.924826
0.2	5.1200	6.518	7.7100	9.68856	1.0973	1.3481	0.38491	0.483681	0.9439	0.96347	0.90766	0.925733
0.1	5.0905	6.7365	7.6055	9.84245	1.0835	1.3666	0.37927	0.493076	0.9414	0.96410	0.90626	0.926735
0	5.0611	6.955	7.5000	9.99756	1.0698	1.3839	0.37445	0.499175	0.9389	0.96471	0.90486	0.927744

Table 4.44 Crisp and Defuzzified Values

System Parameters	Crisp value	Defuzzified value [±15% spread]	Defuzzified value [±30% spread]	Defuzzified value [±60% spread]
Failure rate (hr^{-1})	0.00860	0.00867	0.00879	0.00920
Repair time (hr)	5.5116	5.69200	6.31100	7.1203
Availability	0.95670	0.95508	0.94668	0.94205
MTBF (hr)	121.790	121.032	120.050	115.79
ENOF	0.411289	0.41510	0.42132	0.43763
Reliability	0.66170	0.65950	0.65570	0.64234

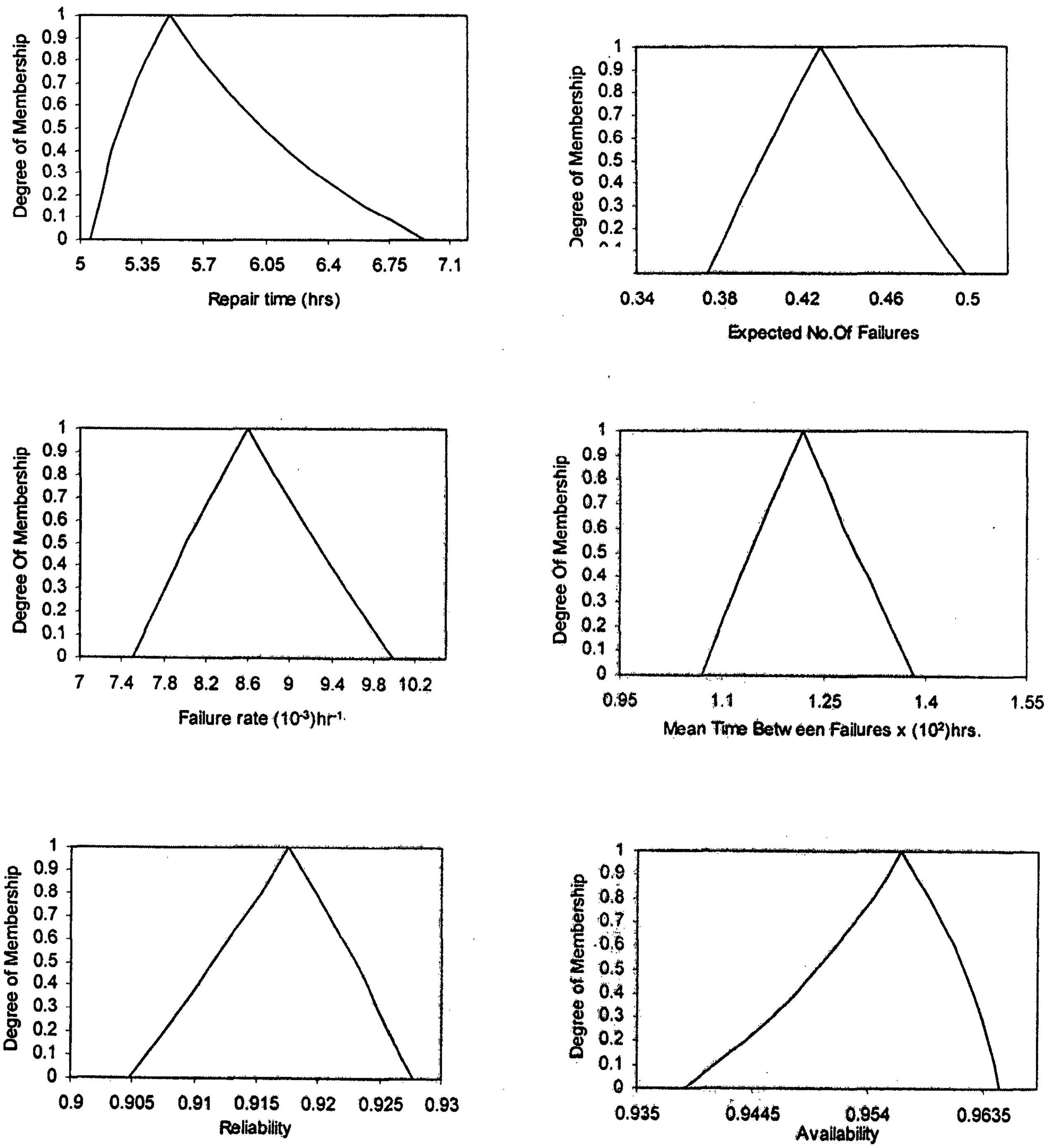
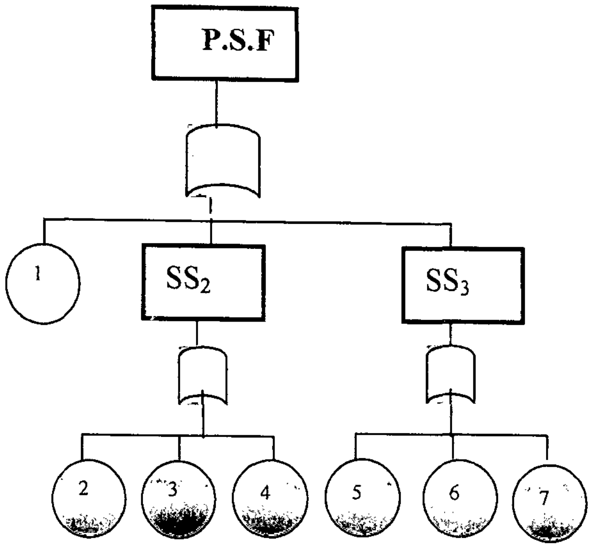


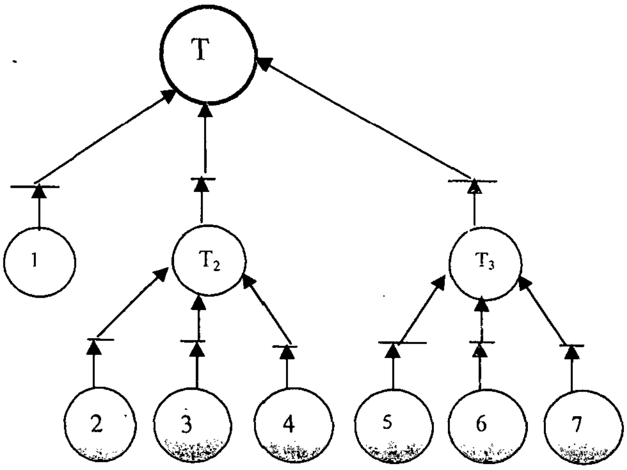
Figure 4.34 Fuzzy Representations of System Parameters (Forming)

Press System

Figure 4.35 (a) and (b) shows the fault tree model and its equivalent Petrinet model of the system. Following the basic steps used in computing algorithm given in Figure 4.20, the fuzzy, crisp and defuzzified results for the system were obtained. The fuzzy results with left and right spread values are shown in Table 4.45 and are graphically presented in Figure 4.36. The crisp and defuzzified values for the system at different spread are tabulated in Table 4.46. The crisp value remains same irrespective of change in spread. From the Table 4.46 it is evident that defuzzified value changes with change in percentage-spread. For instance, repair time first increases by 2.85% when spread changes from ±15% to ±30% and further by 4.95% when spread changes from ±30% to ±60%. Similarly, for failure rate and expected number of failures, with increase in spread, increase in defuzzified values, is observed. On the other hand, at the same time for mean time between failures a decrease of 0.84% when spread changes from ±15% to ±30% and further by 1.77 % when spread changes from ±30% to ±60% is observed. Similarly, for availability / reliability, decrease in defuzzified values with increase in spread is observed. Thus from the above discussions it is inferred that the maintenance action for the system should be based on defuzzified MTBF rather than on crisp value because with the reduced MTBF values a safe interval between maintenance actions can be established and inspections (continuous or periodic) can be conducted to monitor the condition or status of various equipments constituting the system before it reaches the crisp value. It can also be observed that with increase in repair time for the unit, availability decreases.



(a)



(b)

P.S.F = Press System Failure, T = Top Event Failure
SS_1= (Subsystem-1, Press Felt), SS_2= (Subsystem-2, Top roller), SS_3= (Subsystem-3, Bottom roller)
i=1[Felt]; i=2, 5 [top, bottom roller bearing]; i=3, 6[top, bottom roller bending]; *and* i=4, 7 [top, bottom roller rubber wear]

Figure 4.35 Press (a) Fault tree model (b) Petrinet Model

Table 4.45 Computed Parameters (Press)

DOMF	Repair (hrs)		Failure X 10^{-3} (hr^{-1})		M.T.B.F X10^{2} (hrs)		E.N.O.F		Availability		Reliability	
	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S	L.S	R.S
1	3.21970	3.219700	9.10000	9.10000	1.1310	1.13100	0.45371	0.45371	0.97325	0.973250	0.91301	0.91301
0.9	3.15090	3.305653	8.98661	9.226112	1.1172	1.14523	0.44771	0.45992	0.97165	0.973821	0.91182	0.91411
0.8	3.08221	3.39235	8.86561	9.351121	1.1034	1.15943	0.44182	0.46623	0.97014	0.974422	0.91071	0.91522
0.7	3.02862	3.501355	8.74766	9.483132	1.0897	1.17353	0.43612	0.47284	0.96883	0.974951	0.90952	0.91623
0.6	2.97523	3.609432	8.63422	9.616141	1.0766	1.18794	0.43051	0.47943	0.96753	0.975562	0.90833	0.91722
0.5	2.93114	3.745562	8.52542	9.756251	1.0626	1.20245	0.42441	0.48642	0.96591	0.976061	0.90704	0.91821
0.4	2.88723	3.882643	8.41562	9.896321	1.0493	1.21726	0.41981	0.49343	0.96433	0.976822	0.90572	0.91922
0.3	2.85432	4.054646	8.31341	10.04341	1.0361	1.23162	0.41481	0.50074	0.96233	0.977333	0.90451	0.92023
0.2	2.82172	4.226356	8.21232	10.18121	1.0238	1.24593	0.40961	0.50803	0.96013	0.977844	0.90311	0.92114
0.1	2.79413	4.440656	8.11063	10.34113	1.0115	1.26114	0.40451	0.51513	0.95781	0.978315	0.90171	0.92215
0	2.76662	4.661642	8.00753	10.49232	0.9992	1.27644	0.39921	0.52353	0.95541	0.978782	0.90032	0.92303

Table 4.46 Crisp and Defuzzified Values

Parameters	Failure rate (hr^{-1})	Repair time (hr)	Availability	MTBF (hr)	ENOF	Reliability
Crisp value	0.009100	3.2100	0.97240	113.100	0.45371	0.91360
±15% spread	0.009109	3.2980	0.97166	113.079	0.46302	0.90160
±30% spread	0.009200	3.3920	0.96976	112.081	0.47240	0.8988
±60% spread	0.009387	3.5600	0.96766	110.090	0.48970	0.8868

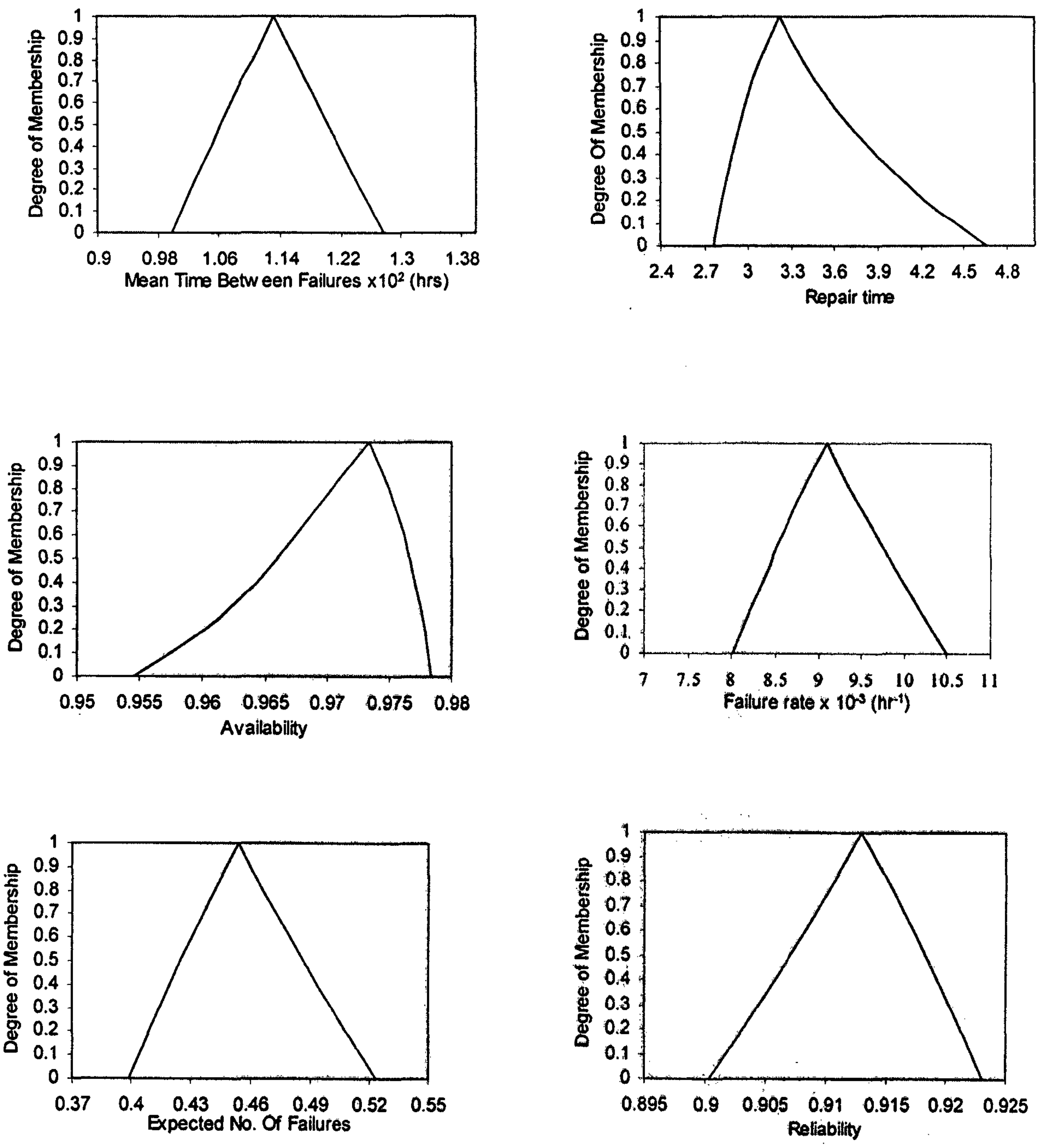
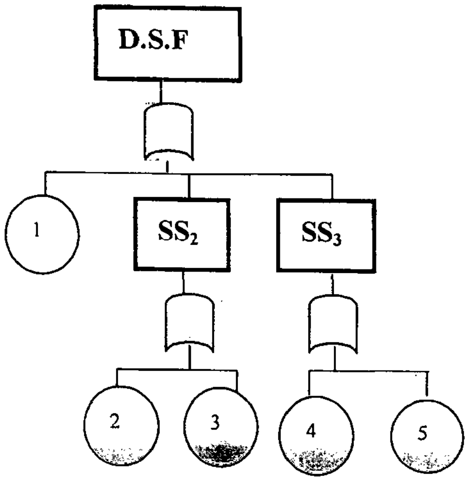


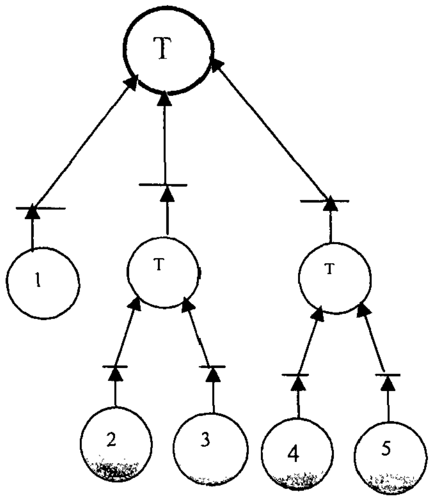
Figure 4.36 Fuzzy Representations of System Parameters (Press)

Dryer System

Figure 4.37 (a) and (b) shows the Fault tree model and corresponding Petrinet model of the system. Following the basic steps used in computing algorithm given in Figure 4.20, the fuzzy, crisp and defuzzified results for the system were obtained. The fuzzy results with left and right spread values are shown in Table 4.47 and graphically presented in Figure 4.38. The crisp and defuzzified values for the system at different spread are tabulated in Table 4.48. From the Table 4.48, it is evident that defuzzified value changes with change in percentage-spread. For instance, repair time first increases by 2.55% when spread changes from ±15% to ±30% and further by 10.60% when spread changes from ±30% to ±60%. Similarly, for failure rate and expected number of failures, with increase in spread, increase in defuzzified values is observed. On the other hand, at the same time for mean time between failures a decrease of 1.42% when spread changes from ±15% to ±30% and further to 3.484% when spread from changes from ±30% to ±60% is observed. Similarly, for availability and reliability decrease in defuzzified values with increase in spread is observed. Thus, from above discussions it is inferred that the maintenance action for the system should be based on defuzzified MTBF rather than on crisp value because with the reduced MTBF values, a safe interval between maintenance actions can be established and inspections (continuous or periodic) can be conducted to monitor the condition or status of various equipments constituting the system before it reaches the crisp value.



(a)



D.S.F = Dryer System Failure, T = Top Event Failure
SS_1= (Subsystem-1), SS_2= (Subsystem-2, Top roller), SS_3= (Subsystem-3, Bottom roller)
i=1[Felt]; i=2, 4 [top, bottom roller bearing]; i=3, 5[top, bottom roller bending]

Figure 4.37 Dryer (a) Fault tree Model (b) Petrinet model

Table 4.47 System Parameters (Dryer)

DOMF	Repair (hr)	Failure X10⁻³hr⁻¹	MTBF X10² (hrs)	Avail.	ENOF	Reliab.	Repair (hrs)	Failure X10⁻³hr⁻¹	MTBF X10² (hrs)	Avail.	ENOF	Reliab
1	3.40982	6.10000	1.6734	0.9800	0.30442	0.940821	3.409820	6.10000	1.67342	0.98000	0.30442	0.9408
0.9	3.33652	5.98001	0.6415	0.9791	0.29851	0.939641	3.470521	6.22634	1.70633	0.98071	0.31073	0.9419
0.8	3.27333	5.86002	1.6097	0.9782	0.29252	0.938474	3.571223	6.35365	1.73924	0.98152	0.31694	0.9430
0.7	3.21933	5.74711	1.5777	0.9772	0.28743	0.937182	3.674233	6.48555	1.77355	0.98211	0.3237	0.9441
0.6	3.16553	5.63422	1.5492	0.9762	0.28122	0.935983	3.777544	6.61643	1.80785	0.98271	0.3302	0.9452
0.5	3.12123	5.52533	1.5195	0.9751	0.27593	0.934654	3.885933	6.75667	1.84268	0.98322	0.3371	0.9462
0.4	3.07933	5.41522	1.4989	0.9740	0.27054	0.933045	3.994443	6.89666	1.87758	0.98388	0.3441	0.9472
0.3	3.04523	5.31251	1.4626	0.9726	0.26555	0.932093	4.128752	7.03855	1.91318	0.98421	0.3514	0.9482
0.2	3.01153	5.21211	1.4353	0.9711	0.26046	0.930713	4.263662	7.18064	1.94877	0.98472	0.3587	0.9492
0.1	2.98073	5.10955	1.4082	0.9694	0.25515	0.929523	4.429552	7.33555	1.98766	0.98513	0.3664	0.9501
0	2.95556	5.00722	1.3801	0.9677	0.24995	0.927832	4.598775	7.49556	2.02676	0.98567	0.3742	0.9511

Table 4.48 Crisp and Defuzzified Values at Different Spread

System Parameters	Crisp value	Defuzzified value [±15% spread]	Defuzzified value [±30% spread]	Defuzzified value [±60% spread]
Failure rate (h^{-1})	6.10×10^{-3}	6.120×10^{-3}	6.2120×10^{-3}	6.368×10^{-3}
Repair time (h)	3.40	3.491	3.580	3. 961
Availability	9.800×10^{-1}	9.795×10^{-1}	9.78707×10^{-1}	9.7599×10^{-1}
MTBF (h)	1.6700×10^{3}	1.6689×10^{3}	1.6455×10^{3}	1.60995×10^{3}
ENOF	3.0422×10^{-1}	3.0546×10^{-1}	3.1006×10^{-1}	3.20889×10^{-1}
Reliability	9.4082×10^{-1}	9.4063×10^{-1}	9.3977×10^{-1}	9.37101×10^{-1}

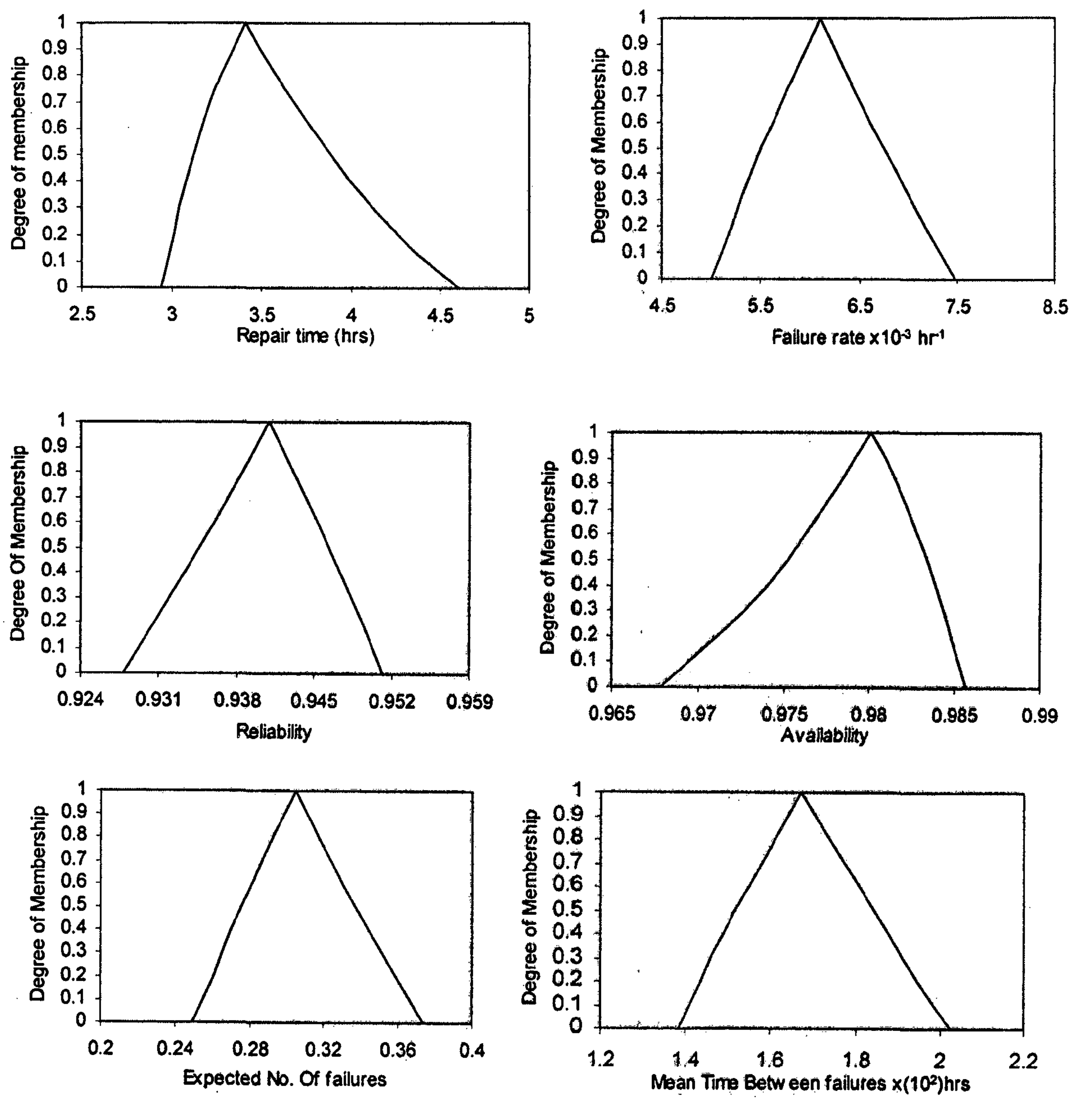


Figure 4.38 Fuzzy Representation of System Parameters (Dryer)

4.4. CONCLUDING REMARKS

The integrated approach presented in the chapter demonstrates the inherent potential of fuzzy methodology to help the reliability/system analysts to define, measure, and characterize the behavior of system in more realistic manner. In the qualitative analysis, first the in-depth analysis of the units was carried out using RCA and FMEA. Using FMEA all possible failure modes, their causes and effect on system function is summarized. Using the selected experts, the values of failure of occurrence (O_f), likelihood of non-detection of failure (O_d), and severity (S) of failure of various components were ascertained and resulting RPN scores were obtained. The limitations associated with the traditional RPN procedure were addressed by using fuzzy decision making system (FDMS) and Grey Relation Analysis (GRA). In the quantitative framework, After obtaining the Petrinet model of the system from its equivalent fault tree model the system failure and repair times were computed (based on the steps discussed in section 4.3.3.1). The computation of various system parameters (failure rate, repair time, expected number of failures, mean time between failures, availability and reliability) at different degree of membership values (depicted with help of fuzzy graphs) will help the maintenance managers to understand the dynamics of system behavior. Depending upon the value of confidence factor (alpha), the analysts can not only predict the reliability measure for the system(s) but also take necessary steps to build reliability into the system.

MAINTENANCE DECISION MAKING

5.1 INTRODUCTION

The demand for higher productivity and increased plant outputs has imposed greater demands on the plant maintenance function. Maintenance managers are being called upon to improve the standards of maintenance and efficiency of working and at the same time to reduce the operational costs. This challenge is more relevant and is gaining importance in the process plants. The process plants are large and are complex engineering systems. In these plants, the equipment requires heavy capital expenditure and thus the down time becomes extremely costly. To ensure maximum plant availability and reliability, maintenance must be carried out at regular intervals. This maintenance must be carefully planned in conjunction with production requirements and schedules so that it causes minimum stoppage and loss of production. Inadequate maintenance can lead to damage, which is extremely costly not only in repair but it also results in production loss. This is the reason why in these plants, the maintenance engineering department is an indispensable part of a production system. Effective maintenance not only helps to retain equipment / facility in proper condition but also extends its life and improves availability. On the other hand, poorly maintained equipment / facility may lead to more frequent failures, poor utilization resulting in production delays. Traditionally many companies employed fire-fighting approach called reactive maintenance for maintenance activities, which means that as and when equipment fails to perform,

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- *International Journal of Quality and Reliability Management (Accepted)

repairs are carried out. This practice not only increases the total down time but also hampers the production. With the advancement in technology, this strategy has been replaced by proactive and aggressive maintenance strategies. A proactive approach calls for preventive and predictive maintenance to prevent sudden sporadic or chronic failures. In present times because of automation and large-scale mechanization, higher plant availability, better product quality and longer equipment life have assumed considerable significance. In order to meet the above challenges, adoption of a suitable maintenance strategy has become essential for organizations to survive. While these newer maintenance strategies require greater commitments in terms of training, resources and integration, they are expected to provide higher levels of equipment and plant performance (Ljungberg 1998, Jonsson and Lesshammar 1999, Pintelon and Wayenberg 2002, 2004, Chan *etal.,* 2005, Pramod *et al.,* 2006, Arunraj and Maiti).

The research issues discussed in the present chapter deals with the following objectives:

(i) To help the maintenance managers/decision makers to select the suitable maintenance strategy for paper machine and its components

(ii) To provide implementation framework for TPM deployment in the paper machine cell coupled with standard tools/techniques and practices

(iii) To present the application of Non-Homogeneous Poison Point Process (NHPPP) model for modeling, analyzing and predicting the repair and replacement decisions with regard to vital components (wire mat and vacuum pumps) of paper machine

To achieve the first objective an approach based on Fuzzy Linguistic Modeling (FLM) to select the most effective and efficient maintenance strategy is developed. An illustrative case from process industry (paper mill) is considered. Three input parameters i.e. historical data [I_1], present data [I_2], and competence of data [I_3] related to failures of a component (gears) are taken to judge the effectiveness of maintenance strategies. These parameters are represented as members of fuzzy set, combined by matching them against (If-Then) rules in rule base, evaluated in fuzzy inference system (mamdani, min-max type) and then defuzzified to assess the capability or effectiveness of maintenance strategy. The various maintenance strategies considered were Frequency Based or Breakdown Maintenance (BDM), Preventive Maintenance (PM), Total Productive Maintenance (TPM), Condition Based Maintenance (CBM), and Reliability Centered Maintenance (RCM). Briefly the aspects of these maintenance strategies, which are investigated using FLM approach, are discussed as under in section 5.2.

The second objective aimed at implementing TPM in the semi automated paper machine cell is achieved by following a structured implementation plan which includes different activities such as formation of TPM secretariat, creation of TPM master plan, and formation of Autonomous maintenance (AM), Planned Maintenance (PM) and Focus improvement (FI) teams. Table 5.6 presents the detailed step by step procedure for TPM implementation.

A framework using NHPPP models (as discussed in chapter 3) [which makes use of modeling of data, goodness of fit tests and regression analysis] has been applied to achieve the third objective i.e. to make repair /replacement decisions for paper machine components (wire ma and vacuum pumps).

5.2 MAINTENANCE STRATEGIES

5.2.1 Reactive or Breakdown Maintenance (BDM):

In reactive maintenance, which is also known as frequency based or breakdown maintenance, repairs are done to bring the equipment back from failure stage to operational stage It results in fluctuation in production, higher down time and increase in the scrap and rework rate Thus, the ultimate effect is increase in overall maintenance costs. No action is taken to detect the onset or how to prevent frequent failures, which accounts for usually high maintenance related costs. In a situation where customer demand exceeds supply and profit margins are large, BDM is feasible approach because the main objective of BDM is to keep the process running in order to maximize the availability. Traditionally, this type of strategy was mainly practiced as an *'action-oriented'* or *'fire-fighting'* approach that solves production problems. However, today stiff global competition and small profit margins had forced the maintenance managers to think and adapt cost effective and reliable maintenance strategies (Pintelon and Gilders 1992, Sheu *et al.* 1994, Swanson 2001, Deshpande and Modak 2003, Eti *et al.,* 2004, Garg and Deshmukh 2006, Pinjala 2006, Moore and Starr 2006).

5.2.2 Preventive Maintenance (PM)

The main objective of carrying out preventive maintenance is to reduce the frequent and sudden sporadic failures by performing repairs, replacement, overhauling, lubrication, cleaning and inspection at a specific predetermined interval of time say *weekly, monthly, bi-monthly, half-yearly or annually* regardless of the condition of the equipment/component (Gits 1992). Thus, PM reduces the probability of equipment breakdown by proper planning of interval (age-based or calendar time), for carrying out preventive maintenance tasks (Dekker 1996).

5.2.3 Predictive or Condition Based Maintenance (CBM):

Predictive or condition based maintenance strategy reduces the probability of sudden sporadic failures with the aid of diagnostics and timely intervention. Vibration-based maintenance (VBM) involves periodic (VBMp) and continuous (VBMc) collection and interpretation of data, which is based on deterministic and probabilistic models. Thus, it provides useful information for diagnoses and prognoses of system components/parts. For instance, diagnostic equipments are used to measure the physical conditions such as temperature, vibration, noise, corrosion etc. about the root cause(s) and failure mechanisms. Vibration technique is always preferred in condition monitoring applied on rotating and reciprocating machines, but limitations and deficiency in data coverage and quality reduce its effectiveness and accuracy (Tsang 1995, Yang *et al.* 1999, Moubray 2000). Now days, application of condition based maintenance had become popular in process industries, such as paper mills, oil-refineries, sugar mills and thermal power plants. In order to achieve an effective implementation of *"zero-failure"* strategy the condition monitoring system helps to discover failure causes, potential failures and mechanisms of failure. For instance, spectral analysis is one of the most useful fault diagnostics tools which provide a basis for identification of failure mechanisms, failure causes and failure modes in mechanical systems, such as rotating and reciprocating machines.

5.2.4 Reliability Centered Maintenance (RCM):

Moubary (2000) defined reliability centered maintenance as a systematic approach used to optimize preventive and predictive maintenance programs to increase equipment efficiency (uptime, performance and quality) while targeting on minimizing the maintenance cost. In RCM methodology the focus is on maintaining system function rather than restoring equipment to an ideal condition. Earlier RCM methodology was restricted to the airline and nuclear industries. But today it offers tremendous opportunities in areas such as fossil power plants, oil refineries, and other process industries. The primary objective of RCM is to preserve system function. To attain this objective various failure modes that cause functional failure are identified, prioritized accordingly to reflect their importance in system functioning. Tools such as Failure Mode and Effect Analysis (FMEA) and Fault tree Analysis (FTA) are used in RCM analysis.

5.2.5 Total productive maintenance (TPM):

Total productive maintenance defined by Nakajima (1988) includes a company wide approach to plant, equipment or asset care that involves the active participation of all from top management to workers on the floor to enhance equipment effectiveness by eliminating the six big losses such as *Downtime losses, Set-up and adjustments losses, Speed losses, Reduced speed, Defect losses*, and *Reduced yield*. In TPM the practice of preventive maintenance is combined with the concept of Total Quality through Employee Involvement (TQEI). Operators maintain their own machines by practicing 5S principles. They compile and interpret maintenance and operating data of their machines that helps to identify signs of deterioration, if any. Routine daily maintenance checks, minor adjustments, lubrication, and minor part changes are the activities performed by the operators. TPM seeks to improve the Overall Equipment Effectiveness (OEE), which is an important indicator, used to measure TPM. An overall 85% of OEE is considered as world class and a benchmark for others (Blanchard 1997, Mckone *et al.* 1999, Chand *et al.* 2000).

5.3 MAINTENANCE MIX SELECTION

To assess and identify the effectiveness and efficiency of various maintenance strategies discussed above, a framework proposing both theory and methodology is developed. An illustrative example concerning paper mill is considered. The failure causes of gears (which are used as a means of power transmission in paper machines) are identified. From the investigations through maintenance log books, interviews with maintenance personnel and experts it was concluded that failure of gears in paper machine mainly depends upon three important parameters

(i) operating conditions,

(ii) environmental conditions, and

(iii) nature of maintenance practices followed by maintenance personnel

The operating conditions include loading modes such as, continuous or intermittent, partial or full load (rpm), and temperature and pressure levels. The environmental conditions include parameters such as ambient temperature, humidity level, lubricant temperature and presence of dirt / dust in the surroundings. The maintenance activities include, operating and maintenance staff skill, their expertise to diagnose and rectify the faults, quality and availability of spares and lubricants used.

5.3.1 FUZZY LINGUISTIC MODELING

The above two causes i.e. operating and environmental conditions mainly responsible for failure of gears are analyzed using Fuzzy Linguistic Modeling (FLM), with an objective to help the maintenance mangers/decision makers to select suitable maintenance strategy. The evaluation methodology consists of the following steps discussed as under:

5.3.1.1 Evaluation Methodology

5.3.1.1 (a) Step1:

(i) Identification of failure causes (criterions) related to the gears (by using machine's history cards, experience and knowledge of maintenance personnel, technical analysis and expert judgment) and assignment of corresponding weight for each criterion to show the importance of failure cause. For instance, (as shown Table 5.1) operating mode (continuous or intermittent), dirt or dust, vibrations, lubricant temperature and quality of lubricants are different failure causes of gears related to paper machine and *very high, high, moderate, low and very low* are the corresponding weights assigned (with the help of experts) to them.

(ii) Identification of various maintenance strategies/criterions practiced in the industry *(BDM, PM CBM, RCM and TPM)* to monitor the status or bring the machine back into operation after failure The assessment capability of various maintenance strategies (as discussed in section 5.2) is done with the help of expert judgment. The experts were asked to provide the weights to each maintenance strategy keeping in mind their effectiveness to handle the failure causes. For instance as shown in Table 5. 2 capabilities to detect vibrations is weak in PM, high in both TPM and RCM and very high in CBM.

Table 5.1 Linguistic Assessment of Failure Causes with Respective Weights

S.No.	Notation	Failure cause	Weight
1	X_C	Operation Mode (continuous or intermittent operation)	+ + +
2	X_L	Load (operating and designed)	+ +
3	X_S	Speed (operating and designed)	+ +
4	X_T	Operating Temperature	+
5	X_{LT}	Lubricant Temperature.	+
6	X_{LQ}	Lubricant Quality	-
7	X_V	Vibrations	+
8	X_D	Dirt and Dust	- -

Note: Very high (+++), High (++), Medium (+), Low (-), Very Low (- -)

Table 5.2 Linguistic Assessment of Maintenance Capability

S.No	Failure Causes	BDM	PM	CBM	TPM	RCM
1	Operation Mode (continuous or intermittent operation)	- -	- -	+ +	+ + +	-
2	Load (operating and designed)	- -	-	+ +	+ +	+
3	Speed (Operating and designed)	- -	-	+ +	+ +	+
4	Operating Temperature	*N.A*	+	+ +	+ +	+
5	Lubricant Temperature.	*N.A*	-	+ +	+ +	+
6	Lubricant Quality	*N.A*	+	+	+ +	+ +
7	Vibrations	*N.A*	-	+ + +	+ +	+ +
8	Dirt and Dust	-	+	- -	+ + +	-

Note: Very weak (- -), Weak (-), Fair (+), Strong (+ +), Very Strong (+++)

5.3.1.1(b) Step 2:

Based upon the subjective assessment of experts with respect to failure causes, the fuzzy membership function for fuzzy linguistic representation of importance of failure causes has been developed (shown in Figure 5.1). Five possible linguistic terms i.e. *low, very low, medium, hig and very high* are used to represent the importance of failure causes. Similarly based upon expe judgement, membership function for fuzzy linguistic representation of assessment capability (maintenance strategies is developed with linguistic terms *very weak, weak, fair, strong and ve strong* as shown in Figure 5. 2.

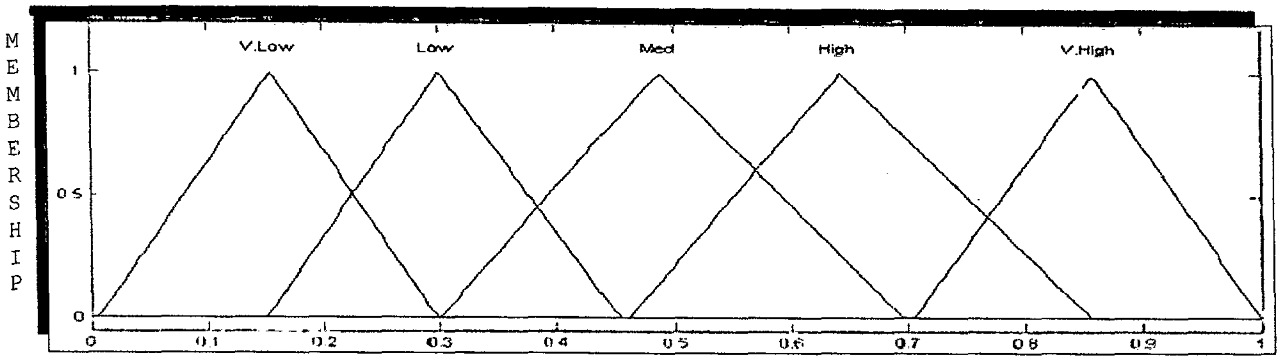

Figure 5.1 Fuzzy Representation of Importance of Failure Causes

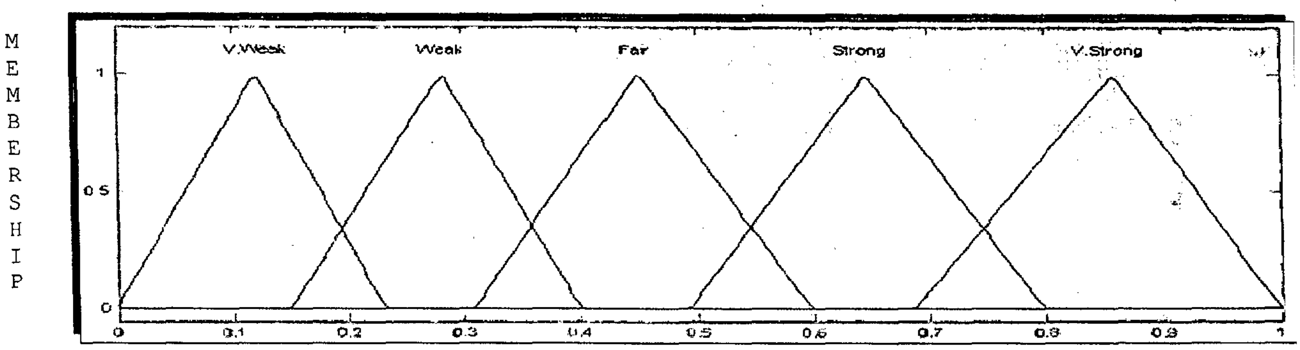

Figure 5.2 Fuzzy Representation of Capability of Maintenance Strategies

5.3.1.1 (c) Step 3:

In this step Fuzzy Inference system (FIS) based upon MISO model (with 3 inputs a 1output) to assess the capability of each maintenance strategy is developed using MATLAB 6 Fuzzy Logic Toolbox as shown in Figure 5.3

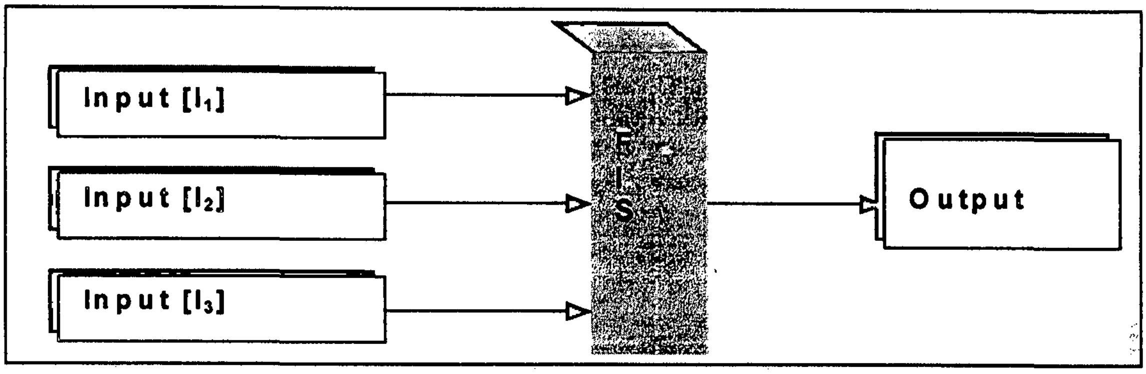

Figure 5.3 Block Diagram [Multi Input and Single Output Model]

Using universe of Discourse [0-1], the input variables I_1 , I_2 and I_3 are fuzzified using appropriate (triangular) membership functions. In brief the main characteristics of the inputs taken in the model are defined as

(1) Input One (I_1): (Historical data). In case of break down maintenance operational failure data regarding failures of gears is collected from maintenance logbooks or summaries. In preventive maintenance, data related to

(i) Number of failures

(ii) Number of planned replacements

(iii) Mean time to repair

(iv) Mean time between failures

is collected while in RCM, in addition to the historical data, previous operating and technical experience (regarding the failures) gained by maintenance experts, and through various analysis tools such as failure mode effect analysis and fault tree analysis is utilized to take decisions.

(2) Input Two (I_2): (Present data). Data regarding the current status or condition of equipment is obtained through real time measurements of key parameters such as temperature, pressure, vibration and noise etc with the aid of diagnostic and prognostic tools such as sensors, spectral analysis. With the help of condition based and vibration based maintenance (CBM and VBM) activities the relevant information regarding the state of components is captured. These measurements help to predict the age of the component. In TPM experience and skill of operation and maintenance personnel is used to collect data related to operational conditions, manufacturing methods, material and operator training etc.

(3) Input Three (I_3): It refers to competence (fitness) of the maintenance strategy, which means the degree of capturing adequate, relevant and satisfactory information about the respective failure modes/causes i.e.

(i) its damage initiation,

(ii) its propagation (growth mechanism), and

(iii) its effect on adjacent component /system performance i.e. deterioration or degradation.

In case of preventive maintenance, the history sheets of machines (monthly, quarterly or six monthly) are used to collect the relevant information while in RCM the information regarding factors affecting the life of the component/equipment mode is collected through analysis methods such as Ishikawa diagrams, Pareto charts, Fault Tree Analysis (FTA) and Failure Mode Effect Analysis (FMEA) (Eisingier *et al.* 2001).

5.3.1.1 (d) Step 4:

Out of the two most common types of fuzzy inference systems (discussed in chapter 3) i.e. Mamdani-type and Sugeno-type, Mamdani's fuzzy inference systems is used to obtain crisp output with respect to particular maintenance strategy. The FIS makes use of well defined set of rules (Table 5.3). The consistency of the rule base is appraised from the output surface plots over the various combinations of input variables [I_1 and I_2 , I_2 and I_3 , I_3 and I_1] as shown in Figure No 5.5(a)-(c).Table 5.4 presents the listing of information on FIS. Figure 5.4(a) presents the output of BDM, 5.4 (b) the output of CBM, and 5.4 (c) the output of TPM as maintenance strategies.

Table 5.3 Format of Fuzzy Rule for Maintenance Mix Selection

Rule # 1 *If* I_1 is Low and I_2 *is* High *and* I_3 *is* High *Then Output is* Strong

Rule # 2 *If* I_1 is Low and I_2 *is* High *and* I_3 *is* Med *Then Output is* Fair

Rule # 3 *If* I_1 is Low and I_2 *is* High *and* I_3 *is* Low *Then Output is* weak

.

.

R_n# *If* In_1 is Med and In_2 *is* Low *and* In_3 *is High Then Output* $_n$ *is* Fair

5.3.1.1 (e) Step 5:

Finally, in order to rank the capability of each maintenance approach rank ordering is done using simple additive weighing. Table 5.5 shows values of Performance Index PI computed after normalizing the scores (N_s). The best informative maintenance management strategies were found to be TPM and CBM with PI values as (0.3150) and (0.3026) and the least informative strategy BDM with a score of 0.042.

The order of selected strategies (with respect to most effective one) obtained is as *TPM >CBM >RCM >PM >BDM.*

From the results, it is observed that aggressive (TPM) and proactive (CBM) maintenance strategy gives high score for performance index as compared to traditional, reactive (BDM) maintenance strategy. This necessitates the importance of CBM as one of the most effective and efficient maintenance strategy for detecting failures with the help of data acquisition systems which allows the maintenance personnel /process engineers to administer or exercise necessary controls before a failure can occur. Also, the implementation of TPM which includes company wide approach to plant equipment and asset care with the involvement and active participation of all to continuously improve the performance –effectiveness as well as efficiency provides valuable information by OEE computation, which is a product of availability, speed and quality.

Table 5.4 Listing of Information on Fuzzy Inference System (FIS)

[System RS]
Name='InfoFIS'
Type='mamdani'
Version=2.0
Num Inputs=3
NumOutputs=1
Num Rules=27
And Method='min'
Or Method='max'
Imp Method='min'
Agg Method='max'
Defuzz Method='centroid'

[Input1]
Name='input1'
Range=[0 10]
Num MFs=3
MF1='Low':'trimf', [0.0 2.5 5]
MF2='Med':'trimf', [2.5 5 7.50]
MF3='High':'trimf', [5 7.50 10]

[Input2]
Name='input2'
Range=[0 10]
Num MFs=3
MF1='Low': 'trimf', [0 2.5 5]
MF2='Med': 'trimf', [2.5 5.0 7.50]
MF3='High':'trimf', [5.0 7.50 10]

[Input3]
Name='input3'
Range=[0 10]
Num MFs=3
MF1='Low': 'trimf', [0 2.5 5]
MF2='Med' :'trimf', [2.50 5.0 7.50]
MF3='High':'trimf', [5.0 7.50 10]

Name='Output1'
Range=[0 1]
Num MFs=5
MF1='V.Weak': 'trimf', [0.0 0.15 0.23]
MF2='Weak':'trimf', [0.15 0.25 0.40]
MF3='Fair':'trimf', [0.31 0.45 0.60]
MF4='Strong': 'trimf', [0.49 0.65 0.80]
MF5='V. Strong':'trimf', [0.69 0.885 1.00]

[Rules]
1 3 3, 4 (1) : 1
1 3 2, 3 (1) : 1
1 3 1, 2 (1) : 1
3 1 1, 2 (1) : 1
3 1 2, 3 (1) : 1
3 1 3, 3 (1) : 1
3 2 3, 4 (1) : 1
3 2 2, 4 (1) : 1
3 2 1, 3 (1) : 1
1 2 1, 1 (1) : 1
1 2 2, 2 (1) : 1
1 2 3, 3 (1) : 1
1 1 1, 1 (1) : 1
1 1 2, 1 (1) : 1
1 1 3, 3 (1) : 1
3 3 3, 5 (1) : 1
3 3 2, 4 (1) : 1
3 3 1, 4 (1) : 1
2 3 3, 4 (1) : 1
2 3 2, 4 (1) : 1
2 3 1, 3 (1) : 1
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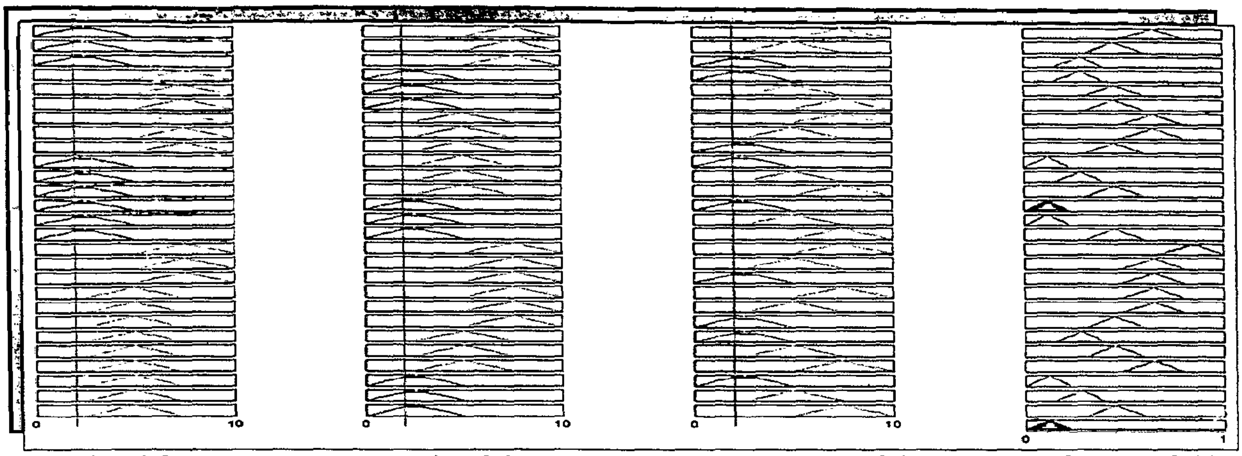
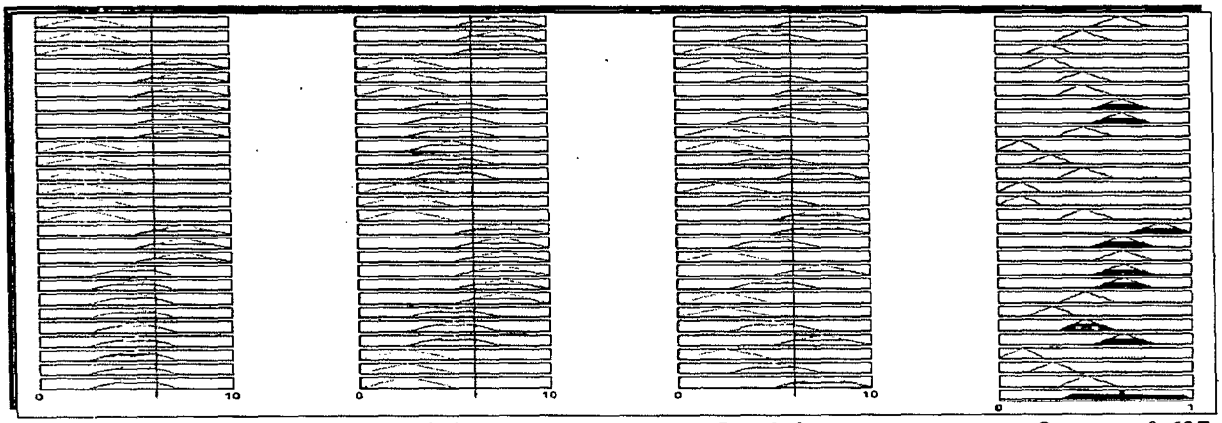
2 1 3, 3 (1) : 1



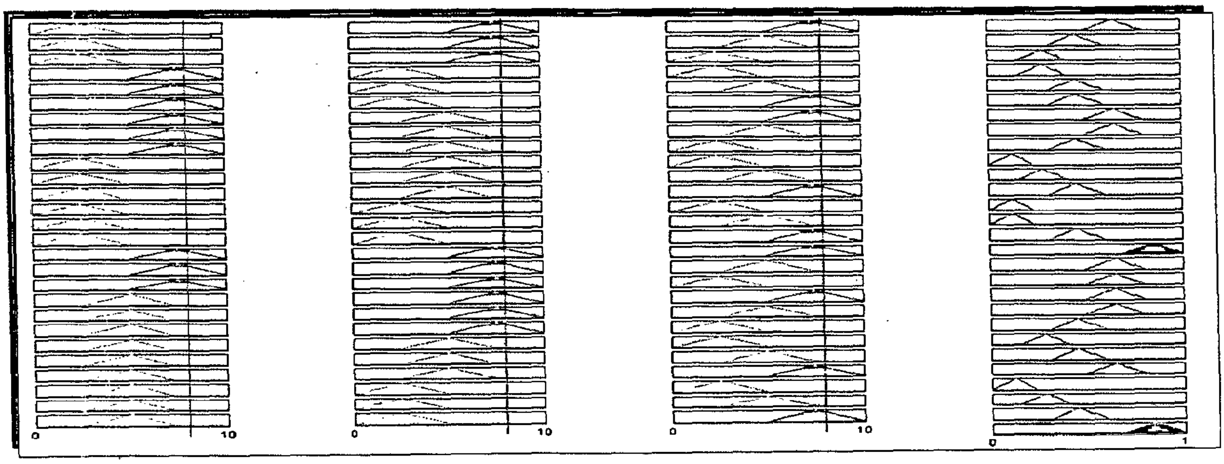
$I_1 = 0.2$ $I_2 = 0.2$ $I_3 = 0.2$ Output = 0.117

Figure 5.4 (a) FIS (Fuzzy Inference System) Output for BDM



$I_1 = 0.6$ $I_2 = 0.6$ $I_3 = 0.6$ Output = 0.637

Figure 5.4 (b) FIS (Fuzzy Inference System) Output for CBM



$I_1 = 0.8$ $I_2 = 0.8$ $I_3 = 0.8$ Output = 0.859

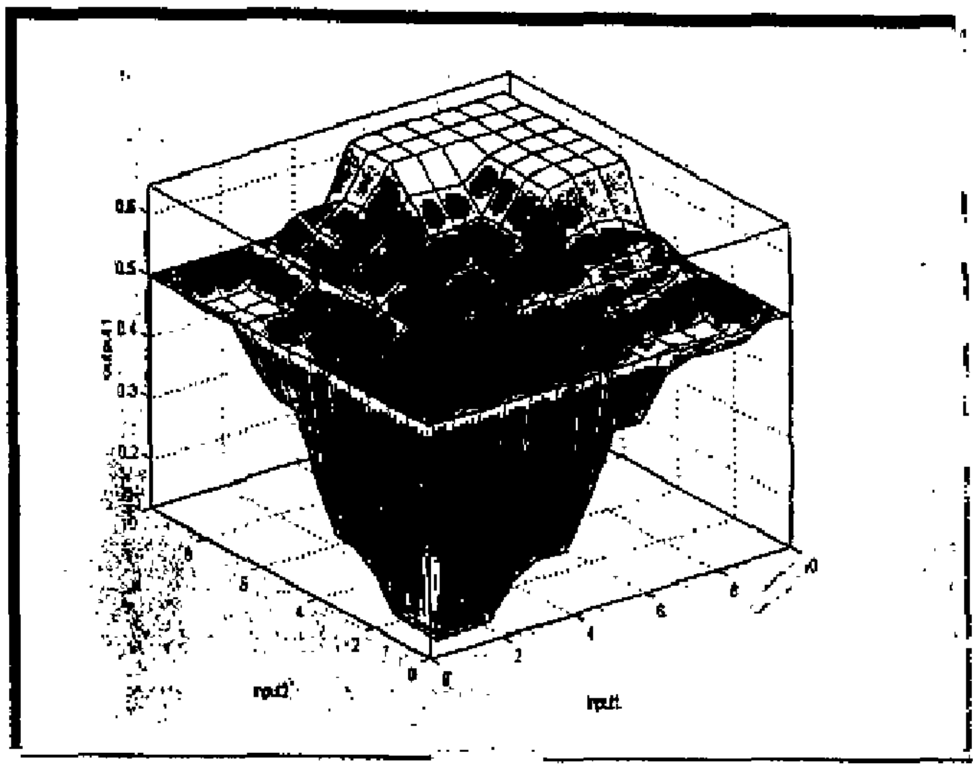
(c)

Figure 5.4 (c) FIS (Fuzzy Inference System) Output TPM

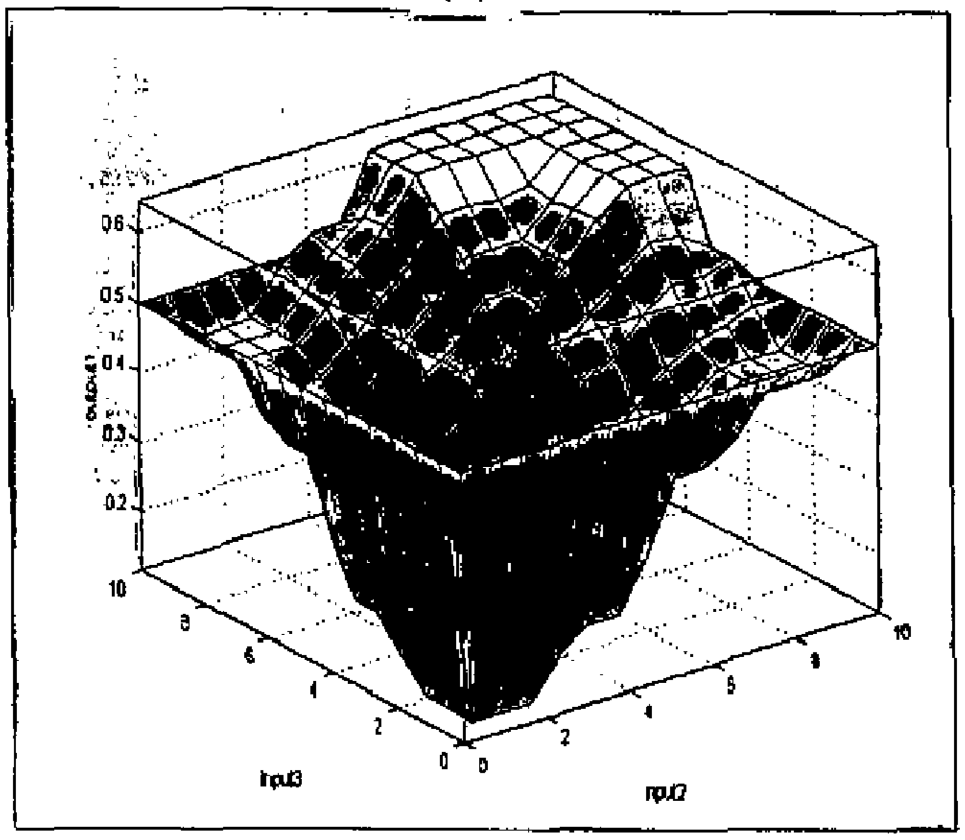
Table 5.5 Rank Ordering of Maintenance Strategies

S.No	Factor Criteria	Factor Weight	BDM	PM	CBM	TPM	RCM
1	X_C	0.85	0.15	0.15	0.70	0.70	0.30
2	X_L	0.70	0.15	0.30	0.70	0.70	0.45
3	X_S	0.70	0.15	0.30	0.70	0.70	0.45
4	X_T	0.45	0.00	0.45	0.70	0.70	0.45
5	X_{LT}	0.45	0.00	0.30	0.70	0.70	0.45
6	X_{LQ}	0.30	0.00	0.45	0.45	0.70	0.70
7	X_V	0.45	0.00	0.30	0.85	0.70	0.70
8	X_D	0.15	0.30	0.45	0.15	0.85	0.30
	N_s		0.38	1.225	2.745	2.85	1.86
	PI		0.042	0.135	0.3026	0.315	0.205
	Rank		**5**	**4**	**2**	**1**	**3**

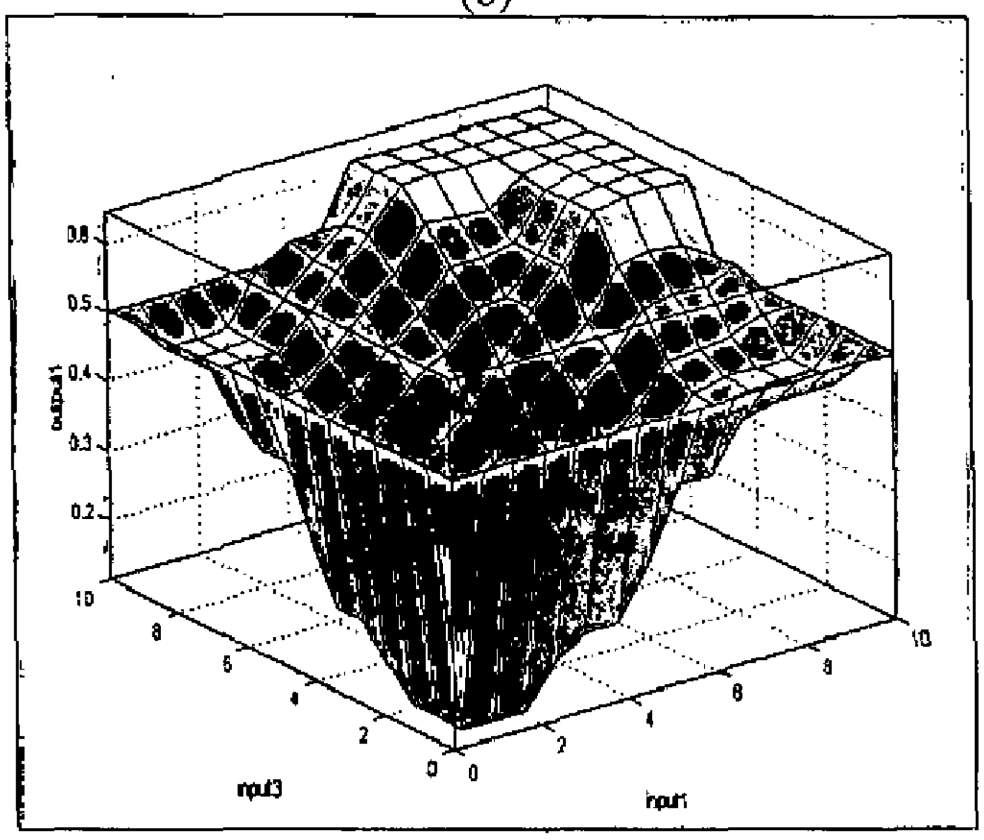
BDM: Breakdown Maintenance, PM: Preventive Maintenance, CBM:Condition Based Maintenance
TPM: Total Productive Maintenance, and RCM: Reliability Centered Maintenance



(a)



(b)



(c)

(c) Figure 5.5 Impact of Inputs (a) [I_1 and I_2] (b) [I_2 and I_3] and (c) [I_3 and I_1] on Output

5.4 TPM IMPLEMENTATION

5.4.1 Implementation Framework

Based upon the FLM results it is observed that TPM as a maintenance strategy is more pragmatic, as evident from PI score (0.315) and defuzzified output 0.859. It provides a company wide approach which includes plant, equipment, and asset care along with active participation of employees. Thus, to achieve the second objective of TPM implementation in the semi-automated paper machine cell, a detailed framework passing through four phases (i) preparation, (ii) introduction, (iii) introduction-execution and (iv) establishment is prepared (as shown in Figure 5.6).

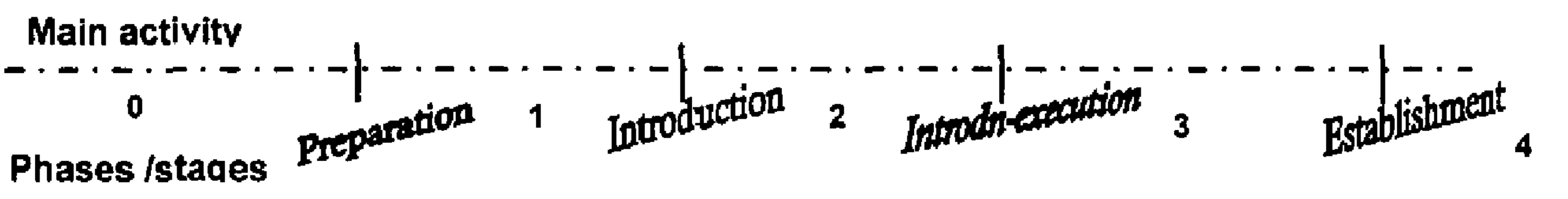


Figure 5.6 TPM Implementation Framework

The paper manufacturing cell consists of two paper machines with three main units (i) Forming unit (consisting of head box, wire mat and suction box) (ii) Press unit (consisting of felt, upper and bottom rolls (iii) Dryer unit (consisting of felt, steam-heated rolls (dryers), steam handling systems).

With respect to higher quality of the paper (as a product) the paper manufacturing business is said to be competitive. The company has to meet both external (stringent customer requirements, competitive pricing, environmental (health, safety hazards) and internal pressures (improvement in 4 M areas, i.e. Man (skill level, morale); Machine (optimize, zero failure); Method (fast flow, accident free); and materials (no waste). Apart from these exigencies the management also feels that maintenance cost account for 15-30% of total manufacturing cost. The emergency repairs are often carried out which are three times more expensive than the same job done in pre-planned manner. Before implementation of the framework all the present problems related to paper machine cell were studied / surveyed and are summarized into four subheadings:

(i) Autonomous maintenance (AM)

(ii) Planned Maintenance (PM)

(iii) Individual performance and improvement (IPI), and

(iv) Education and Training (ET)

(i)Autonomous Maintenance

- Though efficient but operators are not technically skilled to perform autonomous maintenance tasks. It requires skill, adequate knowledge regarding the functional and failure aspects of the components (Hence, skill improvement is realized essential)
- No 5S activities in workplace (need better disciplined work handling)
- As usual waiting for technician to do even minor repairs (I operate, you fix syndrome)
- Lack of employee morale and attitude

(ii) Planned Maintenance

- Breakdown maintenance is in practice (minimal planned/preventive maintenance)
- Breakdowns occur because of sudden /sporadic failures of different components/equipment (aim for no breakdown)
- Lack of control on maintenance cost, spare parts and equipment losses (need application of spare parts maintenance management system)

(iii) Individual Performance and Improvement

- Minimum focus on zero defects philosophy and 3 M (man, material and method) focus on quality issues (machine is outside the focus)
- No plan for individual improvement (need team approach to individual improvement

projects), and

- TPM tools such as why-why, and performance measurement analyses are not in use for individual learning (need use of these to address problems)
- Minimal manufacturing process data being used (although very important)

(iv) Education and Training

- For operators, only production process training (not enough technical skill or AM training)
- For technicians, basic technical/equipment training (not for problem solving)
- For engineers/managers, equipment and management tools (no TPM education and problem handling strategy education using AM, PM and FI teams)

Keeping in view, the above investigations TPM is implemented in the cell .Table 5.6 shows the elements involved in each stage/phase of TPM implementation. Based upon the TPM philosophy, each step has been approached in a systematic manner.

5.4.1.1 Stage 1 - Preparatory

For successful implementation of TPM in the semi automated cell of paper machine, TPM office commonly known as 'TPM secretariat' headed by senior executive of the company is formed. The main task of the office is to define policies / set targets and to co-ordinate the activities for successful implementation and promotion of TPM. Figure 5.7 presents the main functions along with the organization structure of TPM secretariat. The master plan covering key dimensions for TPM implementation is prepared. Initially, the maintenance program (based on Nakajimas seven steps of autonomous maintenance (as listed below) is followed.

- Initial cleaning
- Countermeasures for cause and effects of contamination sources
- Cleaning and lubrication standards

- General Inspection
- Autonomous Inspection
- Organization and Tidiness
- Full Implementation of Autonomous maintenance

To assist operators in performing maintenance tasks, cross-functional teams with members from (AM), (PM) and (FI) teams headed by respective group leaders, with members from engineering, maintenance group and production has been formed. To upgrade/hone the skills of operators / technicians and unearth their hidden capabilities to solve problems, training curriculum consisting of three main modules (i) Equipment knowledge training (EKT),(ii) MSD (Maintenance skill development), and (iii) Analytical techniques training (ATT) has been designed. Each module consists of various tools and techniques (Figure 5.8). These modules are specifically designed to impart necessary skill and training both in, operations and maintenance activities. Modules are briefly described as below:

- In EKT module the programs are designed to help operators learn more about how their equipment functions? What common problems can occur? ; Why they occur? ; and how these problems can be prevented?
- The MSD module highlights the need of autonomous (inspection, lubrication, and fastening) and preventive maintenance activities (overhauling, lubrication, repair/replacements). It also stresses on the importance of 5S activities i.e. Seiri (organization), Seiton (tidiness), Seiso (purity), Seiketsu (cleanliness), and Shitsuke (discipline) for better '*housekeeping*' (Samuel 1998).
- ATT module is designed to educate and train operators/technicians regarding various data collection and interpretation methods. The module consists of various analytical (check sheets, histograms, Pareto analysis, control charts and run charts) and reasoning techniques

explaining their applications in data collection and analysis (cause and effect diagrams, why-why analysis?) (Wang *et al.* 2004).

Table 5.6 Detailed Procedure for TPM Implementation in Paper Machine Cell

Stage /phase	Steps involved and description
Preparation	Step (i) Declaration by Top Management to introduce TPM State TPM objectives and place articles in an internal bulletin or Company's newsletter Step (ii) Launch TPM introduction educational campaign For managerial staff: staff of the same echelon are scheduled together for training For General employees: slide-show presentations Step (iii) Formation of promotion secretariat by forming committees and specialized Sub-committees at every level to promote TPM Step (iv) Establish basic TPM principles and targets Analyze existing conditions Set benchmarks and establish targets Predict results Step (v) Creation of a master plan for TPM implementation From preparation for introduction to undergoing examinations
Start of Introduction	Step (vi) Kickoff TPM Reporting the plans/policy/targets for TPM development Invite external customers, suppliers and affiliated companies.
Introduction-execution	Step (vii) Establishment of a system for improving the efficiency of the production Department - Kobetsu-Kaizen (fight against six major losses through project-team activities and workshop small-group activities) - Jishu Hozen (activities in which each operator perform routine daily inspections) - Planned maintenance activities (Corrective maintenance, periodic maintenance, predictive maintenance) - Hinshitsu Hozen (activities to set equipment conditions to eliminate defective products) - Operation /maintenance skill development - Training of group leaders and skill development of members Step (viii) Development of initial equipment management program -Use MP (maintenance prevention) design -Use SEM (start up equipment maintenance) practice. -Use LCCA approach. Step (ix): Establishment of quality maintenance systems (QMS) Setting conditions to reduce occurrence of defects Step (x) Establishing system for improvement of the efficiency of administrative department(s) Step (xi) Establishing system for safety, health, and environment control i.e. zero accidents and zero pollution
Establishment	Step (xii) Prefect TPM implementation and level improvement by Undergoing examinations for the receipt of PM awards Setting improvement targets

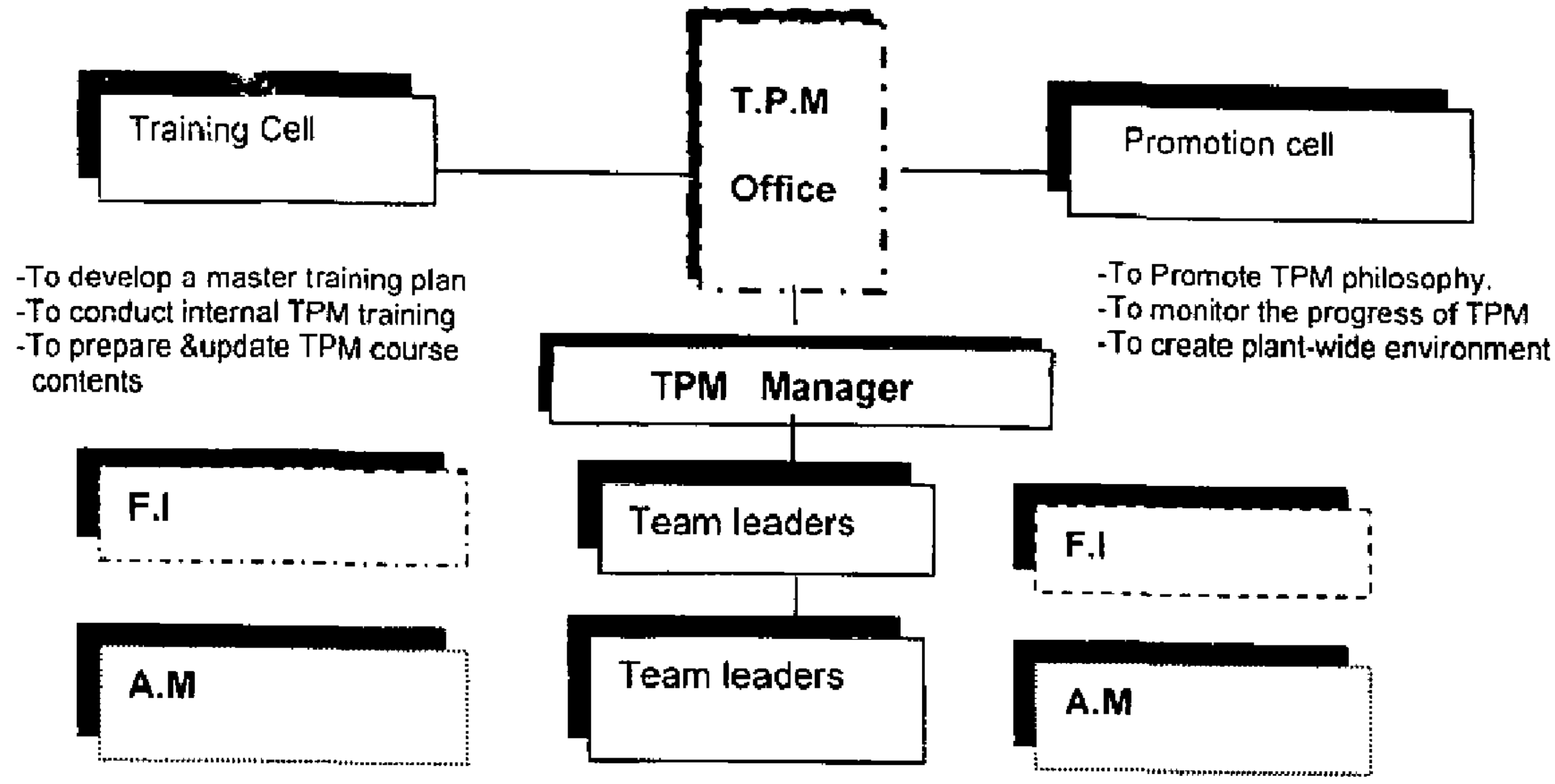


Figure 5.7 Organization for TPM implementation
[F.I = Focussed improvement A.M = Autonomous Maintenance]

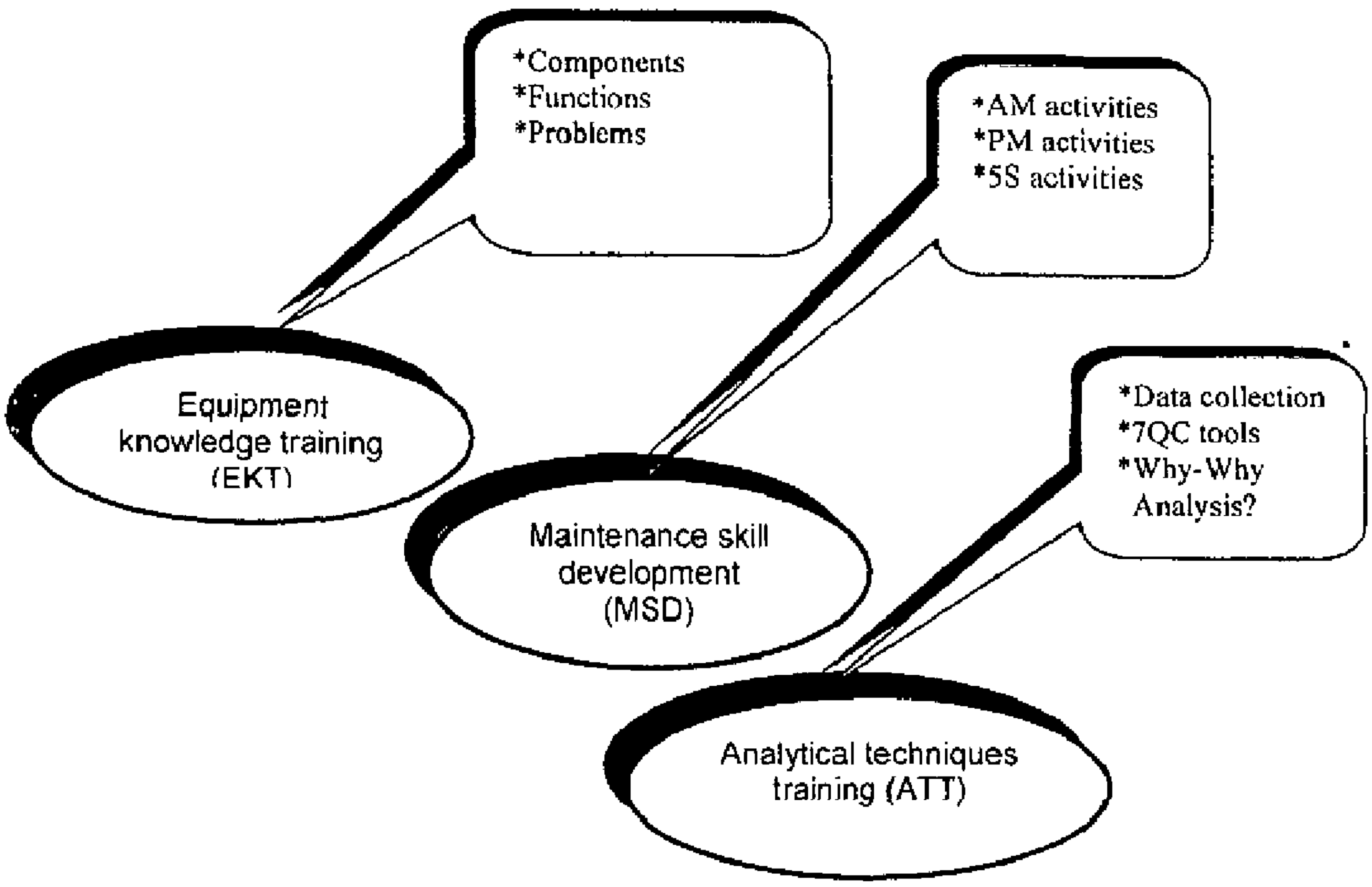


Figure 5.8 Training Modules for Operators and Maintenance Staff

5.4.1.2 -Stage 2. Introduction

During this stage the TPM manager convened a meeting of all TPM members and apprises them with the TPM policy/ targets to be achieved in the various areas and the master plan for TPM development in the cell.

5.4.1.3 -Stage 3. Introduction – execution

The execution stage consists of several activities as listed in Table 5.6. To fight against six major losses [Appendix A-5(i)] in the cell, project-teams and small work-groups has been formed. To support them, a system comprising of team leaders, group leaders, and coordinators is established. The routine maintenance activities such as cleaning, lubrication, oiling and inspection is performed by the operators and planned maintenance activities (periodic maintenance and predictive maintenance) are carried out by maintenance personnel. To enhance the technical knowledge of operation / maintenance staff, a cross-functional team (known as Focused Improvement, FI) with members from engineering, maintenance and production is formed. FI team members helped them to search for the defects untraced by them. All the failure causes related to machine stoppage are identified and recorded in file by FI personnel. The data gathered from machines in the cell is recorded under following headings [from (i)-(vi)] for a period of about six-eight months.

(i) Number of production center/facility
(ii) Time of onset of failure
(iii) Time to repair
(iv) Type of failure
(v) Component(s) involved, and
(vi) Small note describing the cause of the downtime

The total failure causes reported were 1300. Figure 5.9 shows the distribution of various causes (Mechanical failures, hydraulic failures, electronic failures, electrical failures and, human failures). With the help of analytical techniques FI personnel calculated the statistics related MTBF (mean time between failures), and MTTR (mean time to repair).

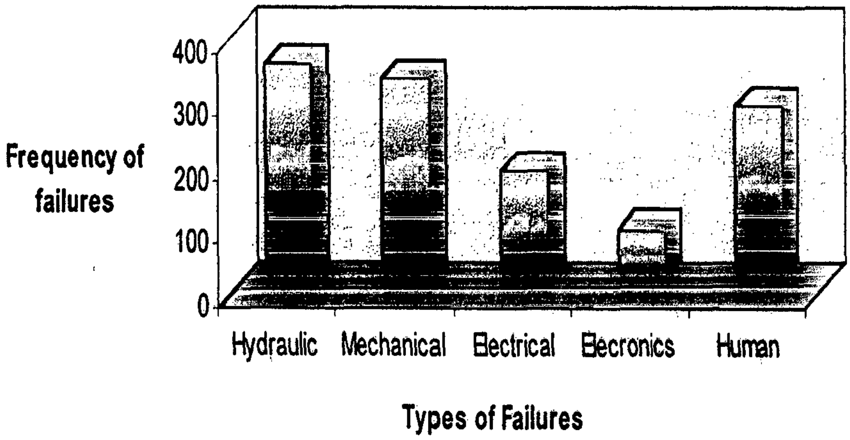


Figure 5.9 Distribution of various Failure Causes

5.4.1.3 (a) Failure Analysis

After collection of the data related to failure and maintenance aspects thorough analysis is carried out. Hydraulic and mechanical Human failures accounted for the largest number of failures followed by human failures. From the statistics presented in Table 5.7 it is observed that in case of human failures the MTTR is 1.28 hrs with MTBF 20 hrs. Failures in this category include any stoppage of the system attributed to improper actions (such as pushing the wrong button or lever, using the wrong weight of oil, failure to take the correct remedial actions such as not closing an interlocking door or not tightening a bolt). Also, maintenance related human failures are there which may be due to errors of omission or errors of commission.i.e lack of attention, confusion in cables (put in wrong order), use of excessive force causing instrumentation cables to break or use of less force resulting in bad connections, untight loose bolts etc. 30% of the failures are hydraulic failures with MTBF 38 hrs. Hydraulic failures normally occur because of contamination of hydraulic components which leads to increased wear and deterioration. Mechanical failures accounted for 28.50% of the total, with failures occurring at an average rate of one after every 54 hrs and the mean time to repair such failures was 1.18 hrs. Untimely stoppages caused by mechanical failures are associated with failures of components such as gears, bearings, and tooling. 17 % of all the failures are classified as electrical failures. Electrical failures displayed the second shortest MTBF, one failure after every 30.20 hrs. The electrical failures required, on average, the least amount of time to repair i.e. 0.40 hrs. Blown fuses or dirty limit switches and failures of the electro-mechanical components such as motors, relays, starters, and wiring were the primarily reasons for electrical failures. Electronic failures which normally consist of failures of solid-state components such as logic buses, power supplies and servo drives accounted for only 9 % of all failures with highest MTBF i.e. 92.80 hrs requiring an average repair time of 0.75 hrs. To assist maintenance managers in understanding the failure behavior and developing a strategic preventive maintenance plan, the failure pattern exhibited by various components used in hydraulic, electronic and mechanical subsystems, in general, is illustrated in Table A-5 (ii) in appendix (Wu *et al.* 1992).

Table 5.7 Failure and Repair Statistics of Paper Machine Cell

Failure Causes	**MTBF (hrs)**	**MTTR (hrs)**
Human failures	20.00	1.28
Mechanical failures	54.20	1.18
Hydraulic failures	38.17	2.00
Electrical Failures	30.20	0.40
Electronic failures	92.80	0.75

5.4.1.3 (b) Countermeasures:

In order to facilitate AM personnel for daily maintenance routine interventions and recognize various trouble shootings (with the help of FI teams) associated with failures of critical component(s) the defect recording system is developed (Table 5.8). It consists of complete record of commonly failed / repaired or replaced components associated with corresponding machining centers with details such as failure detection date, time, mean repair time and mean time between failures. Figure 5.10 shows the respective failure modes associated with the various failure causes. Potential failure modes associated with each type of failures (mechanical failures, hydraulic failures, electronic failures, electrical failures, human failures and software failures) are selected as the target improvement areas. Then, plans for improvement actions are made accordingly in order to improve the Overall Equipment effectiveness (OEE).

5.4.1.4 Stage 4 Establishment stage

In this stage the improvement targets in various areas such as cleaning time, accident rate, defect rate reduction, OEE level were set up in the cell to monitor the continuous performance of TPM implementation in the cell.

5.4.2 Implementation Results

The team leaders and group leaders discussed various improvement plans suggested by the operators with TPM manager and with the help of personnel from production and design department, feasibilities of such plans is worked out. Depending upon the feasibility, the plans were incorporated. The outcomes of TPM implementation are grouped in terms of tangible and intangible benefits.

Table 5.8 Recording System for Maintenance Interventions

Subsystem	Components	Machine No.			Failure detection date & time			Mean repair time (hrs)			Mean Time Between Failures (hrs)		
		1	2	Note	1	2	Note	1	2	Note	1	2	Note
Hydraulic	Piping Hoses Pumps Solenoids Valves Others												
Mechanical	Gears, bearings Tooling, levers, Shafts, valves, Rollers. Others.												
Electronic and Electrical	(i) Inside cabinet • Contactor switches • Relays regulators • Magnets (ii) On machine. • Buttons • Proximity switches • Limit switches • Encoders Others												

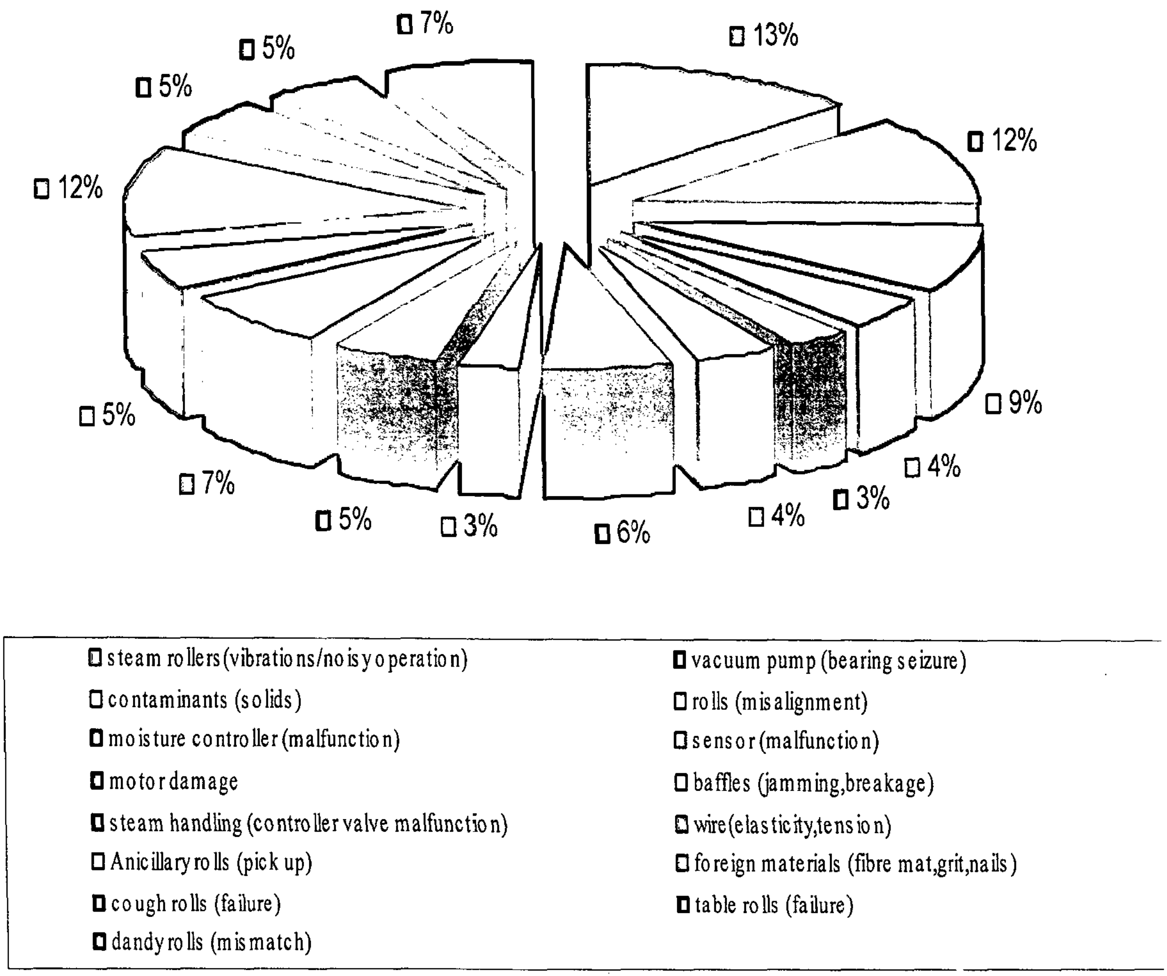


Figure 5.10 Potential Failure Modes of Paper Machine

5.4.2.1 Tangible Benefits

(i) Continuous Improvement (CI) Projects:

Though the Full implementation of TPM takes a few years. But if the improvement proce is started in a systematic manner then the results of successful implementation can be visualiz with in two- three years. In the cell the status of number of CI projects (also known as Kaizen and One Point Lessons, year wise with target and actual values and their final execution is shov in Figure 5.11. It is observed that during the beginning of TPM implementation program out of

CI projects 07 were implemented, which continuously kept on increasing because of involvement of both operator and maintenance staff in improvement activities. As shown in Figure 5.11(a) that after two years of TPM implementation i.e. in IInd quarter of year 2005, the total CI projects in the cell with actual implementation has risen to 65.

(ii) Employee Skill Improvement Projects:

A large number of skill development and skill transfer projects in different areas had been undertaken and executed during the last three years. The programs had helped the operators and maintenance personnel to learn more about equipment functions, common problems, their occurrence and the ways to prevent these problems. Figure 5.12 (a) and (b) shows the results of two such programs one for operators and other for technicians.

(iii) Machine Failure Status:

For the paper machines PM -1 and PM-II the machine failure in terms of hours /week has been reported from the summarized data (obtained from maintenance log books). The graphical projections presenting the failure statistics is shown in Figure 5.13 (a) for paper machine-I and Figure 5.13 (b) for paper machine-II. It is observed from the figures that the failure time has shown a remarkable decrease, since the implementation of TPM progarm. For instance, in case of paper machine-I during the year 2003, the machine failure time per week was 735 minutes which has been reduced to 212 minutes in year 2005. Significant improvement is observed in both machines in terms of failure time because of company/cell wide approach which includes plant, equipment and asset care with the active participation of employees.

(iv) Better Housekeeping:

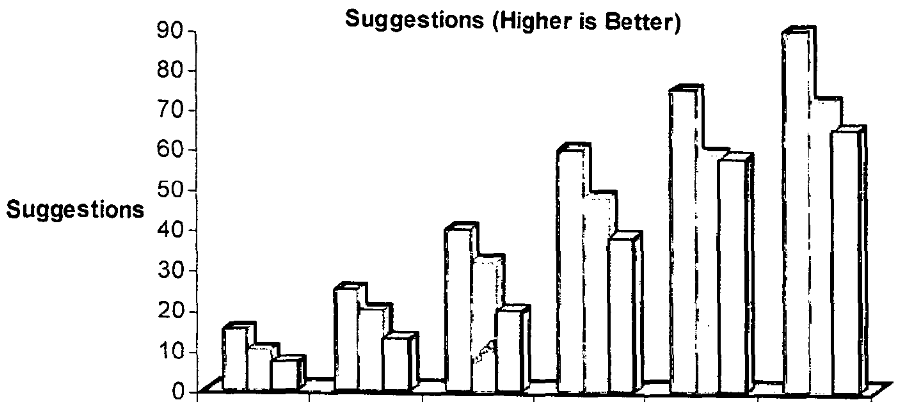
With the introduction of Japanese 5S housekeeping principles and better equipment management practices the cleaning time of the equipment and maintenance of parts in more organized manner resulted in reduction of accident rates, as well as total cleaning time required fro the machines in the cell. The outcome with respect to accident reduction is shown in Figure 5.14(a) and with respect to cleaning time reduction is shown in Figure 5.14(b).

(v) Overall Equipment Effectiveness:

The most important measure of equipment effectiveness in TPM is OEE (Overall equipment effectiveness) level. In the initial period of TPM implementation in cell the target for OEE level for PM–I was set up at 55-60% (For the year 2003).With the passage of time and introduction of various improvement activities aimed at waste reduction (due to the so called TPM losses, defined in appendix A-5(ii)), the OEE level has shown remarkable upswing as evident from time and OEE plots for both the machines in Figure 5.15(a) and (b).

(vi)Quality Improvement:

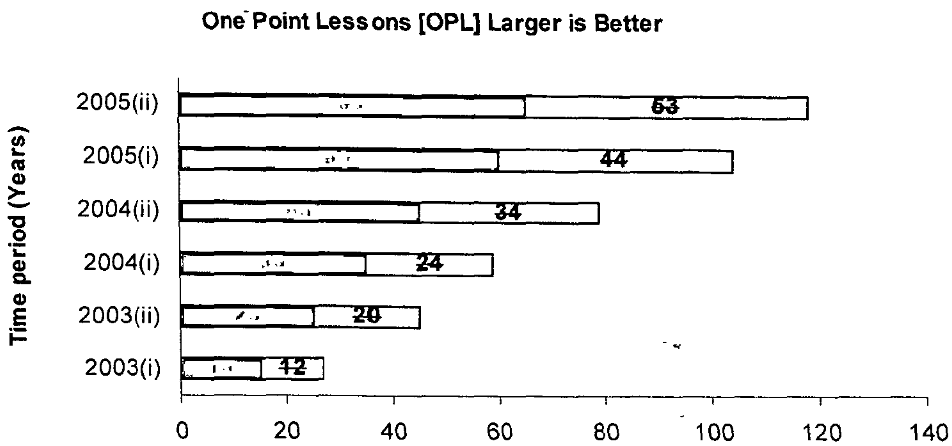
Average Outgoing Quality Level (AOQL), Defect rate, Customer complaints are the most important parameters to measure the success of quality improvement initiatives taken in the cell in the ambit of TPM deployment. The lower the (AOQL), the better is the quality of paper. Same is the conclusion in case of defect rates or customer complaints. Figure 5.16 (a) and (b) presents trends in AOQL, and defect rate over the past three years. As a result of TPM implementation, data related to other performance measures such as rework percentage and maintenance cost versus operation cost has also been collected and the trends are shown in Figure 5.17 and 5.18. From Figure 5.18 it is observed that the rework percentage has reduced (which was about 24% in year 2003) to about 10% in year 2005. Also, considerable reduction in maintenance cost versus operation cost [(from 28 % 2003 (ii) to 20% in 2004(ii) and further to 10% in 2005(ii)] is observed from the descending trend.



	2003(i)	2003(ii)	2004(ii)	2004(ii)	2005(i)	2005(ii)
Target	15	25	40	60	75	90
Actual Received	10	20	32	48	59	72
Implemented	7	13	20	38	58	65

Implementation Period

(a)

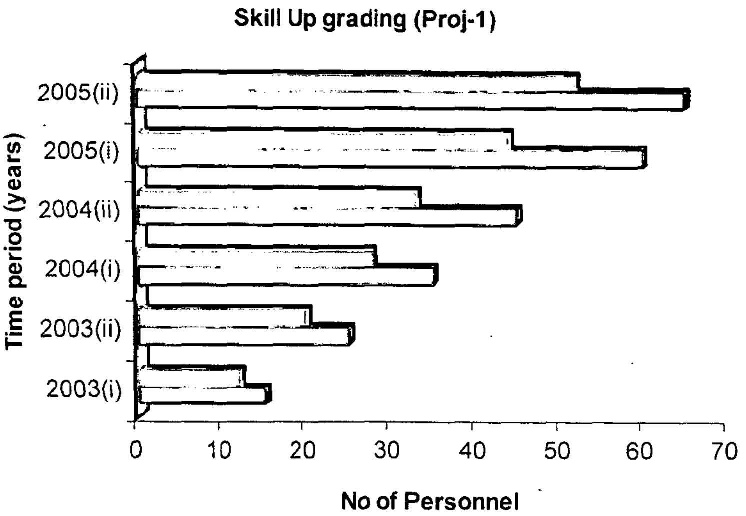


	2003(i)	2003(ii)	2004(i)	2004(ii)	2005(i)	2005(ii)
Implemented	12	20	24	34	44	53
Actual Received	15	25	35	45	60	65

No.of One Point Lessons

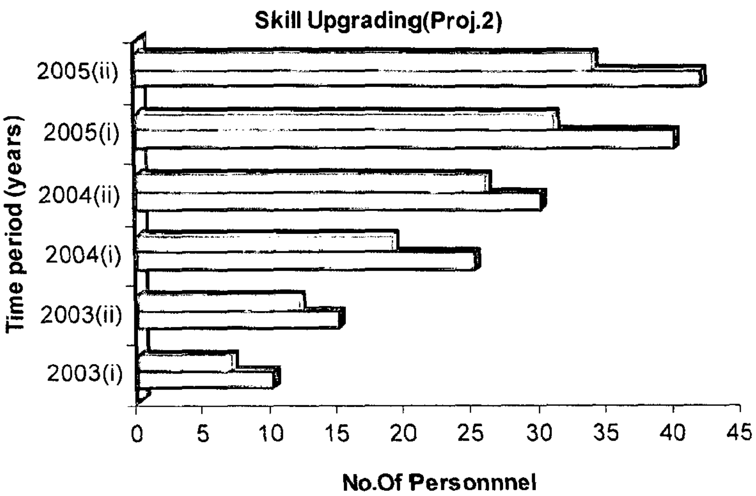
(b)

Figure 5.11 (a) Suggestions (b) One Point Lessons in the Cell



	2003(i)	2003(ii)	2004(i)	2004(ii)	2005(i)	2005(ii)
Achieved	12	20	28	33	44	52
Target	15	25	35	45	60	65

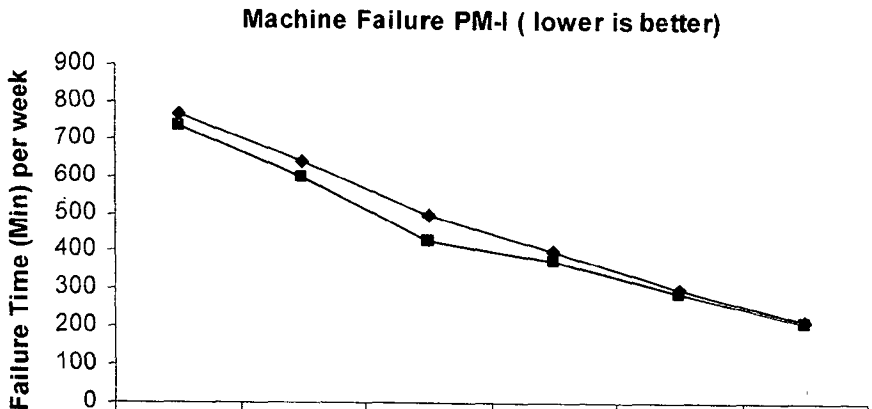
(a) Project-I (Maintenance technicians)



	2003(i)	2003(ii)	2004(i)	2004(ii)	2005(i)	2005(ii)
Achieved	7	12	19	26	31	34
Target	10	15	25	30	40	42

(b) Project-II (Machine Operators)

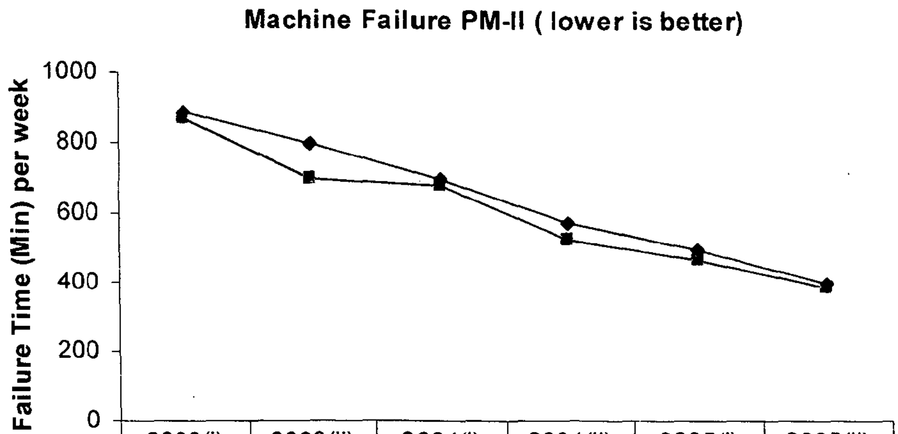
Figure 5.12 (a) and (b) Skill Upgrading Projects in the Cell



	2003(i)	2003(ii)	2004(i)	2004(ii)	2005(i)	2005(ii)
—◆— Achieved	770	640	500	400	300	215
—■— Target	735	600	428	377	290	212

Implementation Period (Years)

(a) Machine Failure – I

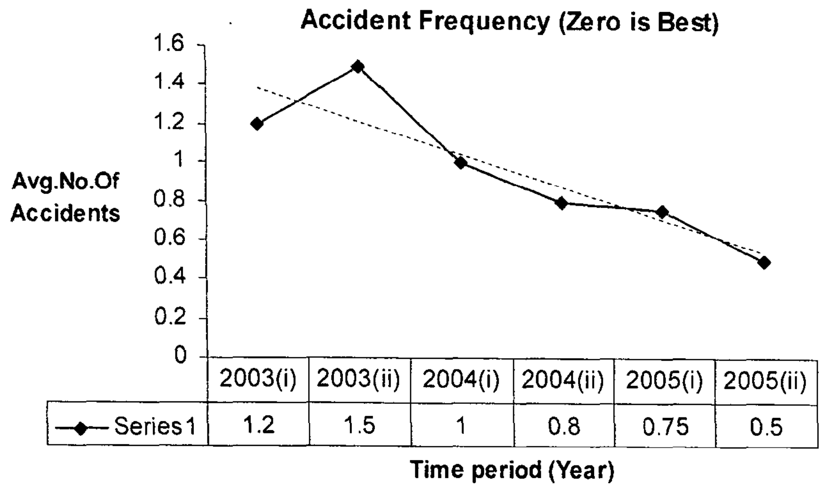


	2003(i)	2003(ii)	2004(i)	2004(ii)	2005(i)	2005(ii)
—◆— Achieved	890	800	700	577	500	400
—■— Target	870	700	680	530	470	390

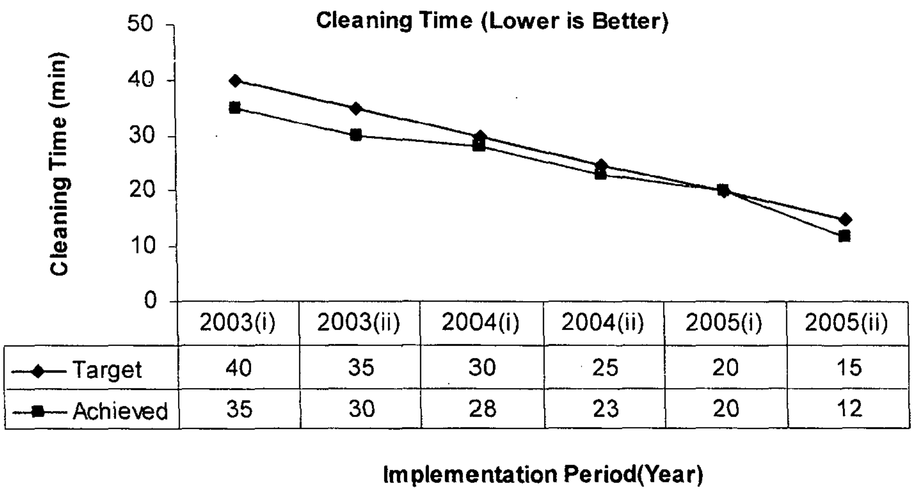
Implementation Period (Years)

(b) Machine Failure – II

Figure 5.13 (a) Failure time Statistics (M/C-I) and (b) M/C-II

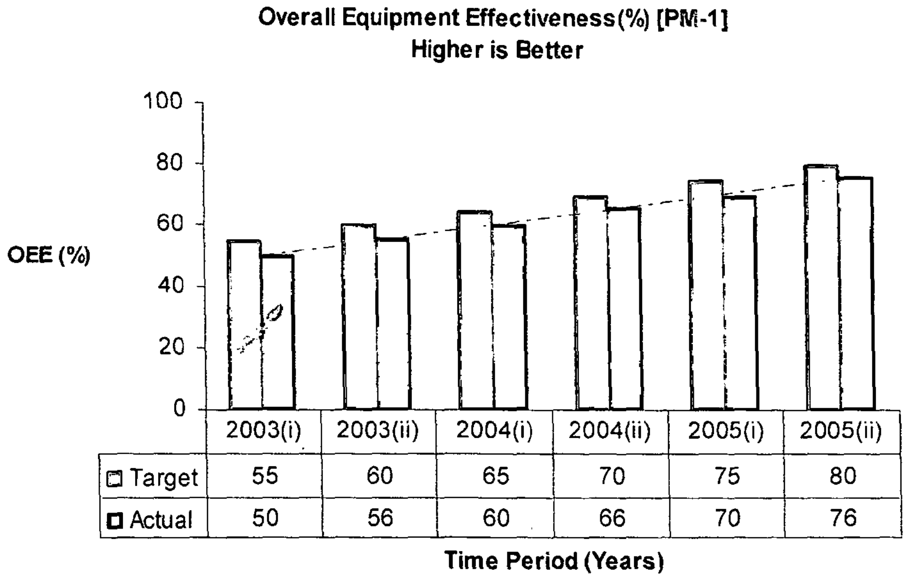


(a)

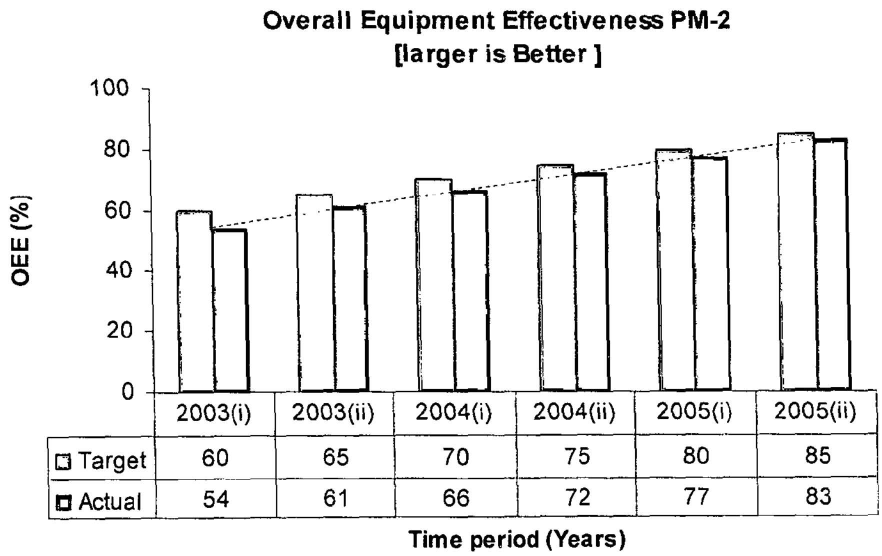


(b)

Figure 5.14 (a) Accident Frequency in Cell (b) Cleaning time Reduction

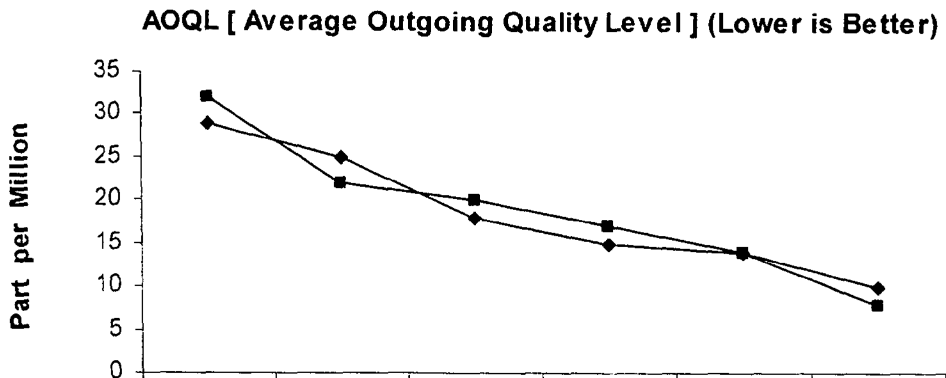


(a)



(b)

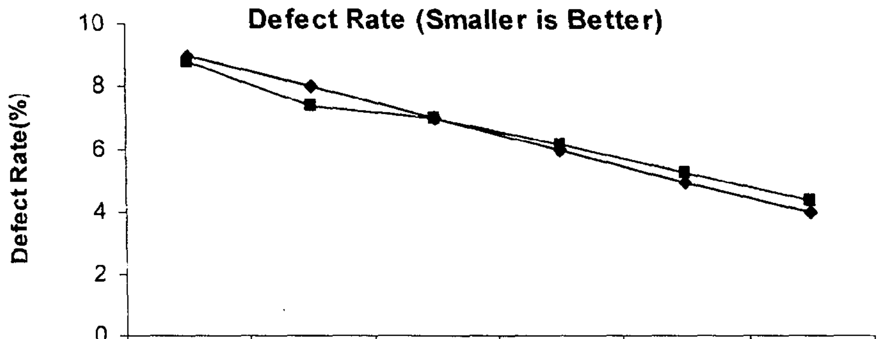
Figure 5.15 OEE Level (a) Machine-I (b) Machine-II



	2003(i)	2003(ii)	2004(i)	2004(ii)	2005(i)	2005(ii)
Target	29	25	18	15	14	10
Achieved	32	22	20	17	14	8

Implementation Period (Year)

(a)



	2003(i)	2003(ii)	2004(i)	2004(ii)	2005(i)	2005(ii)
Achieved	9	8	7	6	5	4
Target	8.8	7.4	7	6.2	5.3	4.4

Implementation Period (Years)

(b)

Figure 5.16 Quality Measures (a) Average Outgoing Quality level (b) Defect Rate

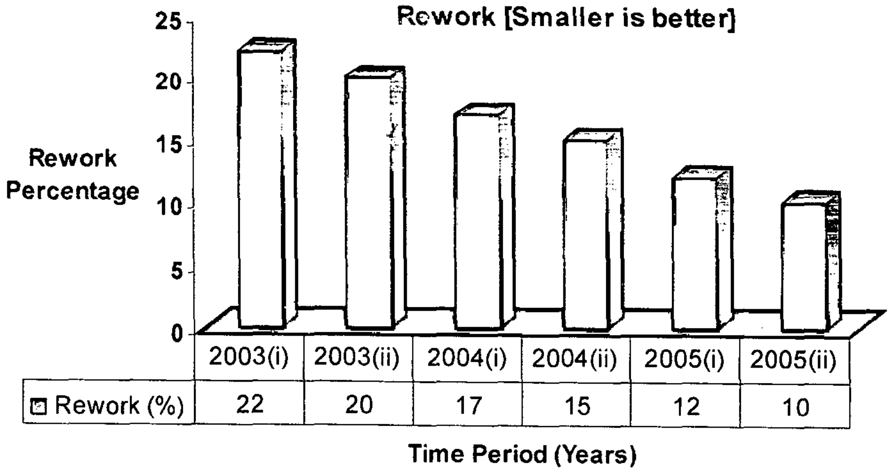


Figure 5.17 Rework Percentage in the Cell

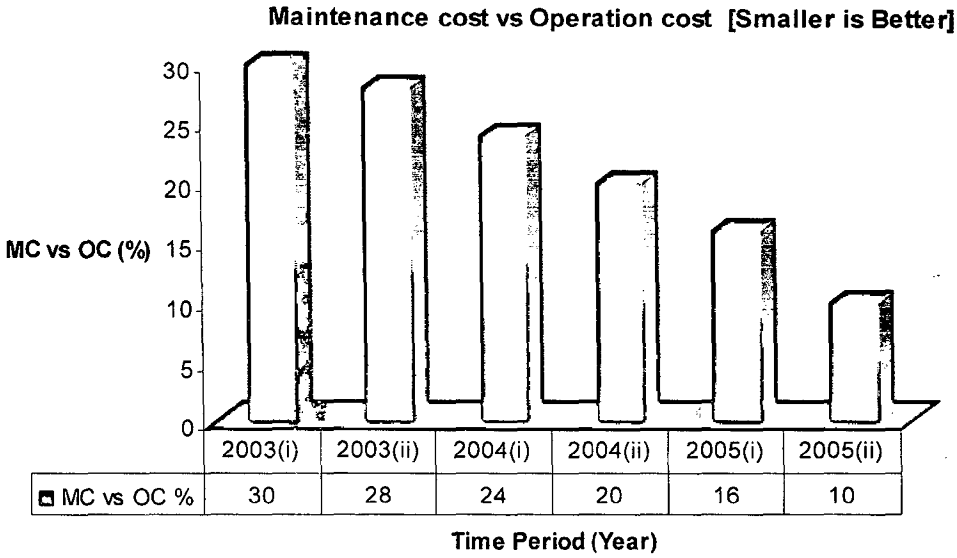


Figure 5.18 Maintenance Cost versus Operation Cost

5.4.2.1 Intangible Benefits

The intangible benefits incurred through implementation of TPM Framework in the sem automated cell of the paper machine are briefly summarized in the following paragraphs:

(i) Setting up of cross-functional teams:

Implementation of TPM in the cell had helped to form cross-functional teams [(AM), (P and (FI)] consisting of team members from maintenance and production departments. Setting up such teams has helped to identify and resolve many basic equipment problems related to handli set-up, maintenance, repair of components, their parts (associated with the machines) in the cell.

(ii) Introduction to Concept of Total Quality Maintenance:

With aim for zero defects through management of 4M (Man, Machine, Method, Materi conditions shown in Figure 5.19, all members/operators showed their responsibility maintaining equipments /facilities by performing routine AM and periodic PM activities (cleani inspection and lubrication). The approach has helped in spreading and growing the concept of t quality maintenance (TQMain) among all in the cell.

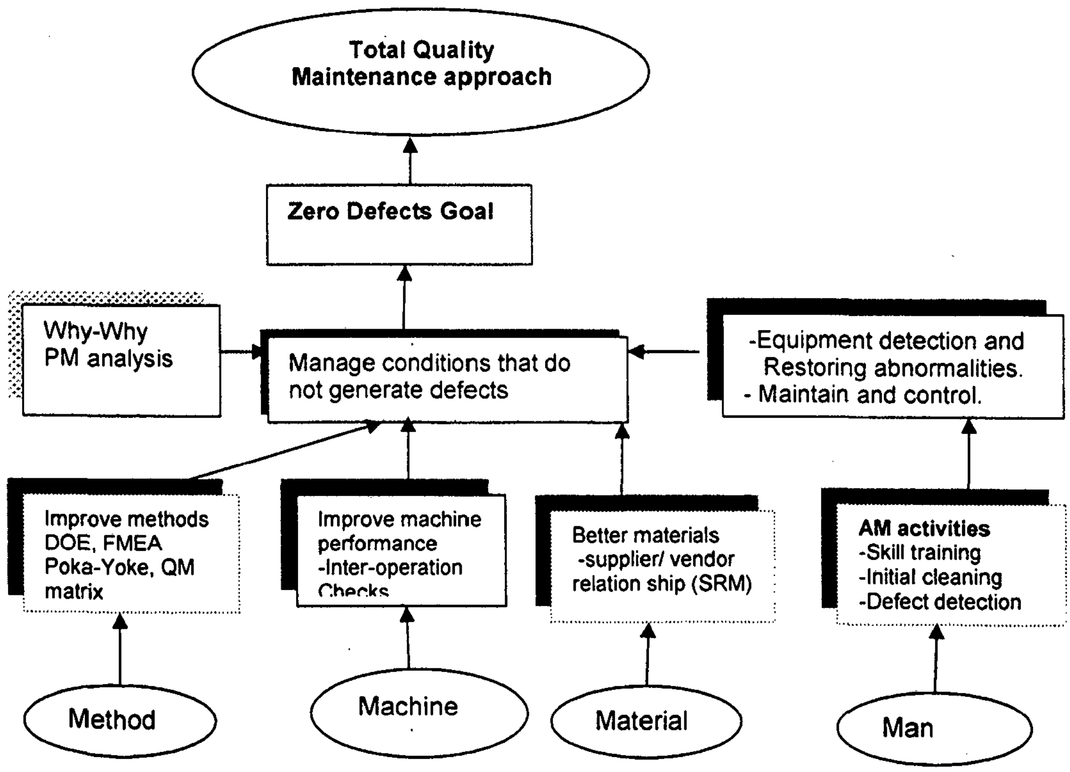


Figure 5.19 Total Quality Maintenance Approach

(iii) Training and Skill development:

The training modules (EKT, MSD, and ATT) which were specifically designed to help operators to learn more about how their equipment functions? What common problems can occur? Why they occur? and how these problems could be prevented? had helped a lot in training and upgrading the skills. Handling of simple repair works with the assistance of FI personnel had nurtured necessary maintenance skills in the operators for solving the problems without causing any further delays.

(iv) Increased Responsibility:

After the TPM implementation in the cell both AM and FI team members accepted their responsibility for maintaining equipment in good condition. Now they not only concentrate on bottleneck free production but also perform simple maintenance tasks. A change in the traditional syndrome “I operate-you fix", had been observed among the operators.

(v) Development of sense of importance for maintaining basic equipment conditions:

The TPM program had promoted more operator involvement in maintaining their equipment(s) by performing routine AM activities such as inspecting, oiling and lubrication the parts/components) and following 5S housekeeping principles. This had helped to generate the sense of importance for maintaining basic equipment among the operators.

5.5 MAINTENANCE DECISIONS USING NON-HOMOGENEOUS POISSION POINT PROCESS (NHPPP) MODEL

The present section of the chapter provides the framework for taking maintenance decisions using NHPPP models (which makes use of modeling of data, goodness of fit tests and regression analysis, as discussed in chapter 3) with respect to repair/replacement of two important components (wire mat and vacuum pumps) of the paper machine.

5.5.1 An illustrative case

The NHPPP models have been applied to model and analyze the failure data of Wire mat (WM) and Vacuum pumps (VP).The wire mat (with main function to carry the pulp) fails mainly because of corrosion, abrasion (due to presence of foreign materials clay, sand and other contaminants in pulp; wear of the roller rubber, roller bearing, roller bending) and excessive vibrations. Apart from these factors any spot plugging the wire will give hole in the paper and any foreign material (metallic particles) sticking to the wire will produce dents and will rapidly wear out the wire. The main reasons related to pump failures that were noticed are (i) lub-oil level of pump system components, (ii) vacuum pressure of pumps, (iii) various leakages, (iv) excessive bearing temperatures, (v) seized bearings, (vi) damaged impeller, (vii) strainer restricted, (viii) vibrations and malfunction indications by sensors or alarms. For the NHPPP analysis, failure data sets (Table 5.9) related to both components is collected for a period of about six months.

Table 5.9 Failure Data of Wire mat and Vacuum pumps

Sr.No	T_i (hrs)		TBF (hrs)		$\ln T_n/T_i$	
	WM	VP	WM	VP	WM	VP
1	580	322	-	-	1.69	2.049
2	1400	860	820	538	0.814	1.0671
3	1790	1626	390	766	0.568	0.430
4	2510	2044	720	418	0.230	0.2013
5	2800	2178	290	134	0.120	0.1378
6	3160	2500	360	322	0	0
	$\sum = 12240$	$\sum = 9530$			$\sum = 3.423$	$\sum = 3.886$

(WM: wire mat; VP: vacuum pump; TBF: Time between failures; T_i: Time of i^{th} failure, T_n: Time of n^{th} failure).

To check the consistency of rate of occurrence of failures (ROCOF), a plot of the accumulated failures times (operation times) versus the number of failures is obtained for both components as depicted in Figure 5.20. As no linearity is seen for the plotted points so it is concluded that the rate of occurrence of failures is not constant and is clearly time dependent. By assuming the relevant cost information with respect to the components, the economic analysis has been done to find trade -off between maintenance cost and capital expenditure incurred.

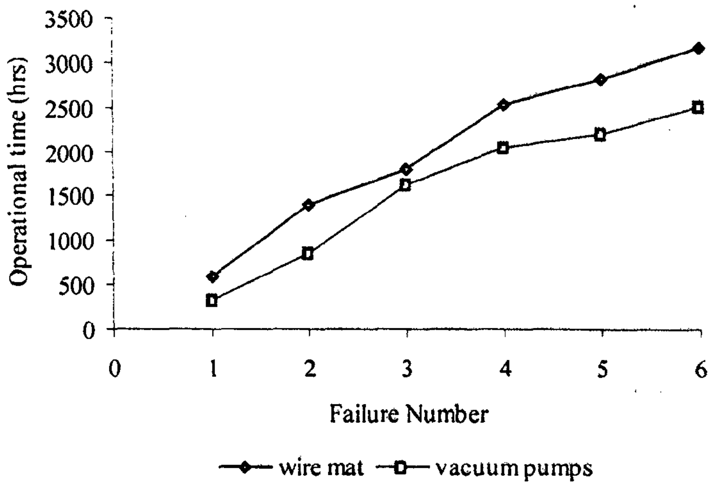


Figure 5.20 Operational Times versus the Number of Failures

The model parameters $\alpha_1, \alpha_0, \beta$ and λ (discussed in chapter 3, under section 3.3.4) for the components are computed and are enlisted in Table 5.10. Using trend test Equation (3.6) the values are tested. For model ρ_1 (t) we get, U= 1.235. (WM) and U=1.19 (VP). Both values are considered large and the estimated parameters are considered adequate for the model. Similarly, for model $\rho_2(t)$, using Equation (3.9), we get V=6.844 (WM) and V=7.7724 (VP). The value is considered small and the estimated parameters are considered adequate for the model. The model equations are represented as:

For Wire mat $\rho_1(t) = e^{(-6..5785+0.0004901t)}$ hr^{-1} $\qquad \rho_2(t) = 4.4x10^{-6}t^{0.7526}$ hr^{-1} (5.1)

For Vacuum pump $\rho_1(t) = e^{(-6.92+0.00062958t)}$ hr^{-1} $\qquad \rho_2(t) = 3.44x10^{-5}t^{0.54392}$ hr^{-1}. (5.2)

In order to select which model is applicable for Wire mat and Vacuum pumps linear regression analysis is done [discussed in Appendix A-5(iii)]. The results are presented in Table 5.10. It is observed from the table that for wire mat $\rho_1(t)$ model adequately fits the rate of occurrence of failures, considering second interval splitting and log likelihood method. Similarly, for vacuum pumps $\rho_2(t)$ model adequately fits the rate of occurrence of failures, considering third interval splitting and log likelihood method. For the selected model interval splitting as shown in Table 5.11 is done. The regression plots of $\ln \rho(b_j) \times b_j$, for $\rho_1(t)$ and $\ln \rho(b_j) \times \ln b_j$, for $\rho_2(t)$ are drawn as shown in Figure 5.21(a) and (b).

By performing adequate aging management actions (predictive maintenance strategies namely condition based monitoring (CBM), vibration based monitoring (VBM) as discussed in chapter 5 and timely replacements) it is possible to decrease the expected number of failures. If under the same prevailing conditions, the two units go on operating i.e. wire mat (3160, 5000) and vacuum pumps (3000-5000), then five failures are predicted by using the Equations (i) and (ii) [Appendix A-5(iii)]. By performing periodic testing, vibration monitoring and timely maintenance these failures can be reduced to two. The respective failure times (in hrs) for the components is given in Table 5.12. To quantify the impact of failure reduction, a trend analysis is performed by means of the NHPPP model, considering the time period (0, 5000) for both of them. The developed trend test expressions are represented by Equation 5.3 and Equation 5.4 respectively.

Table 5.10 Selection of ρ (*t*) for NHPPP Model

Component	Method	Parameters			
		α_1	α_0	β	λ
Wire mat	Log –likelihood method	**0.0004901**	**-6.5789**	1.7582	0.0000098
	Regression method				
	Interval splitting-1	0.0004632	-6.9630	2.1877	0.0000102
	Interval splitting-2	**0.0004899**	**-6.5933**	1.9689	0.0000087
	Interval splitting-3	0.0004460	-6.6822	1.9909	0.0000069
	Interval splitting-4	0.0005120	-6.6799	1.9622	0.0000044
Vacuum pumps	Log –likelihood method	0.00062058	-6.9204	**1.5439**	**0.000034987**
	Regression method				
	Interval splitting-1	0.0004899	-6.3214	2.1009	0.000068834
	Interval splitting-2	0.0005992	-6.1003	1.6916	0.000077900
	Interval splitting-3	0.0006792	-6.1292	**1.5519**	**0.00003577**
	Interval splitting-4	0.00057890	-6.4966	1.7790	0.000099987

Table 5.11 Interval Splitting for Selected Model ρ (*t*)

Component	Selected Model	Time Interval	n_f	bj	ln bj	$\rho(b_j)$	ln $\rho(b_j)$
Wire mat	$\rho_1(t)$	0-1000	1	500	6.2146	0.000473409	-7.65550
		1000-2000	2	1500	7.3132	0.001082400	-6.82855
		2000-3000	2	2500	7.8240	0.001590090	-6.44399
		3000-4000	1	3500	8.1605	0.002048800	-6.19066
Vacuum pumps	$\rho_2(t)$	0-700	1	350	5.8550	0.000825198	-7.099
		700-1400	1	1050	6.9543	0.00149842	-6.5034
		1400-2100	2	1750	7.4600	0.00197192	-6.2259
		2100-2800	2	2450	7.8308	0.00237328	-6.0432

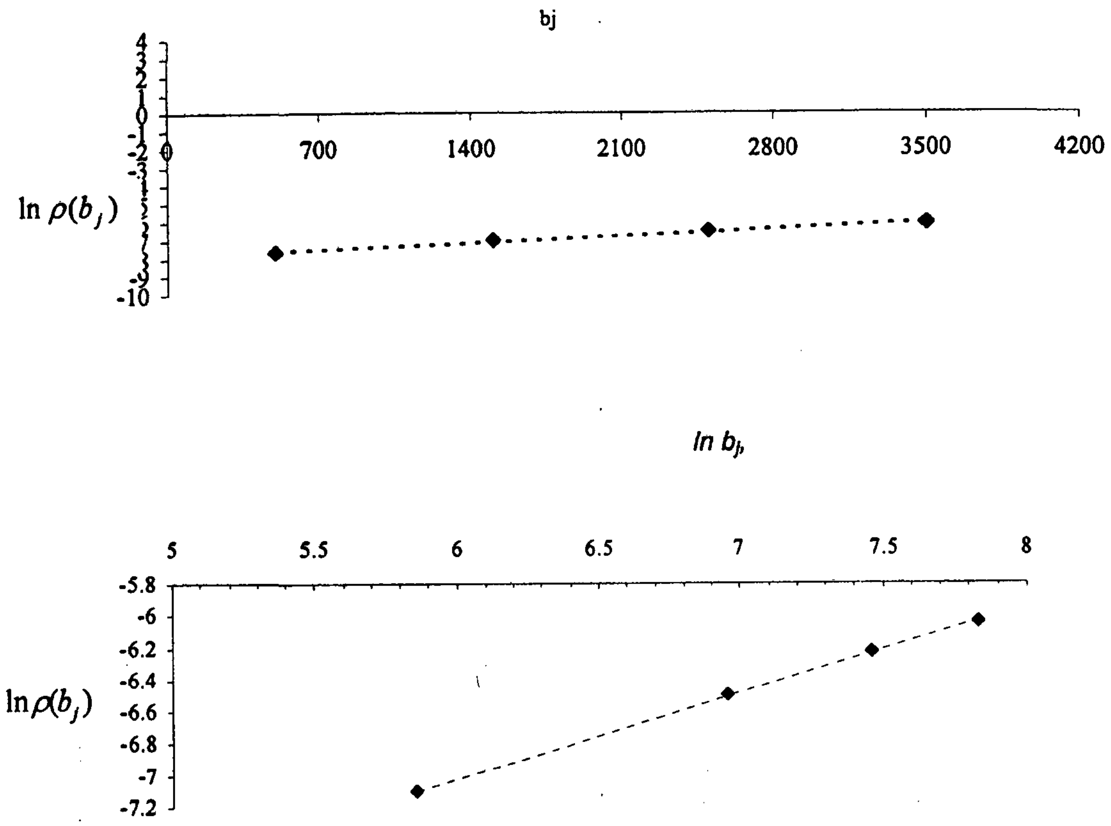


Figure 5.21 Regression Plots for (a) $\rho_1(t)$ and (b) $\rho_2(t)$

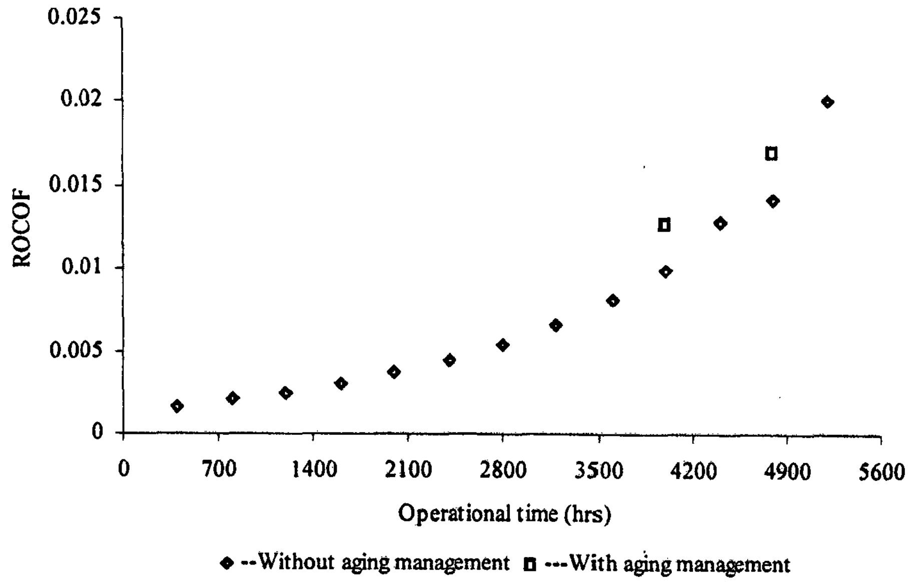
Table 5.12 Failure Forecast for Components

Component	First Time to failure (hrs)	Second time to failure (hrs)
Wire mat	4000	4800
Vacuum pumps	3300	4200

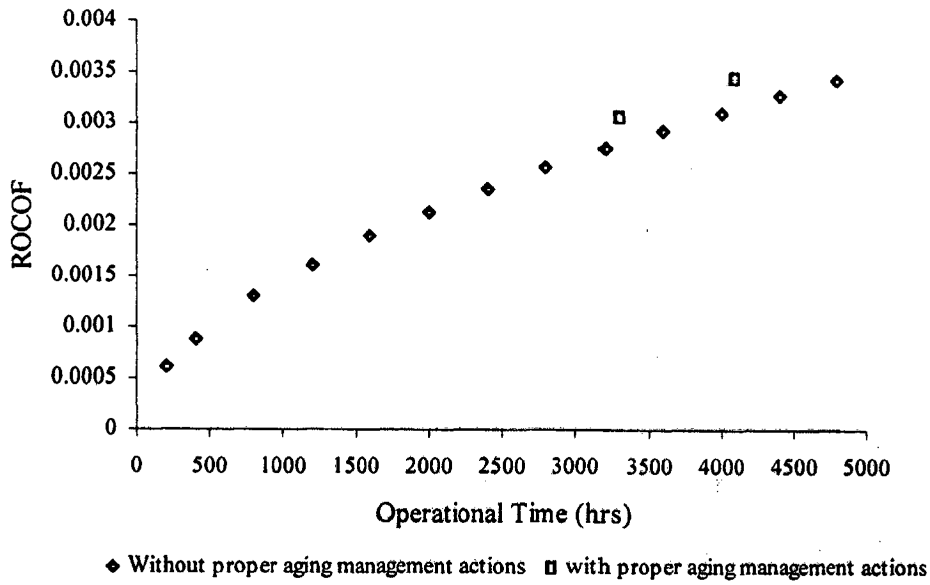
$$\rho_1(t) = e^{\{-5.80+(0.000360 1t)\}}\ \text{hr}^{-1} \quad \text{(For wire mat)} \tag{5.3}$$

$$\rho_2(t) = 4.01x10^{-5} t^{0.535}\ \text{hr}^{-1} \quad \text{(For vacuum pump)} \tag{5.4}$$

Figures 5.22 (a) and (b) displays the comparison of Rate of Occurrence of Failures (ROCOFs) with aging management actions and without aging management actions for both wiremat and vacuum pumps.



(a)



(b)

Figure 5.22 Comparison of Rate of Occurrence of Failures (a) Wire mat (b) Vacuum pumps

5.5.2 Cost Analysis

By assuming the relevant cost information i.e. cost of repair and cost of replacement the co analysis has been done to find trade off between maintenance cost and capital expenditure. Usin Type-II and Type-III replacement policies (Coetzee, 1997), maintenance decisions are optimized i terms of

(i) Optimal operational time (T*)

(ii) Optimal cost / unit time C (T*) and

(iii) Number of minimal repairs (n)

The governing equations, numerical values of parameters, repair and replacement costs for tl components are shown in Table 5.13.

From Table 5.13 it is inferred that, for wire mat, Type-II policy gives the optimal replaceme frequency T* = 3226 hours (nearly after 5 months) and Type-III policy gives the optim replacement frequency n* = 11 (approx.) i.e. minimum11 repairs and then be replaced at the ne failure.

Similarly, for vacuum pumps we get T* = 12,452 hours (nearly18 months.) n* = 73 (approx.)

Table 5.13 Summary of Cost Analysis (Paper Machine Components)

Components		Wire Mat	Vacuum Pumps
Governing Equation	Type –II	$e^{\alpha_1 T^*}(\alpha_1 T^* - 1) = X - 1$	$T^* = [C_0 / \lambda(\beta - 1)]^{1/\beta}$
	Type-III	$n^* = e^{\alpha_0}(m-1)/\alpha_1$	$n^* = C_0 /(\beta - 1)$
Parametric values	α_1	4.9x10^{-4}	-
	α_0	-6.57	-
	β	-	1.5439
	λ	-	0.000034987
Approx costs (Rs x 1000)	Cp	100	40
	C_f	12	10
Results			
Optimal operation time	T*(hrs)	3226	12452
Optimal cost / unit time	C (T*) /hr	82.65	11.65
No. Of minimal repairs	n*	11	73

$X = C_0\alpha_1 / e^{\alpha_0}$, $m = X - 1/\ln - 1$ and $C(T^*) = C_f E(N(t)) + C_p / T$

C_p Cost of replacement
C_f Cost of a repair
C_0 Cost ratio. C_p/C_f
C_f(T*) Optimal operational time,
C (T*) Optimal cost / unit time
(n) Number of minimal repairs
α_0, α_1 Parameters of log-linear NHPP model, $\rho_1(T)$
λ , β Parameters of power law NHPP model, $\rho_2(T)$

5.6 Concluding Remarks

It is concluded from the research carried out on various aspects of maintenance (with the help of a case from paper mill) that simultaneous adoption of maintenance tools cum techniques helps the maintenance managers to make decisions related to repair or replacement of components associated with the system. The application of fuzzy linguistic methodology can be successfully used to assess and identify the effectiveness and efficiency of various maintenance strategies followed for various equipment such as compressors, evaporators, pumps, air coolers, heat exchangers etc. The proposed approach can be extended to assist the maintenance managers/experts to identify the most informative and efficient maintenance strategy for each piece of equipment or system. Further, a company wide maintenance plan can be made by clustering the components, machines or parts in homogenous groups on the basis of their maintainability requirements. From the second part of chapter on TPM implementation it is inferred that in order to meet the challenges of competitive manufacturing, adoption and implementation of well-conceived TPM plan with the help of autonomous maintenance and focused improvement teams helps to bring continuous improvement in the quality of the products and services delivered. The study shows considerable improvement in various performance indices such as skill upgrading increase in mean time between failure, reducing defect rate, rework percentage and maintenance versus operation costs (Figures 5.11-5.17). Lastly, as shown with the help of an illustrative case that the application of NHPPP models in maintenance decision making assists the maintenance managers in understanding the failure behavior of aging components by providing mathematical model. The model not only helps in forecasting future failures but also helps in optimizing the maintenance decisions based on cost dimensions (repair or replacements).

Chapter 6

QUALITY COSTING*

6.1 INTRODUCTION

Quality costing (as a quality management technique) has been around for the last five decades, since the seminal paper of Feignbaum (1956). The importance of quality costing cannot be ignored by organizations to remain competitive on global front. Supervillie and Gupta, (2001) reported in their study that the survey by American Management Association (AMA) revealed that three quarters of managers pointed towards the quality of products and services, as key strategic dimensions to be successful in business. Many empirical studies demonstrated that most of the quality costing methods such as (i) structured [(a) PAF checklist (BS.6143: Part 2, 1992), (b) ABC (Activity-Based Costing BS.6143: Part 1,1990), (c) PCM (Process Cost Modeling)] and (ii) Non-structured [(a) Departmental Costing (b) Questionnaire Approach (c) Problem Solving Approach] though provides ways for registering and analyzing the quality cost information but fails to improve the small firms competitiveness and profitability (Porter and Rayner 1992, Pursglove and Dale1995,Czuchry *et al.* 1999, Noci and Toletti 2000, Dale and Wan, 2002). While conforming on the results of prior research on the practice of quality costing approaches and the problems faced by the companies in implementing a quality management system, a framework based on fuzzy set theory has been developed. The developed framework provides application of fuzzy set theory to elicit, aggregate or synthesize the information related to quality costs (under various cost categories) of an organization.

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- International Journal of Production Research (In press).Taylor and Francis ltd.
- TQM Magazine (An international Journal) (In press) Emerald ltd.

6.2 QUALITY COSTING APPROACHES

The various quality costing approaches can be classified as structured and semi structured approaches

(i) Structured approaches are

(a) Prevention-Appraisal-Failure (PAF) categorization approach (BS.6143: Part 2 [1990]),

(b) Questionnaire, and

(c) Process cost modeling [BS 6143: Part 1 (1992)].

(ii) Semi structured approaches are

(a) Departmental interviews, and

(b) Problem solving approach

Though these approaches are widely practiced by the industries to collect and measure quality costs but many problems are associated with them. Some of the important problems associated with them are briefed in the following paragraphs:

6.2.1 Structured Approaches

6.2.1.1 Prevention Appraisal Failure (PAF) approach

Based on BS 6143: Part 2 (BSI 1990), the PAF approach helps to examine the company operating procedures, accounting systems, and monthly departmental reports to identify various cost elements associated with four cost categories i.e.

(i) Prevention (P)

(ii) Appraisal (A)

(iii) Internal Failure (IF),and

(iv) External Failure (EF)

Owing to the complex nature of relationships, various items are not identified and if identified, only few of them are quantified (as shown in Table 6.1). For instance, under prevention cost category –quality improvement program is identified only but it is difficult to quantify cost items associated with interviews, lectures, brainstorming sessions and skill development programs. Also, various quality cost items related to prevention activity are not traceable because of non existence of explicit cause and effect relationship between department/product (Tsai, 1998).

Another criticism of PAF model is that some of the most significant failure costs such as lost of customer sales and goodwill cannot be quantified effectively (Johnson, 1995). Though information associated with quality costs is subjective in nature so, the fuzzy treatment is most suitable to deal with the linguistic or qualitative information associated with them.

6.2.1.2 Questionnaire Approach (QA):

Dale and Wan (2002) in their work developed a questionnaire to determine

- Intangible costs (associated with time spent by employees on quality related activities) in all the departments of organization, and
- Tangible costs

over a period of around one year. They concluded that though it helps in raising the awareness among the employees regarding quality costs and pinpoints the areas for further investigation but problems such as non-cooperation (staff not completing and returning the responses) and lack of information make the approach more inappropriate for managers to adopt.

6.2.1.3 Process cost modeling (PCM):

The process cost modeling approach described in BS 6143: Part 1 (1992) recognizes the importance of process cost measurement in terms of Cost of Conformance (COC) and Cost of Non-Conformance (CONC) for a particular process. It groups all activities and parameters with in the process by flowcharting the process and finally identifies key areas for process improvement

(Porter and Ryner 1992, Oakland 1993). Numerous computer models such as IDEF (Ross 1977), Q-Map (Cross field and Dale1990), and Hybrid Model (Golden and Rawlins 1995) were subsequently developed by the quality practioneners /researchers to help managers in construction

Table 6.1 Cost Categories with Various Cost Items

Cost category	Element description	Symbols	Identified	Not-Identified	Quantified
Prevention costs	Quality engineering (procedures for planning and control)	P_1	✓		
	Design and development of equipment	P_2		✓	
	Quality review and design verification	P_3	✓	✓	
	Maintenance and calibration of production and inspection equipment	P_4	✓		✓
	Supplier quality planning	P_5		✓	
	Quality audits (internal and external)	P_6	✓		✓
	Quality training (seminars, workshops/lectures)	P_7			✓
	Data Reporting (collection and analysis)	P_8		✓	
	Quality improvement programmes (quality circles, project teams)	P_9	✓		
Appraisal costs	Receiving inspection	A_1			✓
	Laboratory inspection and testing	A_2			✓
	In process inspection (sensors/signals/status)	A_3	✓		
	Final inspection (100% / sampling inspections)	A_4	✓		✓
	Field testing (performance tests and status reporting)	A_5		✓	
	Inspection and test equipment	A_6		✓	
Failure costs	Scrap (Item /quantity /number)	F_1			✓
	Rework and repair (Item /quantity /number)	F_2	✓		✓
	Down grading	F_3		✓	
	Rescheduling (due to down time, machine breakdowns)	F_4		✓	
	Overtime to cover production losses (extra Work in Process-WIP)	F_5	✓		
	Program/software errors	F_6	✓		
	Failure analysis (corrective actions)	F_7		✓	
	Lost profits/sales	F_8		✓	

of process cost models But owing to greater complexity with respect to their application, these models required more expertise and operational skills (Tsai 1998). Dale and Wan (2002) conducted a study on quality costing using PCM by in an organization which manufactures flavorings for the food and drink industry, found that the team members (works manager, quality system coordinator, production engineer, dispatch engineer and three operatives) experienced difficulties in defining the inputs, outputs, controls and resources used and following through the different stages of the process model. They concluded that the PCM approach is not only cumbersome but also it is too time consuming to follow the guidelines outlined in BS 6143: Part 1 (1992) manual.

6.2.2 Semi-structured approaches:

6.2.2.1 Departmental Interviews (DI):

The incidence of quality costs is very broad as it falls through MDMIS (*Marketing –Design-Manufacturing-Inspection and Shipping*) cycle covering each department. The interviews with respective heads and staff of engineering, production control, sales and marketing etc. not only help to identify the major failures and non-conformance items related to quality cost categories but also to reduce the unnecessary costs. In a study conducted by Roden and Dale (2001) in small engineering company reveals that the method is quite inappropriate because of various factors such as (i) blame game (ii) lack of interest (iii) lack of company wide culture (iv) lack of information and accountability. Each department passes the buck to other department responsible for poor quality performance.

6.2.2.2 Problem Solving Approach (PSA):

The use of seven-quality control(7-QC) tools (checklist, run/bar charts, scatter diagram, cause and effect analysis, pareto analysis and control charts) provides a framework to collect, analyze and interpret the data related to quality costs. Depending upon the nature of the problem, a quality costing worksheet (for tracking downtime and resources spent) can be made to register both cost of conformance and cost of non–conformance. Robisons (1997) proposed PSA to integrate quality cost concepts into team's problem solving efforts. The effectiveness of the method was examined by Dale and Wan (2002) by applying it to assess the concern of staff to handle external complaints. They designed a check sheet and supplied to the staff members for getting their responses but the results were not convincing and rather disappointing because of indifferent attitude and lack of discipline among the employees. The present study makes use of root cause analysis to segregate various quality cost items under each quality cost category.

6.3 LIMITATIONS:

Figure 6.1 shows that the incidence of quality costs is very broad as it consists of numerous tangible and intangible cost elements and falls not only through out the *Marketing-Design-Manufacturing-Inspection and Shipping* (MDMIS) cycle but also encapsulates the producers and consumers. Further, these difficulties are compounded by vagaries of manufacturing processes, system configurations, product varieties and company culture. To cope with the complex, uncertain and subjective relationships between various cost segments and to help managers to set up/improve various quality improvement initiatives, the application of fuzzy methodology (FM), is proposed to elicit, aggregate and synthesize various quality costs under the cost categories shown in Table 6.1. Treating quality as a fuzzy notion, the information obtained from wide range of sources (supplier, operators experience, manufacturer's specification and expert opinions etc.) is modeled and analyzed with the help of well-defined fuzzy set principles. Capitalizing on the literature studies and identified gaps (as discussed in chapter 2), an integrated, systematic approach is proposed to plan, implement and sustain a quality-costing program, whic could help the managers in assessment and setting up of quality-based priorities.

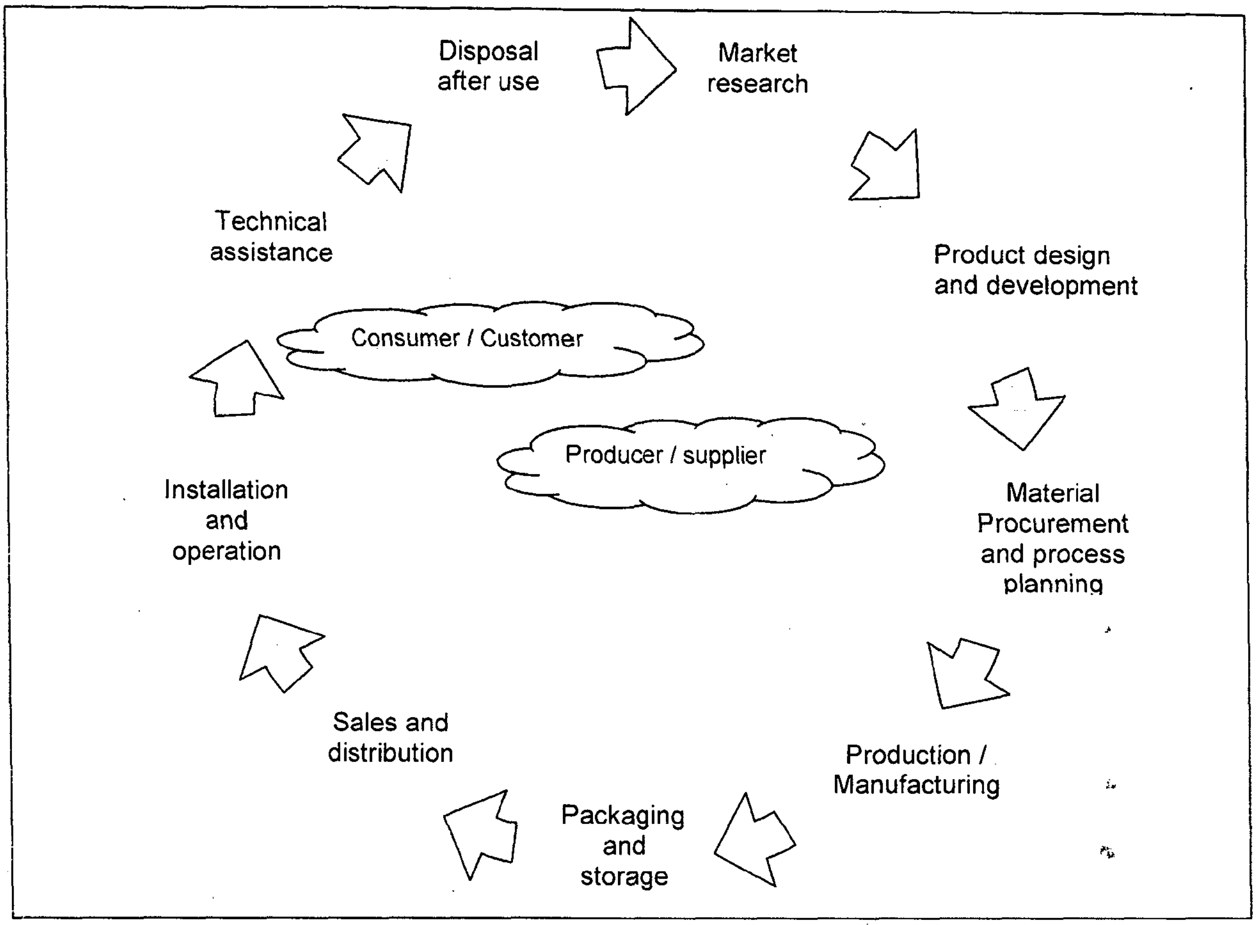


Figure 6.1 Quality Loop

The present study aims to provide a

(i) a structured framework to implement, sustain and manage a quality-costing program ii a process industry after prioritization of alternatives under each cost category

(ii) framework to implement Quality Costing System (QCS) based on Process Cos Modeling (PCM)

In particular, the discussed fuzzy logic approach is mainly concerned with the following thre issues:

(i) Translation of linguistic/subjective assessments related to quality cost information under various cost segments into Fuzzy Number Representation (FNR)

(ii) Operation on Triangular Fuzzy Numbers(TFN)

(iii) Information aggregation using Choquet Fuzzy Integral(CFI)

In the first part of chapter, after briefing about the advantages and disadvantages of various cost accounting approaches practiced by the industries, the need for attaching fuzziness to the notion of "quality" is discussed. After obtaining expert elicitation, the imprecise, vague, and complex information related to quality cost items [under four key cost segments i.e. prevention (P), appraisal (A), Internal failure (IF), and external failure (EF)] is synthesized using well-established principles of fuzzy set theory. To help the management in successful implementation of Quality Cost Accounting System (QCAS) five alternatives for each cost category are considered. By obtaining the priority values with respect to various alternatives, the implementation program has been revived. The comparative analysis carried out after collecting the information under PAF cost segments showed a progressive and significant change in quality costs. The proposed approach is discussed with the help of a case from paper industry.

In the second part of the work, a novel approach to implement QCAS by using PCM after judicious selection of the processes in the paper mill is discussed. The fuzzy set methodology has been applied to prioritize the processes for investing efforts in reduction of (Cost of Non-Conformances) CONCs and allocation of resources.

6.4 DEVELOPMENT OF QUALITY COST ACCOUNTING SYSTEM - QCAS

6.4.1 Illustrative Case

The work is carried out in a paper industry situated in northern part of India. The company is in a process of achieving ISO-9000 certification. To be successful in its effort, the company management decided to implement and sustain Quality Cost Accounting System (QCAS) as it helps to measure, analyze and improve operational efficiency of departments by minimizing waste and inefficiencies. To implement the QCAS a four-step procedure based on continuous improvement cycle [*introduction-mobilization-execution and evaluation*] is designed as shown in Figure 6.2. These stages are defined as follows:

Stage 1. Introduction/Preparatory:

For successful implementation of QCAS in a company, the management commitment is essential as it requires close monitoring and allocation of resources. A committee consisting of senior managers from all departments (production, operation, stores, maintenance, quality and sales) has been set up to define policies / set targets and to co-ordinate the activities for successful implementation and promotion of QCAS in their respective departments.

Stage 2. Mobilization:

This stage includes formation of teams and mobilization of necessary resources to train the employees. The managers have been instructed to organize seminars/talks/invited lectures for spreading quality consciousness among the employees and educate them to collect, interpret and analyze the information.

Stage 3. Execution:

Under this phase, the managers has been entrusted to

(i) identify critical processes/products and improvement areas

(ii) prioritize them and form quality teams to record necessary information related to various cost items under the quality cost categories

Stage 4. Evaluation and Performance monitoring:

The collected information is segregated under different quality cost categories to

(i) identify various non-conformance areas

(ii) review product/process conformances

(iii) devise solution strategies /corrective action plans, and

(iv) implement internal quality audit program

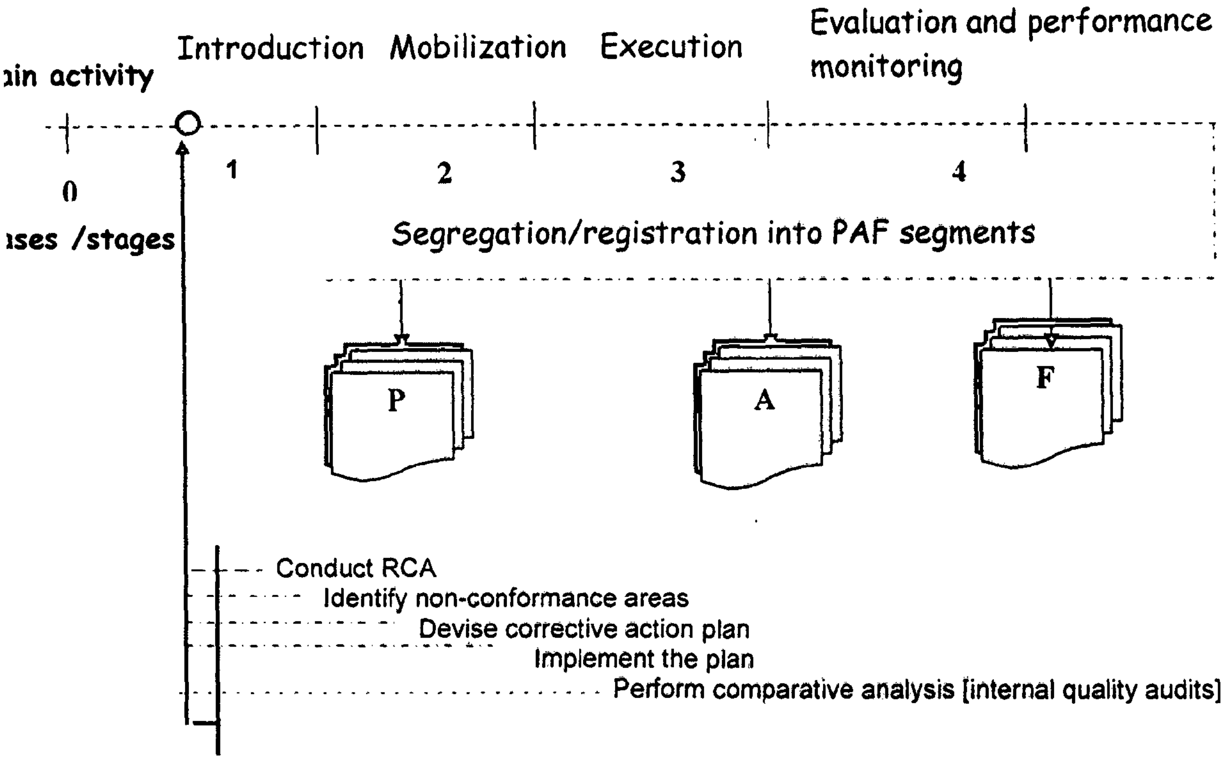


Figure 6.2 Implementation Stages for Quality Cost Accounting System

After forming a committee of members, the QCAS program has been implemented stepwise. First of all, in order to identify and segregate various quality cost elements under each cost category root cause analysis is carried out. The detailed RCA chart is shown in Figure 6.3 giving the details of costs associated under various cost categories in the paper mill. Based on the analysis, a total of 28 cost elements [9 PC, 6AC, 8 IF, 5 EF] has been identified and are given in Table 6.2. The information obtained from various sources such as time sheets, departmental reports, purchase orders, re-work, re-inspect reports, credit and debit memos was pulled together to provide requisite number under different quality segments. But the results were not very convincing because the managers find it difficult to analyze the costs owing to complex relationships among them and initiate quality improvement actions. As a result of this, the management decided to find the areas for quality improvement. To this effect, following five alternatives for each cost category are considered.

A_1 = Quality management (Training, planning, control and coordination)

A_2 = Data gathering, reporting and recording

A_3 = Inspection and testing (equipment and materials)

A_4 = Failure analysis, and

A_5 = Complaint administration

Treating the relationships among various cost items as complex, imprecise and fuzzy in nature and by acknowledging quality as a fuzzy notion, a group of multiple experts (from sales and marketing, production operations, quality, maintenance and administration) is selected to determine the degree of importance of the cost items under each cost segment. The information with respect to cost items is represented using linguistic terms namely UI [Un-Important], LI [Least Important], FI [Fairly Important], VI [Very Important] and CI [Critical]. For carrying out fuzzy operations these terms are translated using fuzzy numbers obtained from expert elicitation.

Figure 6.4(a) shows the assignment of fuzzy numbers and corresponding fuzzy density values with respect to cost items under prevention category. Similar assignments and resulting computations were carried out for cost elements under appraisal and failure cost categories [shown in Appendix 6(i) Figure 6.4(b)–(d)]. Table 6.3 presents the values of fuzzy densities for all four cost categories. These are used as degree of importance in performing fuzzy integrations. The fuzzy membership function representing degree of importance of cost items is presented in Figure 6.5.

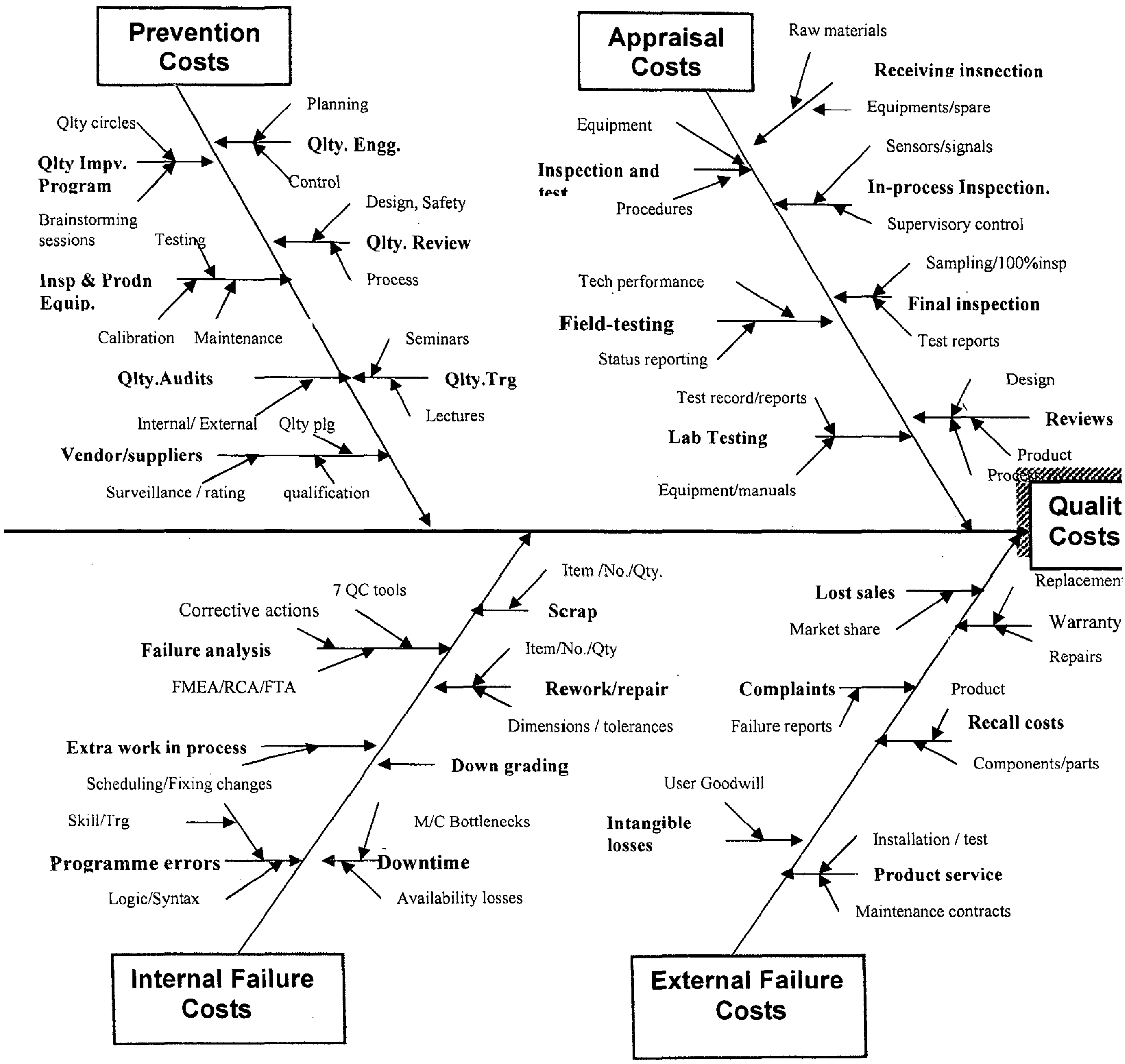


Figure 6.3 Root Cause Analysis for Quality Costs of a Paper Mill

Table 6.2 Various Cost Elements

Cost Category	Element description	Symbols
PC	Quality engineering (procedures for planning and control)	P_1
	Design and development of equipment	P_2
	Quality review and design verification	P_3
	Maintenance and calibration of production and inspection equipment	P_4
	Supplier quality planning	P_5
	Quality audits (internal and external)	P_6
	Quality training (seminars, workshops/lectures)	P_7
	Data Reporting (collection and analysis)	P_8
	Quality improvement programmes (quality circles, project teams)	P_9
AC	Receiving inspection	A_1
	Laboratory inspection and testing	A_2
	In process inspection (sensors/signals/status)	A_3
	Final inspection (100% / sampling inspections)	A_4
	Field testing (performance tests and status reporting)	A_5
	Inspection and test equipment	A_6
IFC	Scrap (Item /quantity /number)	IF_1
	Rework and repair (item /quantity /number)	IF_2
	Down grading	IF_3
	Rescheduling (due to down time, machine breakdowns)	IF_4
	Overtime to cover production losses (extra WIP)	IF_5
	Program/software errors	IF_6
	Lost profits/capacity losses	IF_7
	Failure analysis (corrective actions)	IF_8
EFC	Warranty claims (repairs and replacements)	EF_1
	Product service liabilities (installation and maintenance)	EF_2
	Returned materials and repairs	EF_3
	Recall costs (products/components)	EF_4
	Intangible losses (lost sales, goodwill loss, market share)	EF_5

Where: PC: Prevention Costs; AC: Appraisal Costs; IFC: Internal Failure Costs; and EFC: External Failure Costs

		Fuzzy definition	Fuzzy density
PC	P_1	(0.6,0.7,0.9)	
		(0.5,0.6,0.7)	
		(0.75,0.8,0.9)	0.642
		(0.4,0.5,0.6)	
	P_2	(0.4,0.5,0.6)	
		(0.6,0.7,0.8)	0.594
		(0.65,0.75,0.85)	
		(0.4,0.5,0.6)	
	P_3	(0.3,0.4,0.5)	
		(0.4,0.5 0.6)	0.524
		(0.65,0.75,0.85)	
		(0.4,0.5,0.6)	
	P_4	(0.7,0.8,0.85)	
		(0.7,0.8,0.85)	0.700
		(0.65,0.75,0.85)	
		(0.65,0.75,0.85)	
	P_5	(0.3,0.4,0.5)	
		(0.2,0.3,0.4)	0.523
		(0.3,0.4,0.5)	
		(0.8,0.9,1.0)	
	P_6	(0.7,0.8,0.85)	
		(0.5,0.6,0.7)	0.685
		(0.6,0.7,0.8)	
		(0.65,0.75,0.85)	
	P_7	(0.7,0.8,0.85)	
		(0.8,0.9,1.0)	0.839
		(0.9,1.0,1.0)	
		(0.7,0.8,0.85)	
	P_8	(0.3,0.4,0.5)	
		(0.8,0.9,1.0)	0.573
		(0.2,0.3,0.4)	
		(0.65,0.75,0.85)	
	P_9	(0.8,0.9,1.0)	
		(0.5,0.6,0.7)	
		(0.5,0.6,0.7)	0.685
		(0.65,0.75,0.85)	

Figure 6.4(a) Fuzzy Numbers and Fuzzy Densities (Prevention Cost)

Table 6.3 Fuzzy Density Values of PC, AC, IFC, and EFC Cost Elements

Prevention cost items	**P_1**	**P_2**	**P_3**	**P_4**	**P_5**	**P_6**	**P_7**	**P_8**	**P_9**
Density values	0.624	0.594	0.524	0.700	0.523	0.685	0.839	0.573	0.685
Appraisal cost items	**A_1**	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**			
Density values	0.8390	0.700	0.7369	0.6420	0.5730	0.7950			
IF cost items	**IF_1**	**IF_2**	**IF_3**	**IF_4**	**IF_5**	**IF_6**	**IF_7**	**IF_8**	
Density values	0.7070	0.73690	0.3860	0.6136	0.3630	0.7950	0.6360	0.7970	
EF cost items	**EF_1**	**EF_2**	**EF_3**	**EF_4**	**EF_5**				
Density values	0.7950	0.6136	0.7070	0.3960	0.8390				

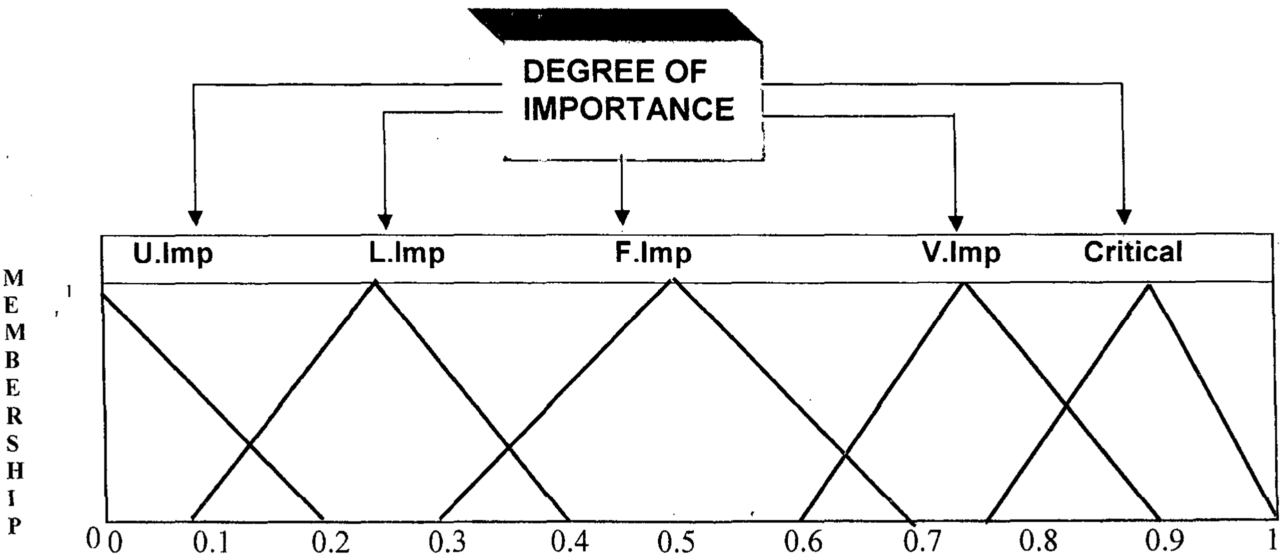


Figure 6.5 Graphical Representation of Fuzzy Membership Function.

To aggregate information of objective evidence from various cost items for the selec alternatives, approximations are carried out using same set of experts and same linguistic ter Table 6.4 presents the approximated Fuzzy Number Representation (FNR) and equival Transformed Values (TV). These transformed values have been used as objective evidence computing fuzzy integral values. Equation 3.27 is used to determine the value of lambda. The objective evidence *h (y)* values, for each cost item, are rearranged in decreasing order with respect to corresponding fuzzy density values. Based on the new order and determined value of lambda, fuzzy measure $g\ (A_i)$ is computed using recursive Equation 3.28. Finally, fuzzy integrations are performed (using Equation 3.29) and integral values are computed to obtain the respective ranking among the various alternatives under each quality cost segment. The results so obtained are presented in Table 6.5. It can be noted from Table 6.5 that

(i) In case of appraisal costs the maximum score is obtained by alternative A_3 i.e. inspection and testing (0.81), which means that maintenance and calibration of both production and inspection equipments is vital to measure the level of deviation and prevention of errors. First-off inspection, inter-operation checks and final inspection are important elements of quality assurance under this category, which needs to be incorporated for reducing non-conformance costs.

(ii) Under prevention cost category the highest score is obtained by alternative A_1 i.e.0.7684.Thus, investment in prevention activities such as process design, training, internal audits, and calibration of equipments will help the organization to control non-conformities associated with process and products. So, more stress should be given on quality planning activities, which include product/process reviews, and supplier quality evaluation programs. According to Zhao (2000), with increase in prevention costs there is considerable reduction in failure costs.

(iii) Under internal failure costs the maximum score is obtained in case of alternative A_4 i.e.0.7250 which is failure analysis. The problem of scrap/rework /retest due to internal failures can be effectively handled by pinpointing the sources of deviations/errors, which needs knowledge of various failure analysis techniques such as Ishikawa diagram, Pareto analysis and Control charts. For instance, the Pareto (80/20 rule) analysis can be used to select the major causes resulting in non-conformities. Also, periodic inspection and preventive maintenance activities will help in long way to reduce the scrap and rework.

(iv) Under external failure costs the main objective of a company was to identify the causes resulting in product recall and customer dissatisfaction. To this effect, the development of complaint management system (acquisition, processing and readdress) as evident from the highest value of alternative A_5=0.746, will help the organization to keep direct contact with the potential customers and make necessary and timely actions to prevent the losses arising out from lost sales, lost market share and lost reputation.

Table 6.5 Choquet Fuzzy Integral Values

Alternatives	**Appraisal cost**		**Prevention Cost**		**Internal Failure Cost**		**External Failure Cost**	
	IV	**R**	**IV**	**R**	**IV**	**R**	**IV**	**R**
A_1	0.2965	5	*0.7684*	1	0.2810	4	0.3326	5
A_2	0.6757	2	0.6390	3	0.6107	3	0.6275	2
A_3	*0.8131*	1	0.6990	2	0.6678	2	0.5902	3
A_4	0.5750	3	0.5048	4	*0.7250*	1	0.4605	4
A_5	0.4720	4	0.4240	5	0.1027	5	*0.7460*	1

IV: Integral Value and R: Ranking

6.4.1.1 Results and Discussions

Further, sensitivity analysis is performed to validate the results. As mentioned earlier in chapter 3 under section 3.2.5.2 that the change in the importance degree of information source with largest objective evidence will have a considerable influence on the integral value of alternatives. The case is examined by specifying the importance degree of information sources at 0.1, 0.3, 0.5, 0.7, and 0.9 under each cost segment as shown in Figure 6.6. It is evident from the results that the resulting integral values obtained for each alternative lies between minimum and maximum objective evidence of all the information sources and with increase in fuzzy density, the integral value also increases.

Table 6.4 Fuzzy Definitions and Transformed Values for Cost Items

	A_1		A_2		A_3		A_4		A_5	
S	**FNR**	**TV**	**FNR**	**TV**	**FNR**	**TV**	**FNR**	**TV**	**FNR**	**TV**
P_1	0.3,0.5,0.7)	0.500	(0.6,07,0.9)	0.695	(0.1.0.25,0.4)	0.282	-	-	-	-
P_2	(0.6,07,0.9)	0.695		-	-	-	-	-	-	-
P_3	-	-	(0.1.0.25,0.4)	0.282	-	-	(0,0,0.2)	0.090	(0.1.0.25,0.4)	0.282
P_4	(0.3,0.5,0.7)	0.500	-	-	-	-	(0,0,0.2)	0.090	(0.3,0.5,0.7)	0.500
P_5	(0.6,07,0.9)	0.695	(0.6,07,0.9)	0.695	(0.3,0.5,0.7)	0.500	(0,0,0.2)	0.090	(0,0,0.2)	0.090
P_6	-	-	(0.3,0.5,0.7)	0.500	(0.1.0.25,0.4)	0.282	-	-	-	-
P_7	(0.3,0.5,0.7)	0.500	(0.3,0.5,0.7)	0.500	(0.75,0.9,1)	0.844	(0.6,07,0.9)	0.695	(0.3,0.5,0.7)	0.500
P_8	(0.75,0.9,1)	0.844	(0.1.0.25,0.4)	0.282	(0.75,0.9,1)	0.844		-	(0,0,0.2)	0.090
P_9	(0.3,0.5,0.7)	0.500	(0.3,0.5,0.7)	0.500	(0.1.0.25,0.4)	0.282	(0.3,0.5,0.7)	0.500	(0,0,0.2)	0.090
A_1	-	-	(0.75,0.9,1)	0.844	(0.3,0.5,0.7)	0.500	(0,0,0.2)	0.090	(0.6,0.7,0.9)	0.695
A_2	-	-	(0.3,0.5,0.7)	0.500	(0.6,0.7,0.9)	0.695	(0.1.0.25,0.4)	0.282	(0.1.0.25,0.4)	0.282
A_3	-	-	(0.6,0.7,0.9)	0.090	(0.1.0.25,0.4)	0.282	(0.3,0.5,0.7)	0.500	-	-
A_4	-	-	(0,0,0.2)	0.090	(0.3,0.5,0.7)	0.500	(0.6,0.7,0.9)	0.695	-	-
A_5	-	-	(0.3,0.5,0.7)	0.500	(0.3,0.5,0.7)	0.500	(0.1.0.25,0.4)	0.282	-	-
A_6	(0.3,0.5,0.7)	0.500	-	-	(0.6,0.7,0.9)	0.695		-	-	-
IF_1	(0,0,0.2)	0.090	(0.6,0.7,0.9)	0.695	(0.75,0.9,1)	0.090	(0.75,0.9,1)	0.844	-	-
IF_2	(0,0,0.2)	0.090	-	-	(0.6,07,0.9)	0.500	(0.3,0.5,0.7)	0.695	-	-
IF_3	(0.3,0.5,0.7)	0.500	-	-	(0.75,0.9,1)	0.695		-	-	-
IF_4	(0,0,0.2)	0.090	-	-	(0.3,0.5,0.7)	0.500	(0.75,0.9,1)	0.844	-	-
IF_5	-	-	-	-	-	-	-	-	-	-
IF_6	-	-	(0.6,0.7,0.9)	0.695	-	-	(0.3,0.5,0.7)	0.50	-	-
IF_7		-	(0.3,0.5,0.7)	0.500	(0.3,0.5,0.7)	0.500	-	-	(0.1.0.25,0.4)	0.282
IF_8	(0.1.0.25,0.4)	0.282	(0.3,0.5,0.7)	0.500	(0.75,0.9,1)	0.844	-	-	-	-
EF_1	-	-	(0.3,0.5,0.7)	0.500	(0.6,07,0.9)	0.695	-	-	(0.6,07,0.9)	0.695
EF_2	-	-	-	-	-	-	(0.6,07,0.9)	0.695	(0.3,0.5,0.7)	0.500
EF_3	-	-	(0.3,0.5,0.7)	0.695	(0.75,0.9,1)	0.844	(0.3,0.5,0.7)	0.500	(0.6,07,0.9)	0.695
EF_4	-	-	(0.3,0.5,0.7)	0.500	-	-	-	-	(0.3,0.5,0.7)	0.500
EF_5	(0.75,0.9,1)	0.844	(0.75,0.9,1)	0.844	-	-	-	-	(0.75,0.9,1)	0.844

$A_{i\ ,i=1\text{-}5}$ Alternatives; CC : Cost Category; S: symbol ;FNR: Fuzzy Number Representation, and TV: Transformed Value

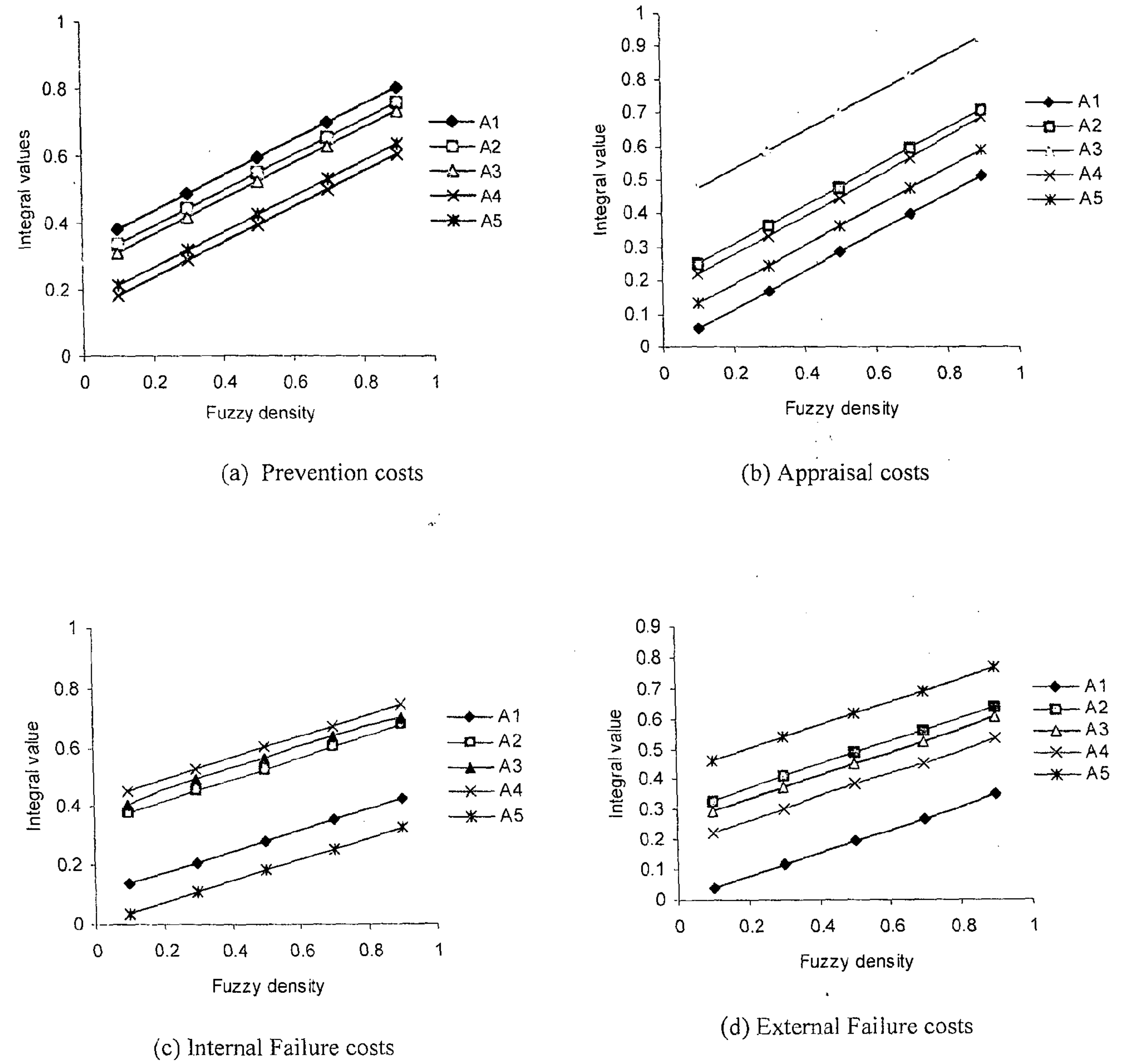


Figure 6.6 Sensitivity Analysis

After setting out the priorities under each cost category the program is revived /invigorated and the data with respect to various cost items under the four cost categories is collected (Quarter-wise) and is presented in Table 6.6.

Table 6.6 Quality Costs Summary

	Quarter Wise Cost Allocation ($) (Year 2004-2005)				
Cost category	**Element description**	**Quarter-I**	**Quarter-II**	**Quarter-III**	**Quarter -IV**
Prevention costs	Quality management	2500	2000	2000	2000
	Process studies	-	700	1000	1000
	Quality Training	700	500	1000	1000
	Others	-	700	1000	1000
Appraisal costs	Incoming inspection	1000	1000	1500	1500
	Calibration and	500	700	1500	1200
	maintenance	500	700	500	500
	Lab inspection/Tests	-	800	600	500
	Others				
Internal failure	Scrap	3000	3000	3500	2200
	Rework	4000	4000	3500	2500
	Retest and Re inspect	2000	2000	2500	1500
	Others	-	800	500	1000
External failure	Product return	1000	800	800	500
	Loss of sales	1000	800	800	500
	Others	800	800	900	800

The percentage of costs in each cost category is calculated and is given (quarter-wise) in Figure 6.7. It is observed from the figures that appreciable increase in appraisal and prevention costs had resulted in bringing down the failure costs. In the first quarter, the failure costs (both IFC and EFC) attributed to about 70% of the Total Quality Costs [QC_{TOT}], which in subsequent quarters had shown a downward trend. At the end of quarter IV the total failure costs had been reduced to 49.74% [40.6%IFCand 9.142%EFC].

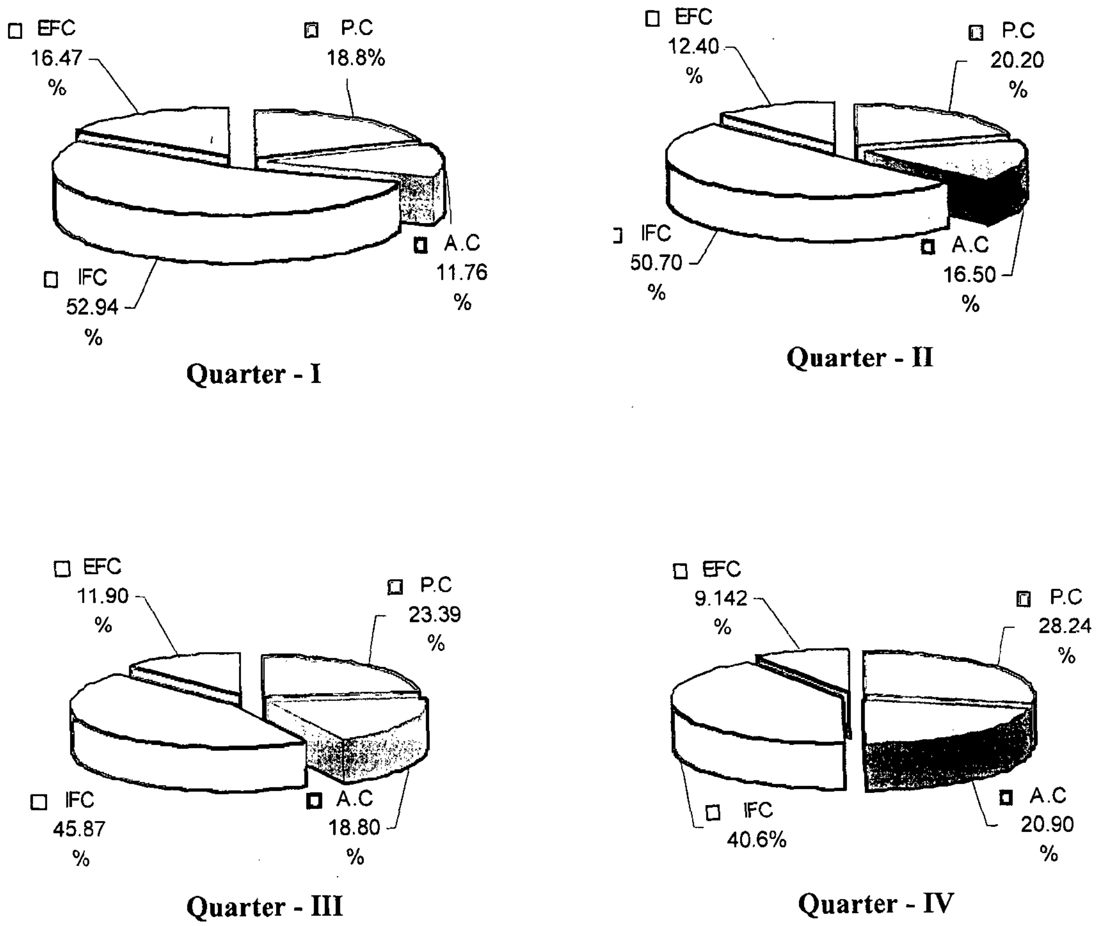


Figure 6.7 Break up of COQ Segments Quarter- I - IV

Figure 6.8 shows the participation of Total Quality Cost (QC_{tot}) with respect to net sales. The trends presented in Figure 6.8 indicate that the efforts invested in quality improvement activities, after careful selection of alternatives under each cost segment had started paying back right from third semester onwards.

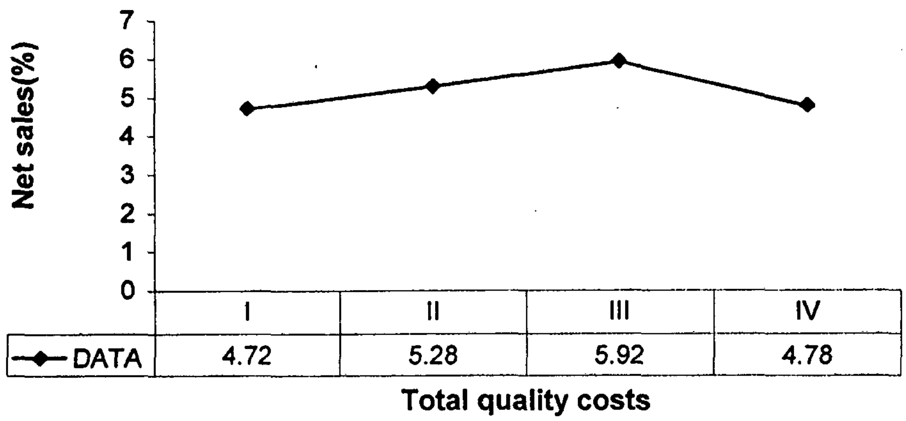


Figure 6.8 Net Sales versus Total Quality Costs

The segment wise (P, A, IF, and EF) break up is shown in Figure 6.9 (a) to (d). The trends commensurate with literature estimates [5-25%] (Bell *et al.* 1994, Pursglove and Dale 1995, Dale and Plunkett 2000).

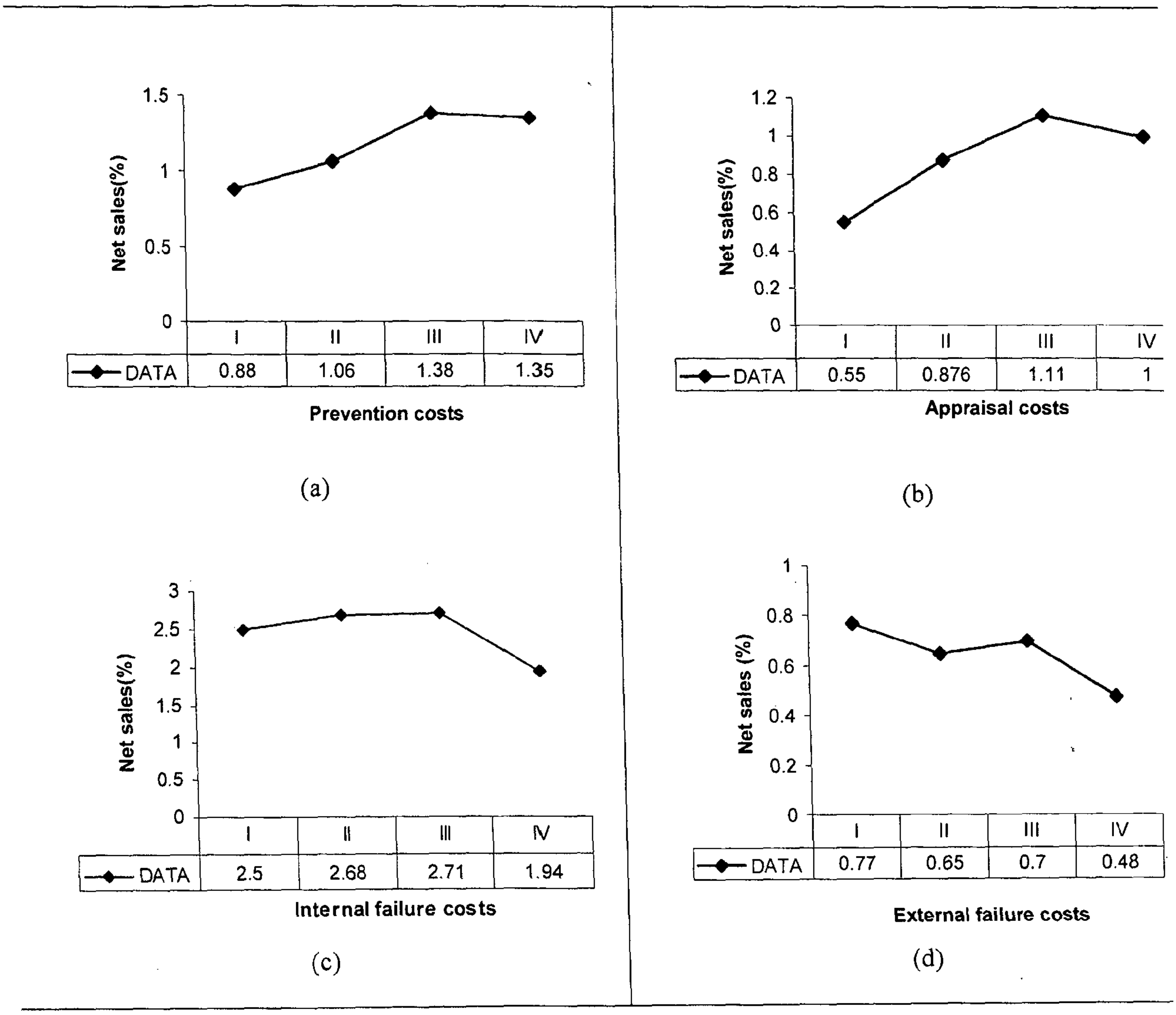


Figure 6.9 (a)-(d) Net Sales versus (a) Prevention Costs (b) Appraisal Costs (c) Internal Failure Costs (d) External Failure Costs

6.5 PROCESS COST MODELING (PCM) APPROACH TO QUALITY COSTING

The production operatives spent high percentage of their working hours on sorting out non-value adding and reworking activities associated with the processes (Dale and Wan, 2002). Also, under the philosophy of process improvement in TQM, analysts should place more emphasis on the cost of each process rather than an arbitrarily defined cost of quality (Goulden and Rawlins, 1995). To this effect among the various approaches to quality costing as discussed earlier, PCM approach is proposed. The approach if applied effectively, it will help to set up a quality costing system as it promotes more interaction and opens up channels for cross functional and bottom up communication. It also recognizes the importance of process cost measurement. The process cost models can be developed for any process and finally key areas for process improvement can be identified and improved upon. As outlined in BS.6143: Part 2, 1992, the approach consists of five stages i.e.

(i) Identification of process to be mapped and its owners
(ii) Formation of improvement teams
(iii) Identification of key activities of process and mapping of cost elements
(iv) Preparation of cost report (using both COC and CONC)
(v) Development of an improvement plan for reducing non- conformance costs

(More details can be had from Oakland, 1993)

6.5.1 An illustrative case

This part of the chapter discusses the use of fuzzy methodology to prioritize the processes (shown in flow chart in Figure 6.10) in the paper mill so that a quality costing system based on process cost modeling can be applied. Based on Oakland's (1993) PCM approach a five step procedure (as shown in Figure 6.11) [on the basis of Deming's (P-D-C-A) cycle], to implement the quality costing system, is formulated.

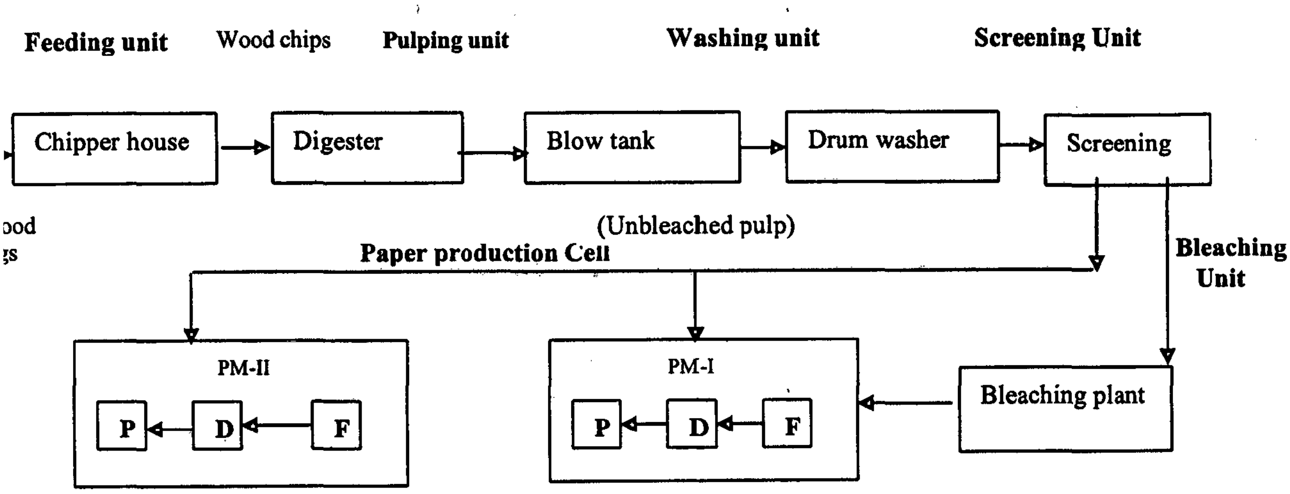


Figure 6.10 Processes in Paper Mill

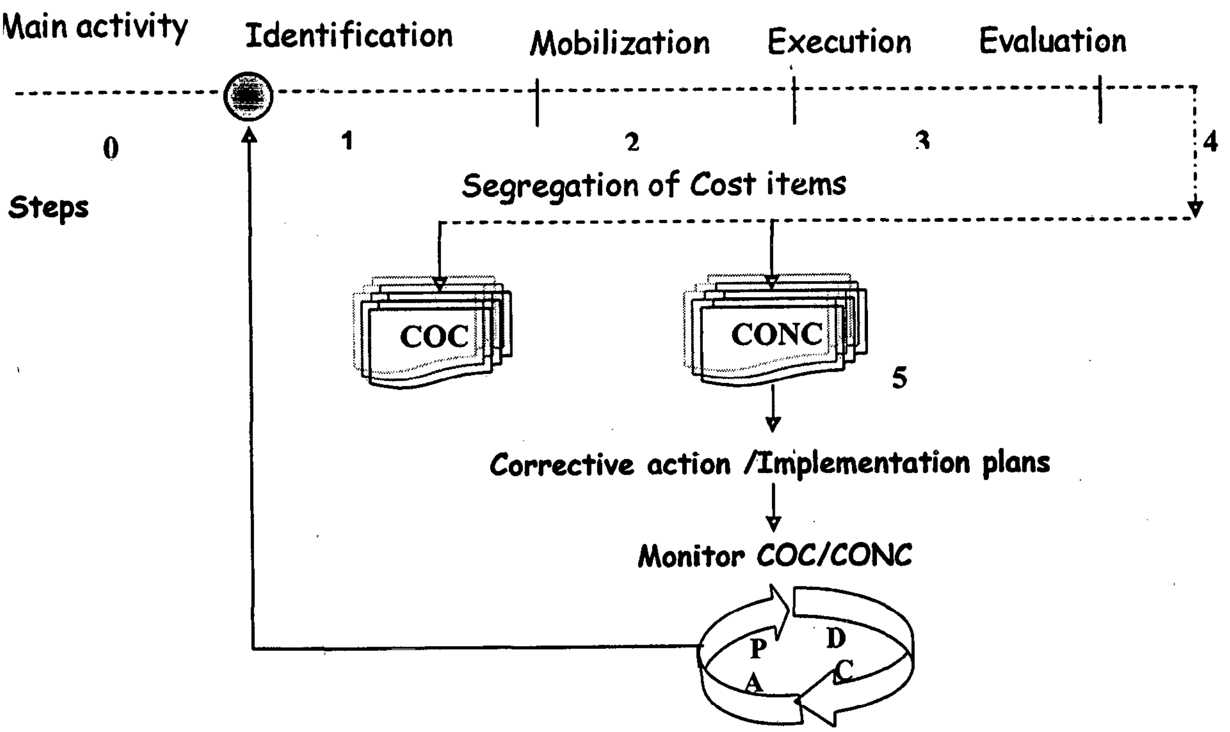


Figure 6.11 Steps in Process Cost Modeling

The steps shown in Figure 6.11 are briefly discussed as below:

Step 1 Identification:

This stage includes identification of the processes, their boundaries and construction of process diagrams to identify the inputs and outputs. The six processes identified are

- Feeding
- Pulping
- Washing
- Screening
- Bleaching, and
- Paper production

Step 2 Mobilization:

This stage includes formation of teams and mobilization of necessary resources to train/educate the employees to collect, interpret and analyze the information related to processes.

Step 3 Execution:

Under this phase the flowcharts are drawn to identify all the activities and parameters related to the processes, which are used to estimate the costs at each stage.

Step 4 Evaluation:

After segregation of quality costs into COC and CONC, the prioritization of costs is done to identify key areas for improvement. Solution strategies /corrective action plans are devised to reduce CONC.

Step 5 Conformance monitoring:

In this phase conformance and non-conformance costs associated with the processes are monitored and reviews are carried out for further improvement.

Starting with identification of processes and their boundaries (inputs/outputs), first the processes are ranked/ prioritized in order to invest efforts in reduction of CONCs and allocation of resources. Treating the relationships among various cost items as complex, imprecise and fuzzy in nature and by acknowledging quality as a fuzzy notion, a group of multiple experts (with one each from production, quality, maintenance and administration) are selected to determine the degree of importance of the cost items. In order to identify various cost items, associated with cost categories PAF checklist BS 6143: Part 2 (1990) is used as a standard. A team consisting of WM (head), AWM (coordinator) and three production operatives from each department is formed.

The information with respect to cost items is represented using linguistic terms namely UI *[Un-important], LI [Least important], FI [Fairly important], VI [Very Important] and CI [Critical]* as shown in Figure 6.5. For instance, under Appraisal costs, for costs A_1 (Receiving inspection) the linguistic definition related to importance of cost items provided by the experts is given by fuzzy numbers

(0.8, 0.9, and 1.0)

(0.9, 1.0, and 1.0)

(0.5, 0.6, and 0.7)

(0.65, 0.75, and 0.85), respectively

which after aggregation is transformed (using Chen's ranking) to obtain the corresponding fuzzy density values. For carrying out fuzzy operations these terms are translated using fuzzy numbers given by different experts. Consequently, the fuzzy numbers are assigned for each cost element and corresponding fuzzy density values with respect to them are determined. From Table 6.3 the values of fuzzy densities for the cost categories (A, P and IF), are treated as importance degree of items in performing fuzzy integrations.

To aggregate the information of objective evidence from various cost items for the six processes, approximations are carried out using same set of experts and same linguistic terms. Table 6.7 presents the approximated Fuzzy Number Representation (FNR) and equivalent Transformed Values (TV).These transformed values were used as objective evidence for computing fuzzy integral values. Using Equation 3.27 value of λ is determined. The objective evidence $h\ (y)$ values for each cost item, so obtained are rearranged in decreasing order with respect to corresponding fuzzy density values. Based on the new order and determined value of λ, fuzzy measure $g\ (A_i)$ is computed using recursive Equation 3.28. Finally fuzzy integrations are performed using Equation 3.29 and integral values are computed to obtain the respective ranking among the various processes under each quality cost segment. The results so obtained are presented in Table 8 and are graphically represented in Figure 6.12. As both degree of importance and objective evidence of the cost items are defined in interval [0,1] with membership degree varying from 0 to 1, therefore the resulting integral values should lie between 0 and 1.Greater the integral value, higher will be the confidence level and hence higher will be the priority for selection of the process .

Table 6.7 Fuzzy Definitions and Transformed Values for Cost Items

Process →		Feeding		Pulping		Washing	
CC	S	FNR	TV	FNR	TV	FNR	TV
PREVENTION	P_1	-	-	(0.6,07,0.9)	0.695	(0.1.0.25,0.4)	0.282
	P_2	-	-	-	-	-	-
	P_3	(0.1.0.25,0.4)	0.282	(0.1.0.25,0.4)	0.282	-	-
	P_4	(0.3,0.5,0.7)	0.500	-	-	-	-
	P_5	(0,0,0.2)	0.090	(0.6,07,0.9)	0.695	(0.3,0.5,0.7)	0.500
	P_6	-	-	(0.3,0.5,0.7)	0.500	(0.1.0.25,0.4)	0.282
	P_7	(0.3,0.5,0.7)	0.500	(0.3,0.5,0.7)	0.500	(0.75,0.9,1)	0.844
	P_8	(0,0,0.2)	0.090	(0.1.0.25,0.4)	0.282	(0.75,0.9,1)	0.844
	P_9	(0,0,0.2)	0.090	(0.3,0.5,0.7)	0.500	(0.1.0.25,0.4)	0.282
APPRAISAL	A_1	(0.6,0.7,0.9)	0.695	(0.3,0.5,0.7)	0.500	(0.3,0.5,0.7)	0.500
	A_2	(0.3,0.5,0.7)	0.282	(0.6,0.7,0.9)	0.695	(0.3,0.5,0.7)	0.500
	A_3	-	-	(0.1.0.25,0.4)	0.282	(0.75,0.9,1)	0.844
	A_4	-	-	(0.3,0.5,0.7)	0.500	(0.6,0.7,0.9)	0.695
	A_5	-	-	(0.3,0.5,0.7)	0.500	-	-
	A_6	-	-	(0.3,0.5,0.7)	0.695	-	-
				-			
FAILURE	F_1	-	-	(0.75,0.9,1)	0.090	(0.75,0.9,1)	0.090
	F_2	-	-	(0.6,07,0.9)	0.500	(0.6,07,0.9)	0.500
	F_3	-	-	(0.75,0.9,1)	0.695	(0.3,0.5,0.7)	0.500
	F_4	-	-	(0.3,0.5,0.7)	0.500	(0.6,0.7,0.9)	0.695
	F_5	-	-	-	-	(0.75,0.9,1)	0.844
	F_6	-	-	-	-	(0,0,0.2)	0.09
	F_7	(0.1.0.25,0.4)	0.282	(0.3,0.5,0.7)	0.500	-	-
	F_8	-	-	(0.75,0.9,1)	0.844	-	-

CC : Cost Category; S: Symbol; FNR: Fuzzy Number Representation and TV: Transformed Value

-Table 6.7 Contd-

Process →		Bleaching		Screening		Paper production	
P							
R	P_1	-	-	0.3,0.5,0.7)	*0.500*	-	-
E	P_2	-	-	(0.6,07,0.9)	*0.695*	(0.75,0.9,1)	*0.844*
V	P_3	(0,0,0.2)	*0.090*	-	-	(0.3,0.5,0.7)	*0.500*
E	P_4	(0,0,0.2)	*0.090*	(0.3,0.5,0.7)	*0.500*	(0.3,0.5,0.7)	*0.500*
N	P_5	(0,0,0.2)	*0.090*	(0.6,07,0.9)	*0.695*	(0.75,0.9,1)	*0.844*
T	P_6	-	-	-	-	(0.3,0.5,0.7)	*0.500*
I	P_7	(0.6,07,0.9)	*0.695*	(0.3,0.5,0.7)	*0.500*	-	-
O	P_8	-	-	(0.75,0.9,1)	*0.844*	(0.6,0.7,0.9)	*0.695*
N	P_9	(0.3,0.5,0.7)	*0.500*	(0.3,0.5,0.7)	*0.500*	(0.3,0.5,0.7)	*0.500*
A							
P	A_1	-	-	(0.75,0.9,1)	*0.844*	(0.3,0.5,0.7)	*0.500*
P	A_2	-	-	(0.3,0.5,0.7)	*0.500*	(0.3,0.5,0.7)	*0.500*
R	A_3	-	-	(0,0,0.2)	*0.090*	(0.6,0.7,0.9)	*0.695*
A	A_4	-	-	(0,0,0.2)	*0.090*	(0.6,0.7,0.9)	*0.695*
I	A_5	-	-	(0.3,0.5,0.7)	*0.500*	-	-
S	A_6	(0.3,0.5,0.7)	*0.500*	-	-	-	-
A							
L							
F	F_1	(0.6,0.7,0.9)	*0.695*	-	-	-	-
A	F_2	(0.3,0.5,0.7)	*0.500*	(0.75,0.9,1)	*0.844*	(0,0,0.2)	*0.090*
I	F_3	-	-	(0.3,0.5,0.7)	*0.695*	(0,0,0.2)	*0.090*
L	F_4	-	-		-	(0.3,0.5,0.7)	*0.500*
U	F_5	-	-	(0.75,0.9,1)	*0.844*	(0,0,0.2)	*0.090*
R	F_6	(0.6,0.7,0.9)	*0.695*	-	-	-	-
E	F_7	(0.3,0.5,0.7)	*0.500*	(0.3,0.5,0.7)	*0.500*	-	-
	F_8	(0.3,0.5,0.7)	*0.500*	-	-	-	-
				-	-		

CC : Cost Category; S: Symbol; FNR: Fuzzy Number Representation and TV: Transformed Value

Table 6.8 Fuzzy Integral Values for Processes

Processes	Appraisal Cost		Prevention Costs		Failure Costs	
	IV	R	IV	R	IV	R
Feeding	0.4690	5	0.4256	6	0.1047	6
Pulping	0.8121	1	0.6411	4	0.6679	3
Washing	0.7455	2	0.6990	3	0.7770	1
Bleaching	0.3000	6	0.5049	5	0.6111	4
Screening	0.6788	3	0.7689	2	0.7233	2
Paper Production	0.5760	4	0.7996	1	0.2820	5

IV- Integral Value and R -Ranking

6.5.1.1 Results and Discussion

From Table 6.8 it is observed that

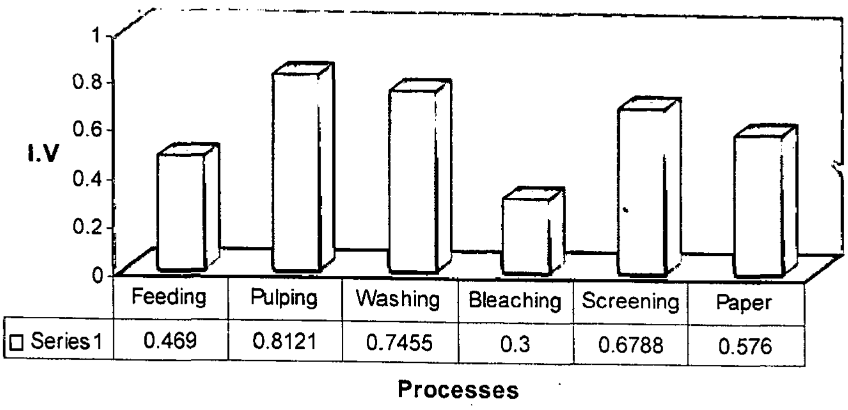
(i) Under *appraisal costs*, the maximum score is obtained by Pulping process (0.8121), followed by Washing (0.7455) and Screening (0.6788), which means that to reduce the non-conformances mainly due to lack of process control measures such as liquor concentration, time of cooking of chips and steam temperature in pulping process, interoperation checks and calibration of both production and inspection equipments are important elements to ascertain the quality of process under appraisal category.

(ii) Under *prevention cost category*, the highest score is obtained by Paper Production process i.e. (0.7966) which is closely followed by Screening system (0.7689). It means that investment in prevention activities such as process design, operator training and calibration of equipments will help to control non-conformities associated with the processes. For instance, training the operators about machine's structure, operation and common areas of bottlenecks will help to minimize uncertain and sporadic failures resulting in downtime. So, more stress should be given on quality planning activities, which include process reviews, and formation of quality improvement teams.

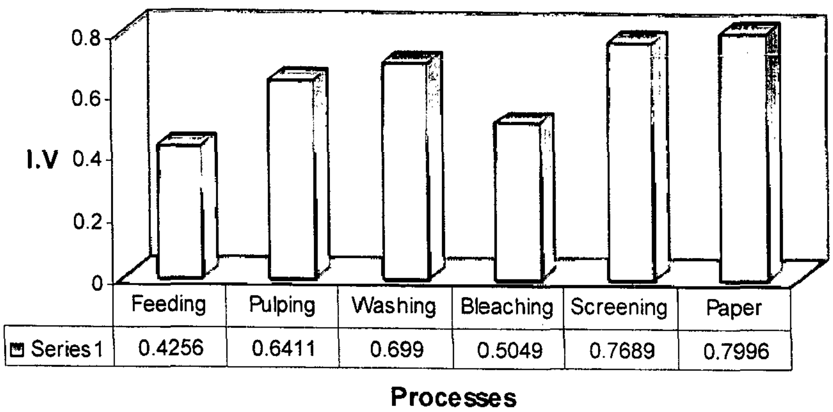
(iii) Under *failure costs*, the maximum score is obtained in case of Washing i.e. (0.777) which means that the problem of rework /scrap mainly occurs at later stage is basically due to improper washing of pulp. The blackness of the pulp if not completely removed, it will affect the quality (brightness) of the paper, which ultimately results in loss in profits/sales, as the paper produced have to be downgraded. In case of Screening process, which figures second with a score of 0.7233, adequate screening of waste material, foreign particles, knots and large insoluble fibers are more important. All these if not treated, add to process inefficiencies mounting to process costs. So investment in inspection and preventive maintenance activities will help in long way to reduce the scrap and rework.

After setting out the priorities for processes under each cost segment, the PCM approach can be successfully applied to

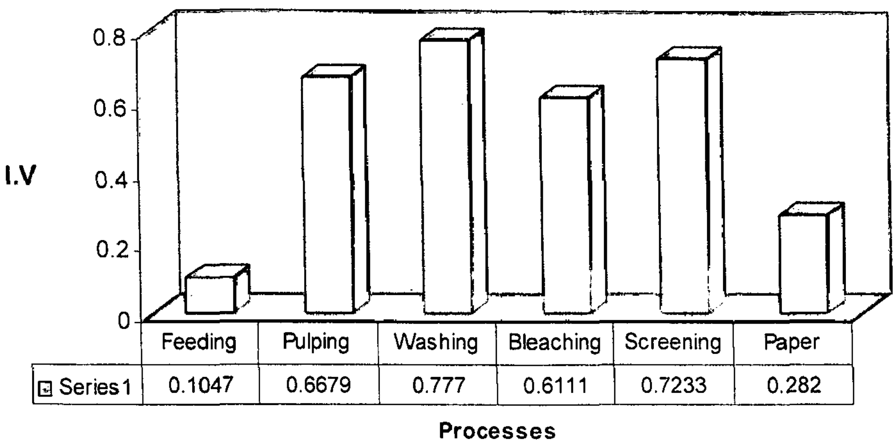
- Identify all the activities and parameters related to the processes
- Estimate both COC and CONC at each stage of the process
- Devise solution strategies/corrective action plans to reduce the losses due to CONCs



(a)



(b)



(c)

Figure 6.12 Graphical Representation of Integral Values (a) Appraisal (b) Prevention (c) Failure Costs

6.6 Concluding Remarks

The main aim of the research issues addressed in the chapter was to acknowledge the need to attach fuzziness to notion of "quality" in order to deal with imprecise, vague, and complex information related to cost items under PAF segments. By using the fuzzy principles for information elicitation and aggregation, it is shown that managers can prioritize quality based taxonomies in more realistic manner. Once the top priority areas for improvement are recognized, Cost Driver Analysis (CDA) of significant activities can be carried out. This will help to direct improvement efforts to the cause of cost and avoid treating the symptoms. For example, conducting an inspection of incoming material is non-value adding activity and its cost driver will be quality of material received from suppliers. If we have sufficient confidence in the quality of material received from suppliers we may conduct sampling inspection, even no inspections for incoming material, otherwise we may need 100% inspection. Therefore, the best way to reduce the efforts of incoming material inspection is to choose the supplier that provides better quality of material or to help suppliers to establish quality control/assurance programs. As shown in the study that with the revival of quality costing program after working upon prioritized areas, a progressive change in Quality costs with respect to sales is observed. Thus, in general the approach presented in the study to implement quality cost accounting system can be mimicked by other organizations.

In the second part of chapter a novel approach to implement quality costing system based on process cost modeling (PCM) approach, after judicious selection of the processes is discussed. Thus, the proposed approach if implemented successfully it will help the management to obtain true picture regarding the processes and direct efforts in right direction, which might help the organizations to bring handsome rewards after careful investments in quality costs.

CHAPTER 7

RESOURCE OPTIMIZATION AND ALLOCATION*

7.1 INTRODUCTION

Traditionally many companies employed fire-fighting approach called reactive maintenance for maintenance activities, which means that as and when equipment fails to perform, repairs are carried out. This practice not only increases the total down time but also hampers the production. With the advancement in technology, this strategy has been replaced by proactive and aggressive maintenance strategies as discussed in chapter 5. A proactive approach calls for preventive and predictive maintenance to prevent sudden sporadic or chronic failures. In present times because of automation and large-scale mechanization, higher plant availability, better product quality and long equipment life had assumed considerable significance. The process industries are particularly vulnerable to plant, process, and product failures. Among the main reasons are the complexities of the technology involved, the range of products, and the often-subtle nature of compositional changes, process shifts and hidden product flaws (Witherell, 1991). The effective use of manpower with planned maintenance and repair schedules is essential for reliable performance of the system and the consequent sub-systems. Due to the high cost of down time in process industries, it is vital to estimate and allocate the required resources properly and efficiently (Knapp and Mahajan 1998, Segelod 2002). To this effect the chapter provides a mathematical model based on dynamic programming to optimize the maintenance and manpower cost decisions with respect to various interrelated sub-systems in a paper mill. A recursive approach is used to solve the complex optimization problem related to facility planning/resource management of the paper mill.

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reating the problem as Multi-Stage Decision Making (MSDM) the complete industrial system has been ıodelled as a 8 stage [Stage-1 (Feeding), Stage-2 (Pulping) , Stage-3 (Washing), Stage-4 (Screening), tage-5 (Bleaching), Stage-6 (Forming), Stage-7 (Press) and Stage-8 (Dryer)] system in series operating nder constraints such as availability of maintenance resources, manpower etc.

.2 MATHEMATICAL MODEL

ymbols and Notations Used

j	Resource allocated to the activity *j*
	State function (Total resource allocation)
0	Optimal resource allocation
	Lagrange's multiplier [Budgeting coefficient]
j	Reliability of successful operation
s	Cost of sales
	Coefficient for component cost
	Coefficient of manpower cost

Let us assume that at any stage say, j a decision is to be made regarding the amount of resource be allocated to the activity *j* (i.e. C_j). The decision for the K^{th} *i.e.* the last stage can be made on the ısis of allocations made in previous *k-1* stages. The optimum allocation ($C_{j,\ J=1,2,3,4,k}$) would depends ›on the total quantity of the resource ($\in$) available for allocation to the *K* stages. If stage *j* comprises X_j components with reliability P_j, then the resource allocated at the j^{th} stage will be C_j., whose value is ven by $Cj = F_1.Xj$.

ıe reliability of successful operation at the j^{th} stage, i.e. $R_j(C_j)$, is given by Equation (7.1)

$$R_j(C_j) = [1-(1-P_j)^{Cj/F_1}] \qquad (7.1)$$

nce all the *K* stages are in series, the overall reliability of the system is given as

$$R_s = R_1.R_2..........R_j = \prod_{j=1}^{k} R_j(C_j) = \prod_{j=1}^{k}[1-(1-p_j)^{C_j/F_1}] \qquad (7.2)$$

Or, it can be expressed as

$$\ln R_s = \ln R_1 + \ln R_2 + ... + \ln R_j = \sum_{j=1}^{k} \Phi_j(c_j) = Z(say) \qquad (7.3)$$

Where; $\Phi_j(c_j) = \ln R_j(c_j) = \ln[1-(1-p_j)^{C_j/F_1}]$

Thus, the problem is formulated as

$$Maximize\, Z = \sum_{j=1}^{k} \Phi_j(c_j), c_j \geq 0, \quad j = 1,2,3,..........,K \text{ , subjected to} \qquad (7.4)$$

$$\sum_{j=1}^{k} c_j x_j \leq c_1$$

$$\sum_{j=1}^{k} m_j c_{j'} \leq c_2 \quad \text{And} \quad c_1 > c_2$$

Where;

C_1 : the total maintenance resource available and

C_2 : the total available manpower budget for maintenance.

X_j and M_j are the number of components and manpower, respectively at the, at the j^{th} stage and are known before hand.

Since the manpower required for maintenance depends upon number of units/components at stage j, the manpower cost $C j'$ can be taken proportional to C_j, i.e. $C j' = F_2 C_j$ (i.e. For a greater number of components the cost will be more, hence the maintenance manpower cost will also be more, in general). F_2 is known as the coefficient of manpower cost and lies in range $0<F_2<1$. For computational simplicity, the Lagrange's multiplier (λ) is introduced to reduce the problem to single constraint as

$$Maximize\ Z_1 = \sum_{j=1}^{k} \Phi_j(c_j) - \lambda \sum_{j=1}^{k} m_j\, c_j\, F_2(c_j > 0) \text{ Subjected to } \sum_{j=1}^{k} c_j x_j \leq c$$

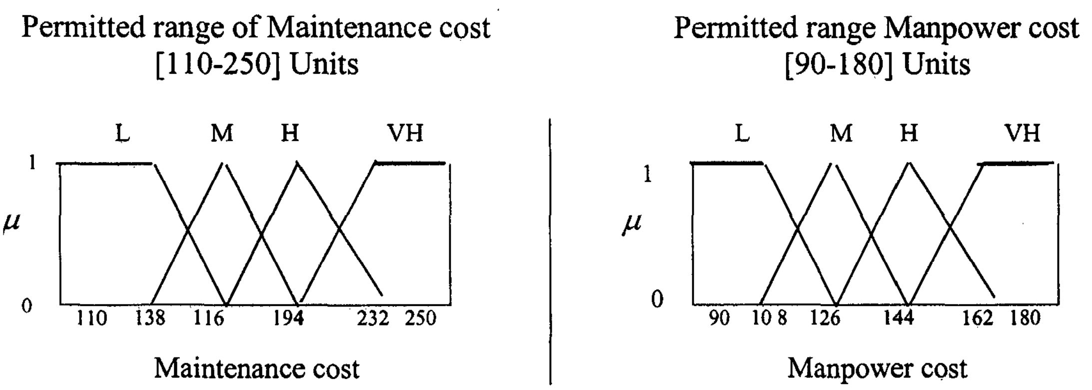
e recursive equation (7.5) for the n^{th} stage problem obtained is as

$$(\varepsilon) = Max\{\ln[1-(1-p_j)^{C_j/F_1}] - \lambda m_n c_n F_2 + f_{n-1}(\varepsilon - c_n x_n)\} \quad (7.5)$$

Based on expert judgment with respect to factory conditions the values of F_1 and F_2 are taken as 5 d 0.6 respectively. From the quantitative analysis for the respective subsystems discussed in chapter 4, : crisp output values of reliability have been taken. The entire data including the number of mponents and number of manpower with permitted range (shown with the help of fuzzy membership ictions) of maintenance and manpower cost is presented in Table 7.1

Table 7.1 Input Data for Resource Allocation

ages	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
iit reliability	96.6	93.50	95.79	94.90	93.20	91.75	91.36	94.01
) of components	5	8	8	6	4	6	7	5
) of personnel	5	6	3	5	4	4	5	4



7.2.1 Allocation Results

Following the algorithm steps as shown by the flowchart [Appendix, A-7(a)], starting with the first stage, the value of allocation with λ=0.001, (known as budgeting coefficient), for which the state function (ε) is maximum, is determined using the recursive relationship Equation 7.5. Since the budget is the controlling parameter, therefore, in order to seek or arrive at optimal solution regarding resource allocation, the new value of λ are chosen i.e. 0.002, 0.003, 0.004 and 0.005 respectively and the allocation is repeated for each stage. The results for all the stages from stage1 to stage 8 are shown in Tables A-7(i)-(viii) in the Appendix, A-7(b) and the summarized results at different values λ are presented as below (Table 7.2).

7.2.2 Economic Analysis

The results presented in Table 7.2 shows that with increase in the value of reliability, the maintenance and manpower cost also increases, which means more money is required for both. Hence, in order to find minimum run point break-even analysis has been performed.

The cost of sales (C_s) is computed from following relation.

$$C_s = [R_{op} \times (C_m + C_{mp}) + C_f] \quad (7.6)$$

Where: R_{op}: Optimum Reliability

C_m: Maintenance cost

C_{mp}: Manpower cost

C_f: Fixed cost

Considering that sales volume is proportional to optimum value of system reliability and assuming that fixed cost is about 30% of the total cost and the sales cost 10 units per ton of production. The break-even oint (no profit-no loss situation) is found at 35% system reliability, as shown in Figure 7.1. Depending pon the plant /units maintenance strategy, the managers can set the optimal level of reliability to enerate targeted profits (as shown in Table 7.3).

Table 7.2 Summarized Allocation Results

λ (Budgeting coefficient)	**0.001**	**0.002**	**0.003**	**0.004**	**0.005**
Allocation (units)	27,43,44,33, 27,39,41,30	23,35,37,27, 23,33,34,26	21,30,33,24 ,20,29,29,23	19,27,30,22, 19,26,26,21	18,24,28,20, 17,24,24,19
Maintenance Cost(units)	284	238	209	190	174
Manpower Cost(units)	198	166	146	133	121
Optimum Reliability (%)	0.8562	0.7432	0.6386	0.5555	0.4761
Cost of Sales (units)	650	547	476	427	388
Earning of Sales(units)	856	743	638	555	4761
Profit (units)	205	194	161	127	87

Table 7.3 Optimal Level of Reliability with Targeted Profit

Targeted Profit (units)	205	194	161	127	87
Optimal Reliability	85.62%	74.32%	63.86%	55.55%	47.61
λ **(Budgeting Coefficient)**	0.001	0.002	0.003	0.004	0.005

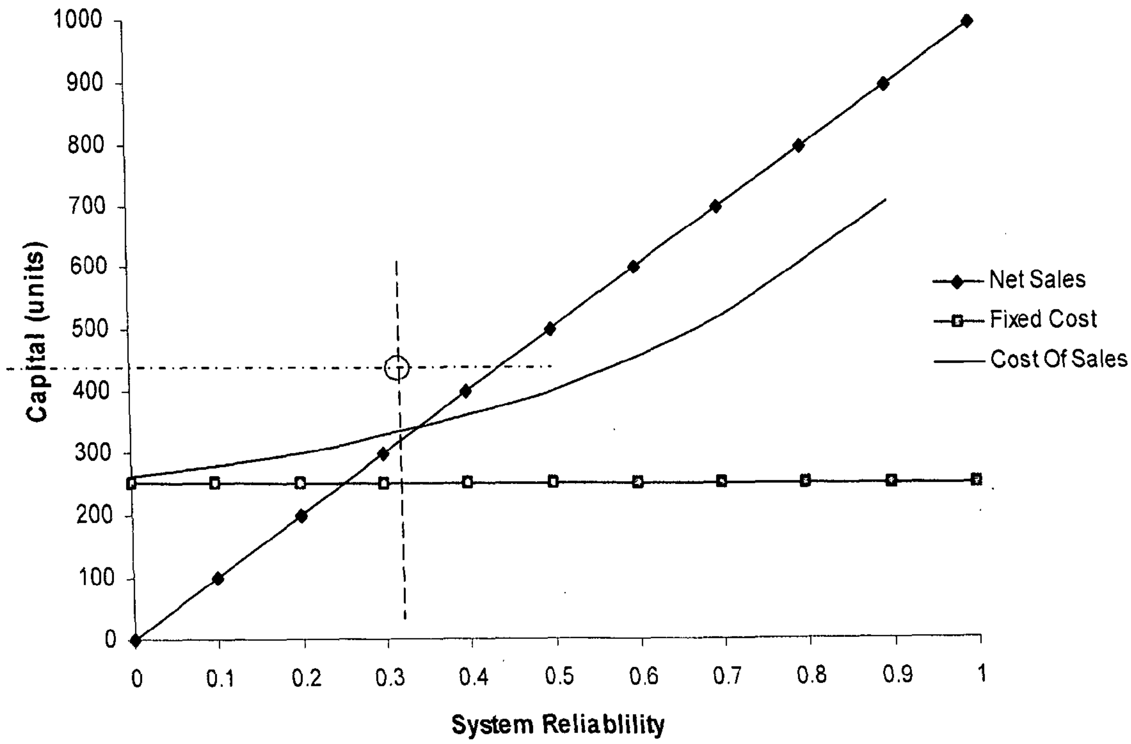


Figure 7.1 Break-Even (Optimal Run Point)

7.3 Concluding Remarks

In the chapter, a dynamic programming approach to optimize the maintenance and manpower cost decisions with respect to resource allocation in the paper mill has been developed. The approach can be used to allocate resources in other process industries (such as sugar, fertilizer, petrochemicals etc.) usually operating under the constraints of maintenance resources, manpower etc. Starting with the first stage of the process and continuing up to the last stage, the allocations at different values of budgeting coefficient called 'λ'i.e. at 0.001, 0.002, 0.003, 0.004 and 0.005 for which the state function ($\mathcal{E}$) is maximum can be determined using the recursive relationship. Depending upon the available budget constraints, the managers can decide upon the respective allocations. For instance, as shown in the study to achieve the reliability of 85%, 284 units of maintenance cost and 198 units of manpower cost is required if the budgeting coefficient is 0.001. Further, in order to find out minimum run point i.e. no profit-no loss situation for the plant, economic analysis has also been carried out. Based upon the plant /units maintenance strategy the managers can set the optimal level of reliability to generate targeted profits (Table 7.3).

Chapter 8

SUMMARY OF MAJOR RESEARCH CONTRIBUTIONS AND SCOPE FOR FUTURE WORK

8.1 INTRODUCTION

The chapter presents a comprehensive summary of major research contributions made through in previous chapters of this thesis. It also outlines the managerial implications for the purpose of implementation of recommendations related to QRM aspects in totality. Finally, the suggestions for future work to extend the frontiers of the research reported in the thesis have been outlined.

8.2 SUMMARY OF MAJOR RESEARCH CONTRIBUTIONS

The research was attempted to facilitate the reliability/ analysts / practioneners/engineers to study, characterize, measure and analyze the uncertain behavior of system using fuzzy methodology. An extensive review of literature was conducted to identify the gaps and relevant research issues in the areas of quality, reliability and maintainability. Based on the critical review of literature with respect to QRM issues related to production systems, it was felt that the managers are always confronted with the problem of decision making because of imprecise, incomplete and subjective information they get through various sources. To this effect the study makes use of fuzzy set methodology, as an effective tool to solve the problems related to quality, reliability and maintainability aspects.

8.2.1 Quality Aspects

The following conclusions can be made with respect to major research contributions from the research carried out in the Chapter 6 on issues related to quality costing.

(1) While conforming on the results of prior research on practice of quality costing approaches and the problems faced by the companies in implementing a quality management system, the proposed method is a step forward application of fuzzy set theory to synthesize and aggregate the quality cost information, which can help them to implement QCAS successfully. Though the results still depend upon the analysts/experts judgment and the quality of the information derived from different sources, as with any modeling framework one has to exercise great care to ensure that the data and inputs presented to the method are of good quality without which the results could be biased. In particular, the fuzzy logic approach as discussed in the study mainly concerned with three issues, namely

(a) Translation of linguistic/subjective assessments related to quality cost information under various cost segments into Fuzzy Number Representation (FNR).

(b) Operation on Triangular Fuzzy Numbers (TFN).

(c) Information aggregation using Choquet Fuzzy Integral (CFI).

(2) Quality costs provide an important yardstick and mechanism to measure and monitor the performance of quality costing system. There are wide variety of ways in which organizations can set about collecting and measuring quality costs. However, whether the approach is based on the PAF categorization (BS.6143: Part 2 [1992]) or it is activity-based to match the ways in which a business operates (BS.6143: Part 1 [1990]) or it utilizes the price of conformance and price of non-conformance, or is based on any other form of categorization such as those discussed in the study, the main and most important thing is to facilitate the management in strategic decision

items is very essential to receive full, true and the actual data related to the quality costs. Owing to its sound logic, effectiveness in quantifying the vagueness and imprecision in human judgment, the fuzzy set theory is applied to elicit expert opinion to cope with complex, uncertain and subjective information with respect to cost items. These relationships can be synthesized using well-defined and established fuzzy set principles.

(3) By using the fuzzy principles for information elicitation and aggregation with respect to the selected alternatives, the managers can prioritize areas for improving the process of registration and analyzing the costs in PAF model.

(4) Thus, using the principles of Fuzzy methodology, and acknowledging fuzziness attached to notion of "quality", the holistic framework developed to implement Quality costing system in industry successfully addressed the imprecise, complex and subjective information related to cost items under PAF cost categories.

8.2.2 Reliability Aspects

In the present work a structured and methodological framework based on knowledge based approximate reasoning techniques i.e. fuzzy methodology and grey relation analysis is developed to model, analyze and predict the system behavior in both qualitative and quantitative terms. The conclusions made from the work presented in Chapter 4 are summarized below:

(1) The qualitative analysis of system using Root Cause Analysis (RCA) and Failure Mode Effect Analysis (FMEA) helps to create a knowledge base to deal with problems related to process/product unreliability by listing out all possible failure causes. The proposed fuzzy based decision support system known as FDMS not only addresses the seriously debated disadvantages associated with traditional procedure for conducting FMEA but also integrates expert judgment,

experience, and expertise in more flexible and realistic manner using well-defined membership functions.

(2) In the grey relation analysis the introduction of weighting coefficient provides the analyst the enough flexibility to decide which factor among failure of occurrence (O_f), likelihood of non-detection (O_d), and severity (S) of failure is more important to the analyst, the outcome of which provides valuable information with respect to risk associated with the system components. Thus, in totality it is concluded from the study that the proposed framework which makes use of both fuzzy and grey approach in system failure engineering will help the system / reliability analysts to

- analyze the complex behavior of industrial systems
- model and predict the behavior of industrial systems in more realistic manner
- plan suitable maintenance practices /strategies for improving system performance
- provide an effective way to combine expert knowledge and experience for conducting FMEA
- deal with the notion of uncertainty and imprecision related with information provided in reliability databases more realistically

(3) The quantification of various reliability parameters with fuzzy, defuzzified and crisp results helps the maintenance experts /managers/practioneners to predict the behavioral dynamics of the respective units more realistically. Depending upon the value of confidence factor (alpha), the analyst(s) can predict the reliability measure for the system(s) and take necessary steps to improve system performance.

(4) The problem of resource allocation to various units of paper mill solved using dynamic programming in Chapter 7 (by treating the problem as multistage decision making) will assist the maintenance /plant engineers to estimate maintenance resources, manpower etc. and

also to optimize the maintenance and manpower cost decisions with respect to various sub-systems in a paper mill. Based upon the plant /units maintenance strategy, the managers can set the optimal level of reliability to generate targeted profits. The technique can be used to solve problems related facility planning / resource management, inventory control, network analysis and job shop scheduling etc.

(5) The study has successfully incorporated a unified (both qualitative and quantitative) approach to evaluate and assess system failure behavior using fuzzy methodology because of its sound logic, effectiveness in quantifying the vagueness and imprecision inherent in human judgment. Though the results still depends upon the analysts/experts judgment and the quality of the information derived from different sources, as with any modeling framework one has to exercise great care to ensure that the data and inputs presented to the method are of good quality without which the results could be biased.

8.2.3 Maintainability Aspects

Numerous authors had studied and worked on maintainability aspects related to production systems in industries. Currently, the majority of maintenance planning is based on mathematical optimization. Added to its disadvantage various traditional mathematical & statistical models, needs large amount of data and even if data is available, it is often inaccurate and thus, subjected to uncertainties. Further, age, adverse operating conditions and the vagaries of manufacturing /production processes affects each part/unit of system differently. However, it may be difficult or even impossible to establish rational database to accommodate all operating and environmental conditions. Keeping in view the above listed challenges the study attempts to provide both theory and methodology for selection of suitable maintenance strategy in process industries.

(1) In general, there are number of equipments associated with industrial process facilities such as compressors, evaporators, pumps, air coolers, heat exchangers etc. and maintenance managers are always confronted with the dilemma of adoption and practice of suitable maintenance strategy. In the proposed methodology a Multi-Input Single-Output (MISO) model based on Fuzzy linguistic approach is developed which will definitely help the managers to select the most informative and efficient maintenance strategy for each piece of equipment or system as it successfully integrates fuzzy linguistics with the database obtained through log books, historical records, equipment manuals and expert judgment.

(2) In the second part of chapter 5 the concept of TPM has been successfully employed in a semi automated paper machine cell of a company. It is observed that a well conceived plan for TPM implementation not only improve the equipment efficiency and effectiveness but also brings appreciable improvements in other areas of plant. It creates cohesive small group autonomous teams and increases the skill and confidence of individuals. It results in minimization of customer complaints, reduction of inventory levels, and increases the quality production rates, as well as sales and profit status. However, for continuous improvement of various performance indices (Kaizen Improvements, Skill Upgrading, MTBF, Accident Prevention, Cleaning Time, OEE, AOQL Level, Defect Rate, and Rework Percentage etc) the following preventive measures should be initiated:

- ***Data collection and processing:*** To achieve more realistic results, use of computerized system for data collection and processing should be done which is at present done manually.
- ***Employee skill upgrading:*** Skill upgrading is a continuous effort and all autonomous maintenance, planned maintenance and focused improvement team members should be well conversant with the applications of why-why and PM analyses toward

accomplishment of more 'Zero' cases i.e. 'Zero' accident, 'Zero' defects. It will not only results in continuous skill development and skill transfer to create more easy-to-operate equipment environment but also in development of good , harmonious and safe workplace environment .

- ***Total quality:*** Better quality can be achieved through, Zero defects rate and attaining lower AOQL level. Further reduction of defect rates and achievement of zero cases can be done by expanding quality management activities to all workstations through the expansion of quality approach.
- ***Safety and environment***: The incorporation of environment safety and health awareness into TPM activities will help to develop eco-friendly equipment and processes which is must to achieve ISO 14000 certification.

In the third part of the chapter on maintenance decision making an application of Non homogeneous Poisson point process models to optimize maintenance decisions based on cost dimensions model is discussed to help the mangers in predicting / forecasting the time for repair or replacements of vital components associated with the paper machine.

8.3 MANAGERIAL IMPLICATIONS OF THE RESEARCH

The important managerial implications of the present research are to enable the managers/ practioneners / researchers to define, measure, analyze and predict the uncertain, imprecise and subjective information associated with QRM aspects related to the production systems. The major managerial implications are summarized as under:

(i) After analyzing the system with the help of RCA, the maintenance managers can develop better insight into the system constituents, their function, failure mode and its effect on system performance. The development of proposed FDMS and grey relation approach for conducting FMEA will not only help them to conduct failure mode effect analysis of the system but also to model the uncertainties / ambiguities associated with the traditional FMEA.

(ii) Maintenance managers / practioneners are always confronted with the problems of selection of suitable maintenance mix for the component/part/system. The development of both theory and methodology for solving the maintenance mix problem using Fuzzy linguistic methodology will definitely help them to make decisions. A step by step approach to implement TPM as a maintenance strategy will prepare the managers to face the challenges put forward by globally competing economies. TPM implementation not only leads to increase in efficiency and effectiveness of operations but also prepares the plant to meet the challenges put forward by globally competitive economies and to achieve World Class Manufacturing (WCM) status. The step by step program (discussed in chapter 5) can be mimicked by various process and product industries to improve the efficiency and effectiveness of their operations. Thus, in totality managers can employ the TPM activities to improve the

- Overall plant's productivity (i.e. more effective operation and resource utilization)
- Throughput rate (by quicker action/reaction to failure symptoms leading to reduced downtime)
- End-product quality (through better-maintained plant and machines)

(iii) The quantification of various reliability parameters in terms of fuzzy, defuzzified and crisp results helps the reliability analysts /engineers to predict the behavioral dynamics of the respective units more realistically. The methodology will assist the managers to

- carry out design modifications, if any, required to achieve minimum failures
- help in maintenance (repair and replacement) decision making

(iv) In order to meet the challenges of competitive global economy by improving the quality of products or services delivered, a framework to implement and sustain QCS developed in the present study will help the managers to

(i) properly identify the set of alternatives required to define the taxonomy of quality-based investments

(ii) set-up both exogenous and endogenous quality priorities

After setting up a successful QCS, the managers can use it as

- *Performance indicator*: The QCS helps in promoting quality as a business parameter by comparing quality cost indices
- *Planning and control tool*: QCS provides a means for planning and controlling future quality costs by ensuring that the project tasks are completed with in time
- *Budgeting tool*: Quality costs can be used as guide to budget both short and long term actions required to improve the quality of products /processes

(v) To take care of QRM aspects in totality with respect to production systems, an optimization model based on multi stage dynamic programming formulated in the study for resource allocation will help the managers to optimize maintenance and manpower decisions related to a particular system /or subsystem.

8.4 SCOPE FOR FUTURE WORK

The method of analysis, design and optimization of QRM aspects in the production systems can be extended in the following directions:

(i) Similar studies can be extended to evaluate system behavior in other process industries (petroleum, food processing, chemical, sugar etc.). A holistic analysis using FM can uncover various kinds of problems, in the area of quality, reliability and maintainability which needs the management attention.

(ii)The work can also be extended to devise methodology

- For conducting cost benefit analysis.
- For conducting operational capability studies.
- For developing inventory and spare parts maintenance management system.
- For repair and replacement decisions related to critical parts/components associated with the system.

(iii) Planning of suitable maintenance practices /strategies for improving system performance after understanding the behavioral dynamics associated with functioning of systems.

(iv) Apart from QRM issues, the work can be extended to take care of other aspects such as safety and productivity related to production systems. Also, the application of various innovative management practices in unison with quality, reliability, and maintainability aspects can be practiced.

(v) The technique used to work out resource allocation problem can be used to solve problems related with facility planning / resource management, inventory control, network analysis and job shop scheduling etc.

8.5 CONCLUDING REMARKS

It is claimed that the work presented in the thesis provides a novel approach to deal with quality, reliability and maintainability aspects of the production systems. From the study following conclusions can be made

1. The development of FDMS and grey relation approach not only integrates subjective judgments and expertise of experts in more realistic and flexible manner but also addresses the serious limitations of traditional FMEA.
2. To deal with the maintainability issues related to the system, the study provides a framework to implement TPM and a MISO model to select suitable maintenance strategy with respect to failure causes.
3. The quantification of system parameters in terms of fuzzy, crisp and defuzzified values with the help of the fuzzy methodology will help the system managers to understand the system behavior more realistically.
4. The framework to implement and sustain QCS developed in the present study will help the managers to (i) properly identify the set of alternatives required to define the taxonomy of quality-based investments (ii) set-up both exogenous and endogenous quality priorities and finally to meet the challenges of competitive global economy.
5. Further to take care of QRM aspects of system collectively, the resource allocation model developed in the study provides necessary safe guards.

It is expected that the research issues discussed in the study will prove to be helpful to the system managers/practioneners in improving the system performance and to meet the challenges put forth by global competition. Though, the outcome of the proposed approaches used to solve the various issues related with QRM aspects still depends upon the analysts/experts judgment and the quality of the information derived from different sources, as with any modeling framework one has to exercise great care to ensure that the data and inputs presented to the method are of good quality without which the results could be biased.

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A-3(i) Illustration for Developing Petri Net Model from its Equivalent Fault Tree Model

Figure A-3(i) shows a pumping system and the Figure A-3(ii) represents the fault tree model of system. To represent relationship among various events in a system in a similar manner as fault tree mo represents the equivalent Petri net model for the system is developed as shown in Figure A-3(iii).

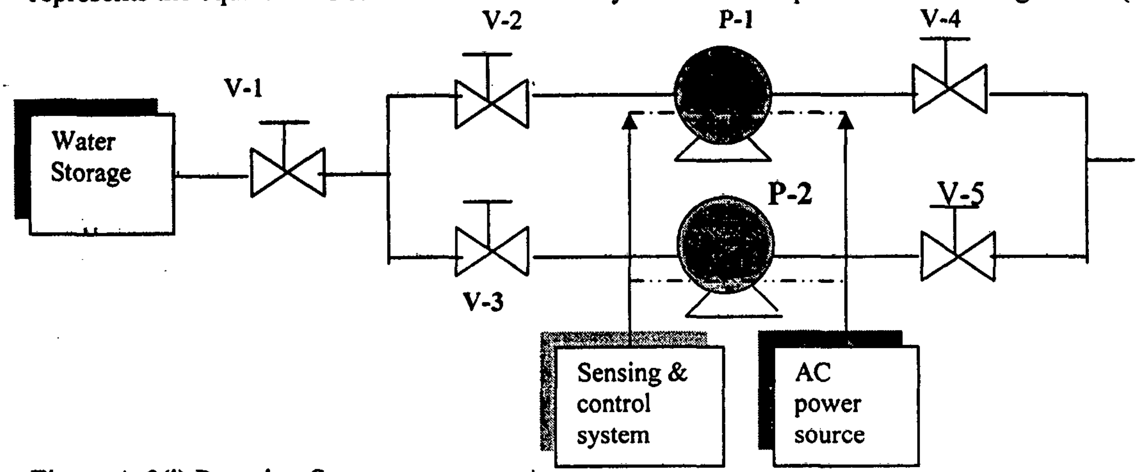


Figure A-3(i) Pumping System

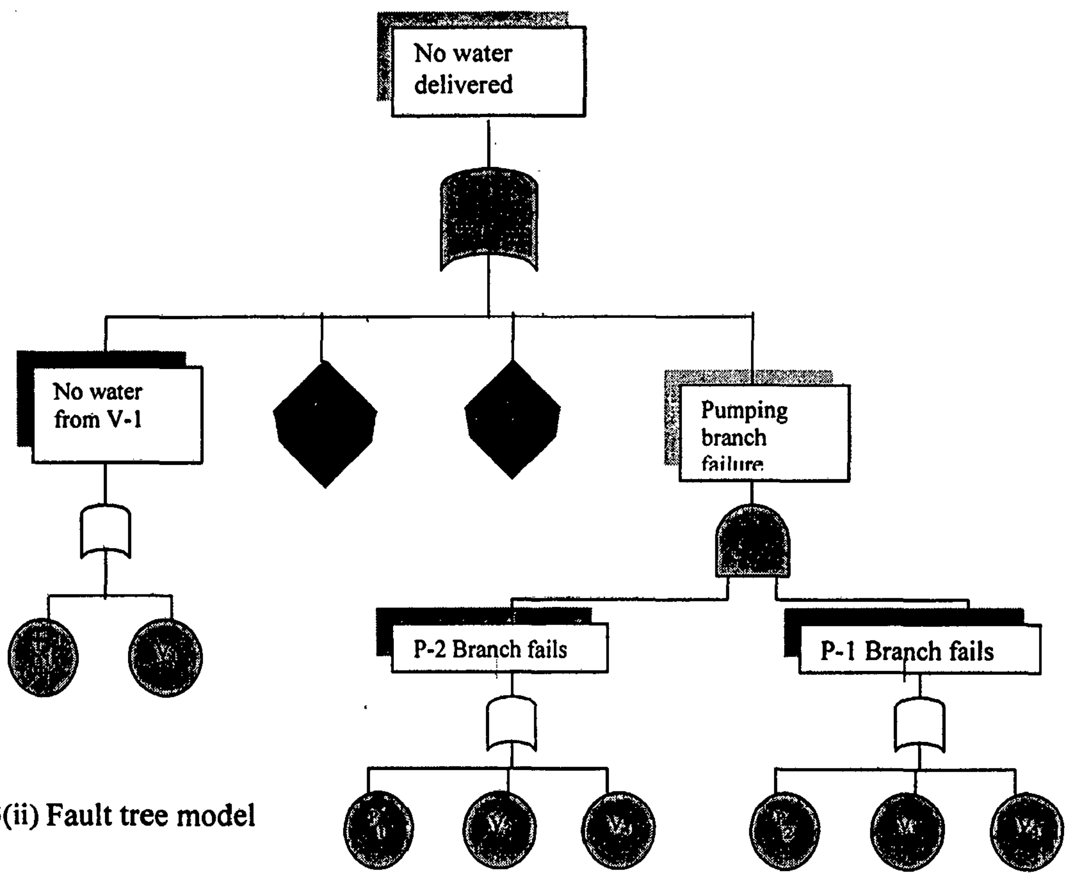


Figure A-3(ii) Fault tree model

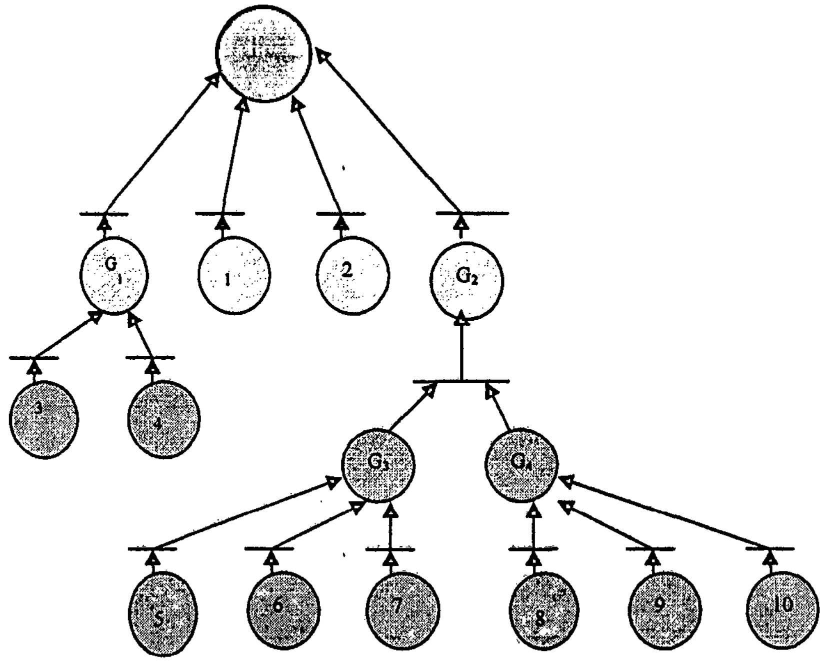


Figure A-3(iii) Petrinet Model

Appendix A-3(iv) Illustration for Developing Petrinet Model

The absorption property of Petri nets for the above model (static condition) is illustrated in A-3(iv)

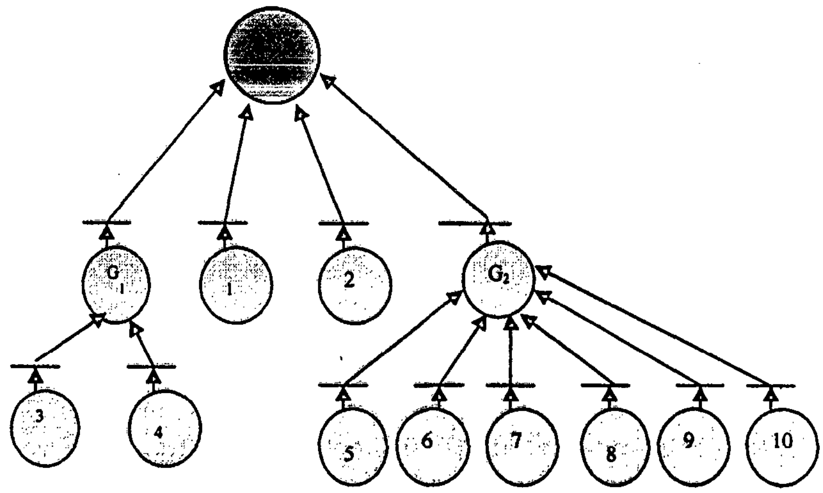


Figure A-3(iv) Petrinet Model after Absorption

The application of matrix method to determine minimal cut set and path sets for the system showr in Figure A-3(iii) is presented as below.

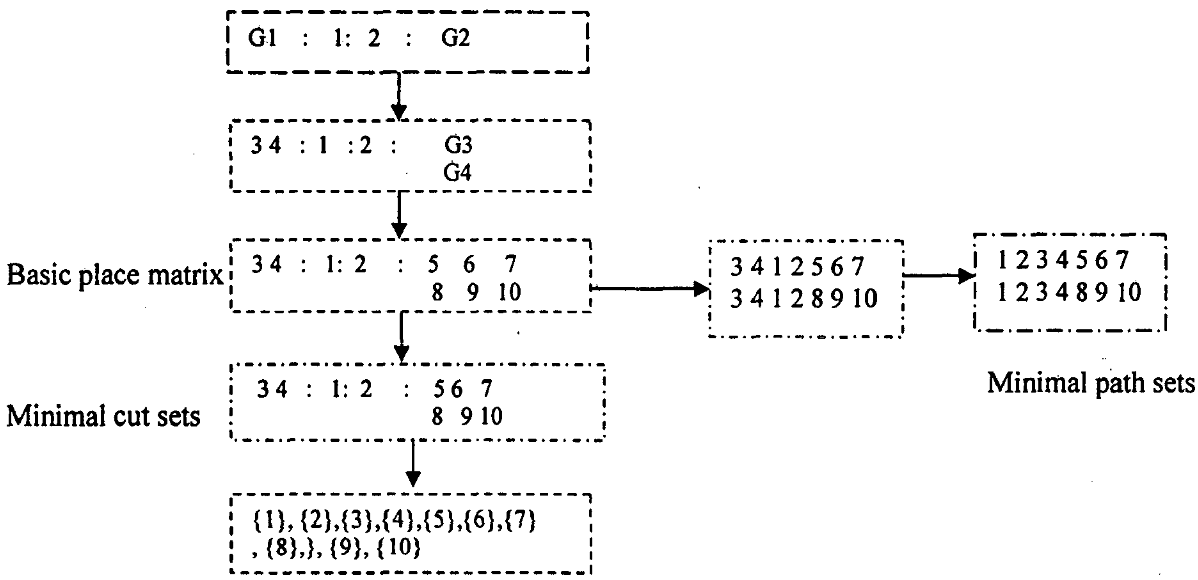


Figure A-3(iii) Minimal Path and Cut Set Determination (using matrix method)

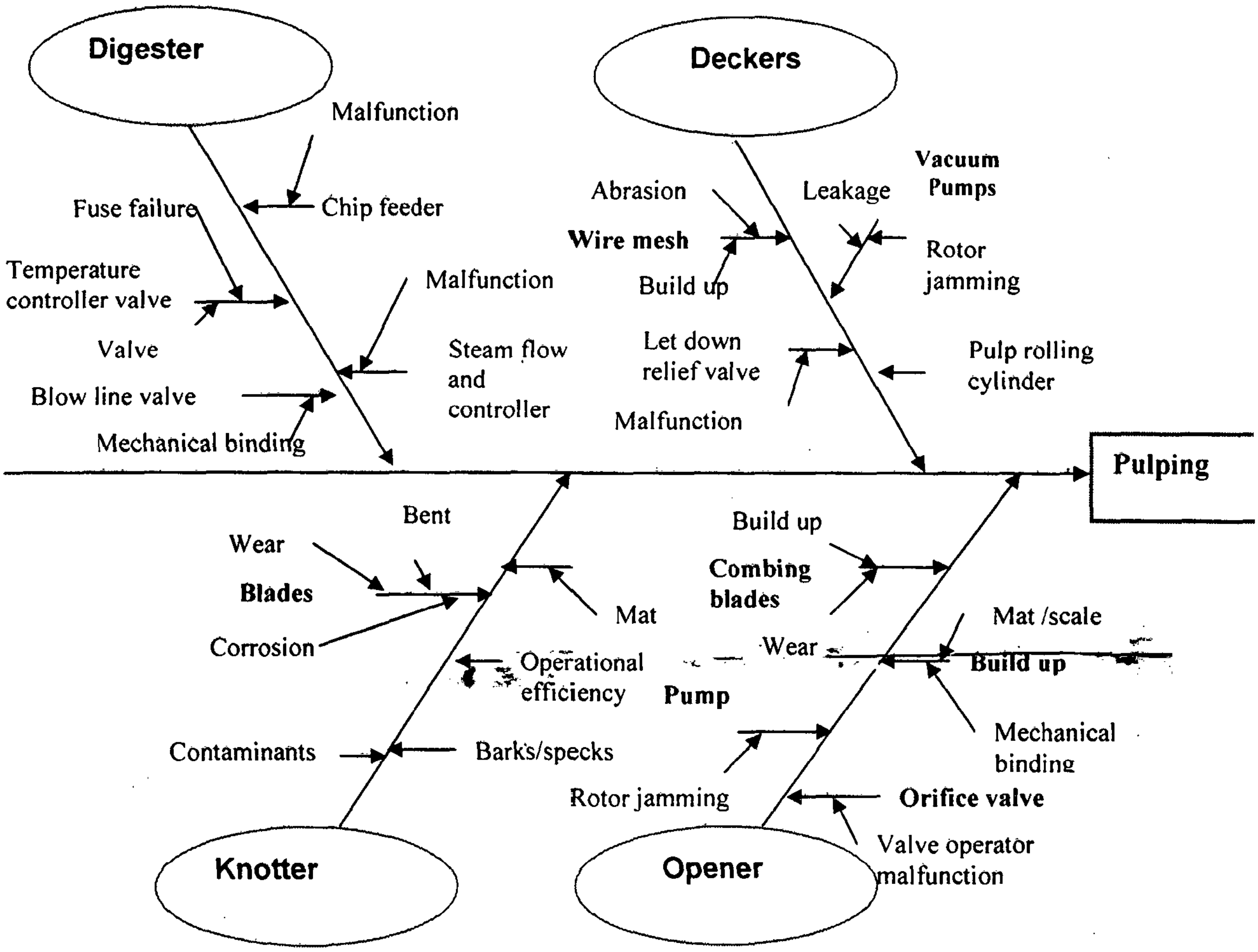


Figure 4.9 Root Cause Analysis [Pulping System]

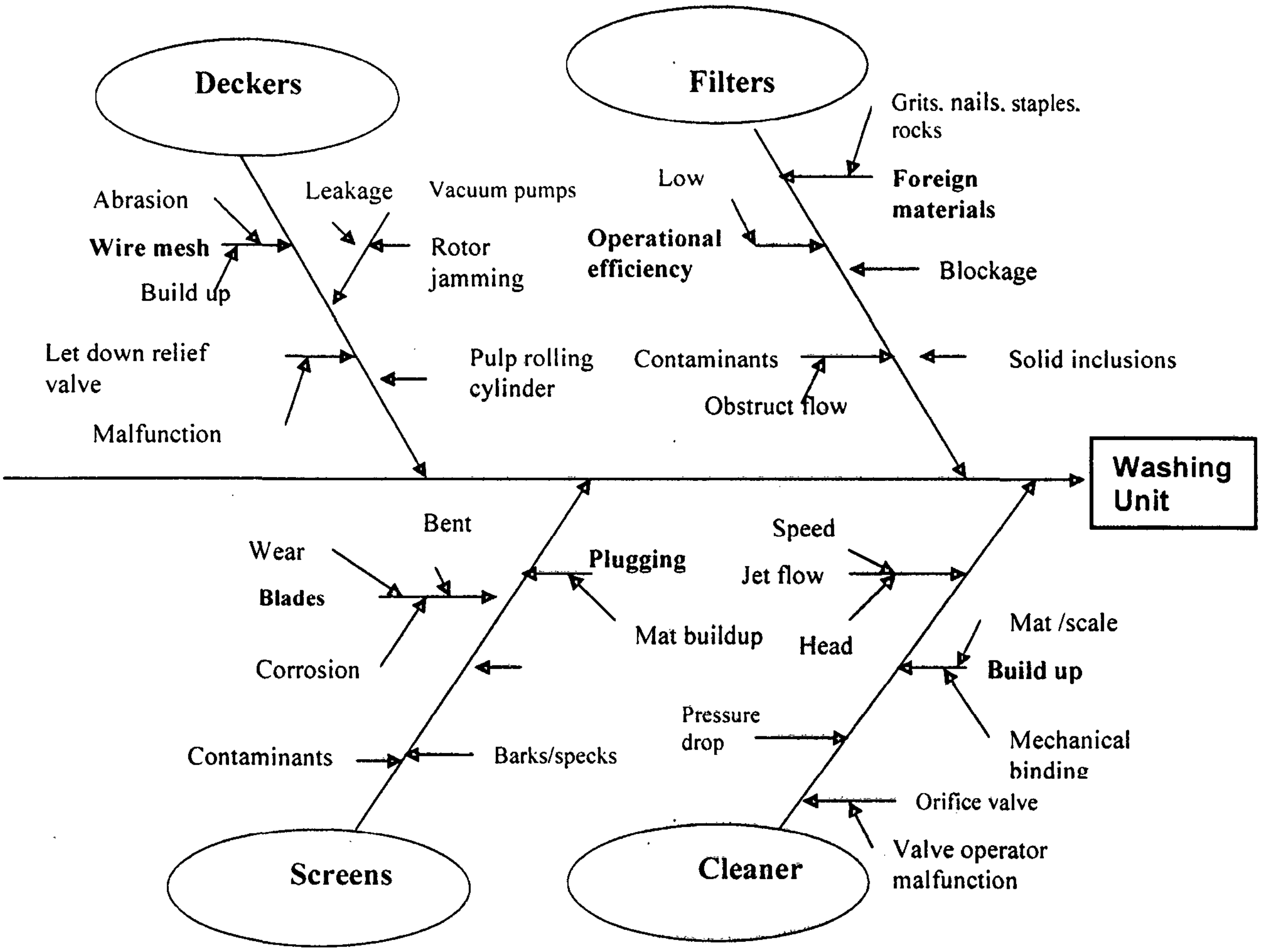


Figure 4.10 Root Cause Analysis [Washing System]

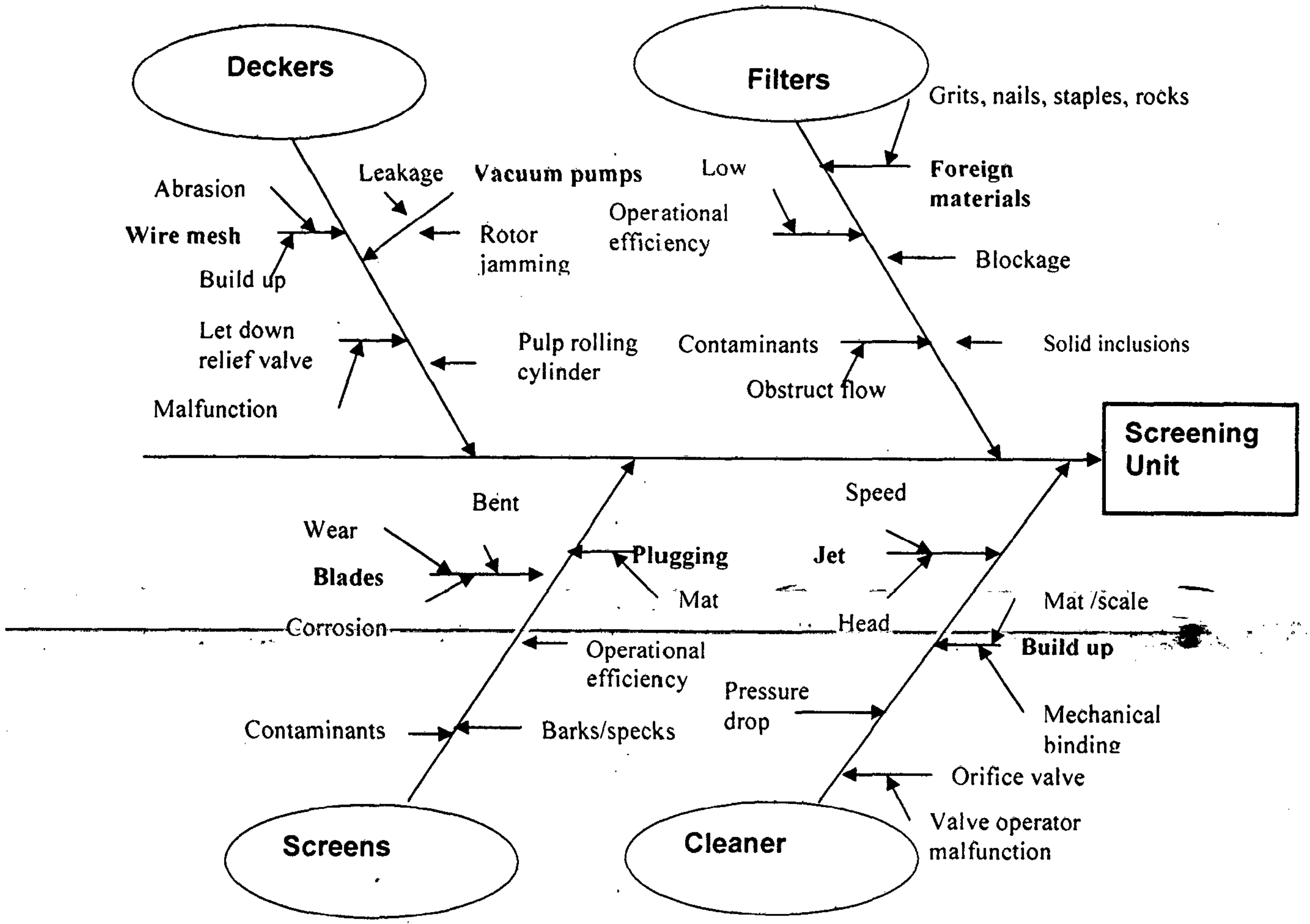


Figure 4.11 Root Cause Analysis [Screening System]

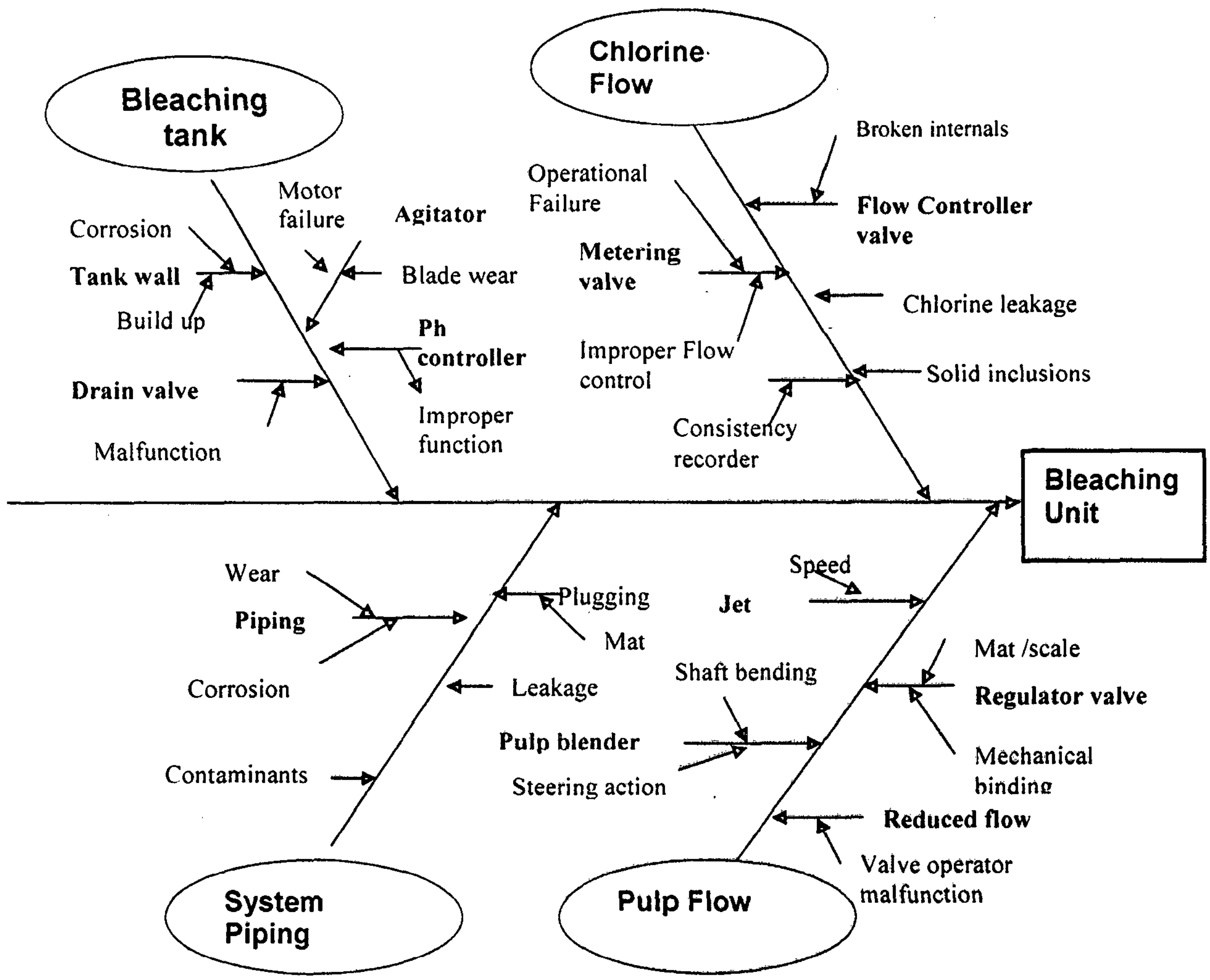


Figure 4.12 Root Cause Analysis [Bleaching System]

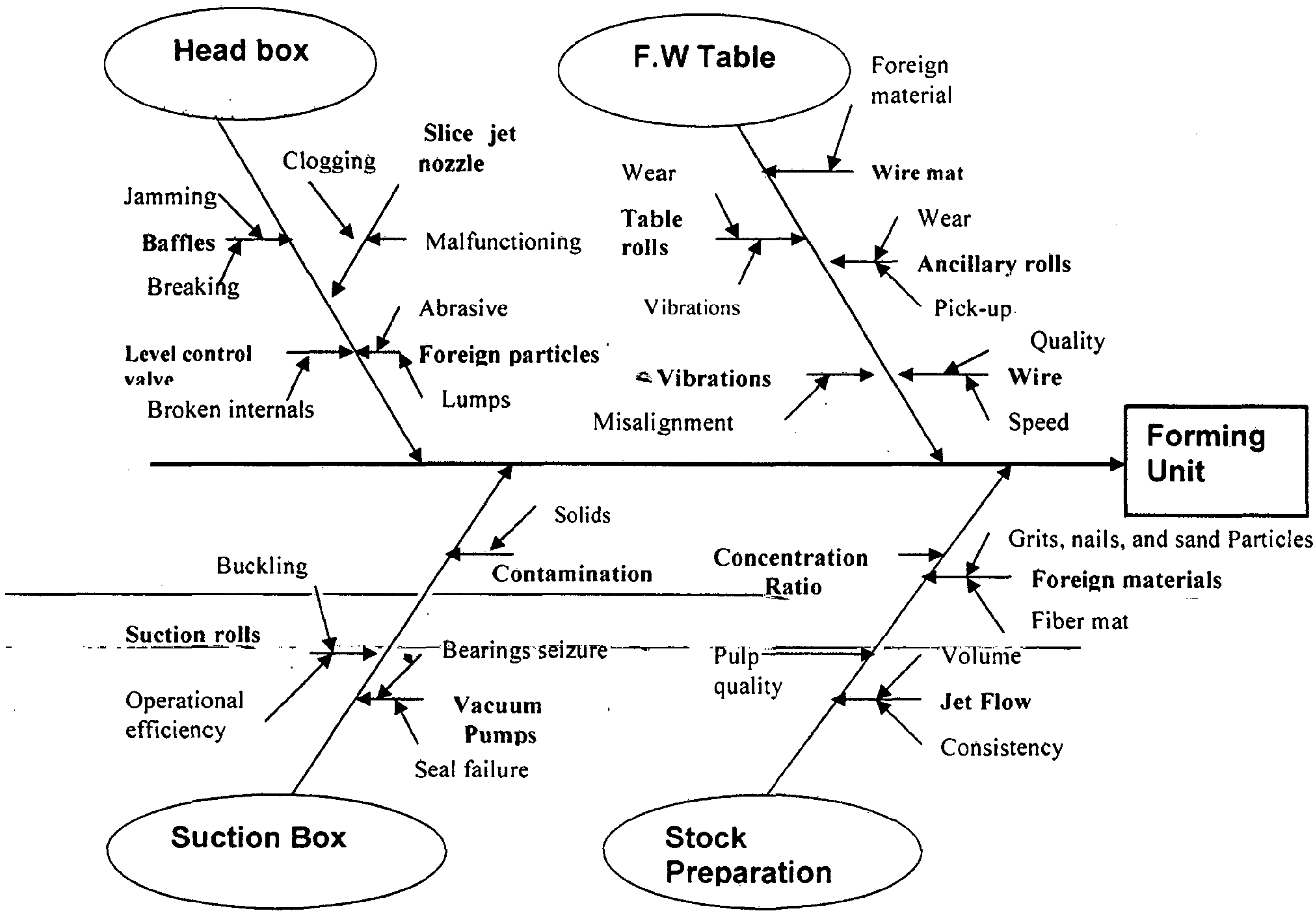


Figure 4.13 Root Cause Analysis [Forming System]

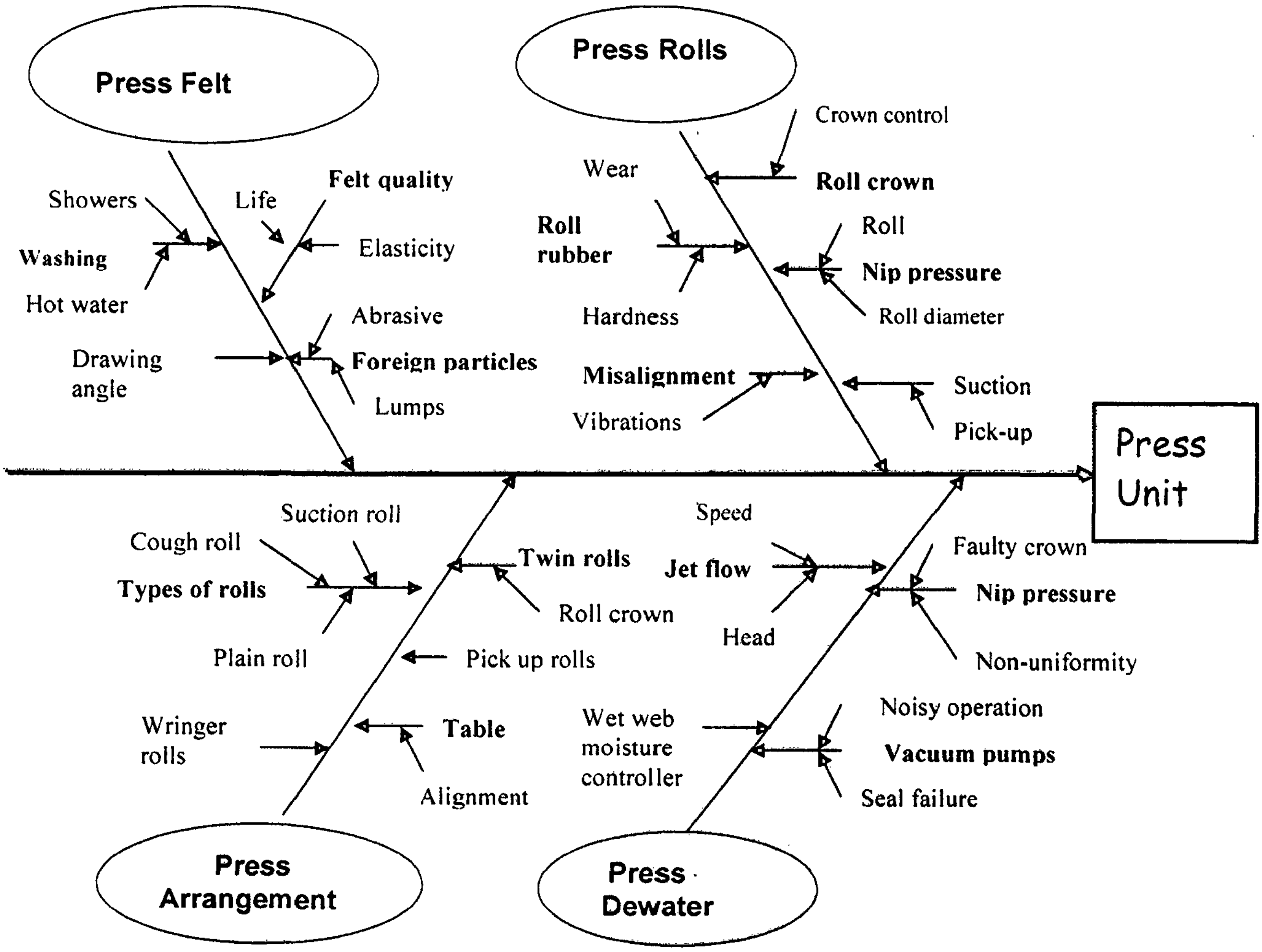


Figure 4.14 Root Cause Analysis [Press]

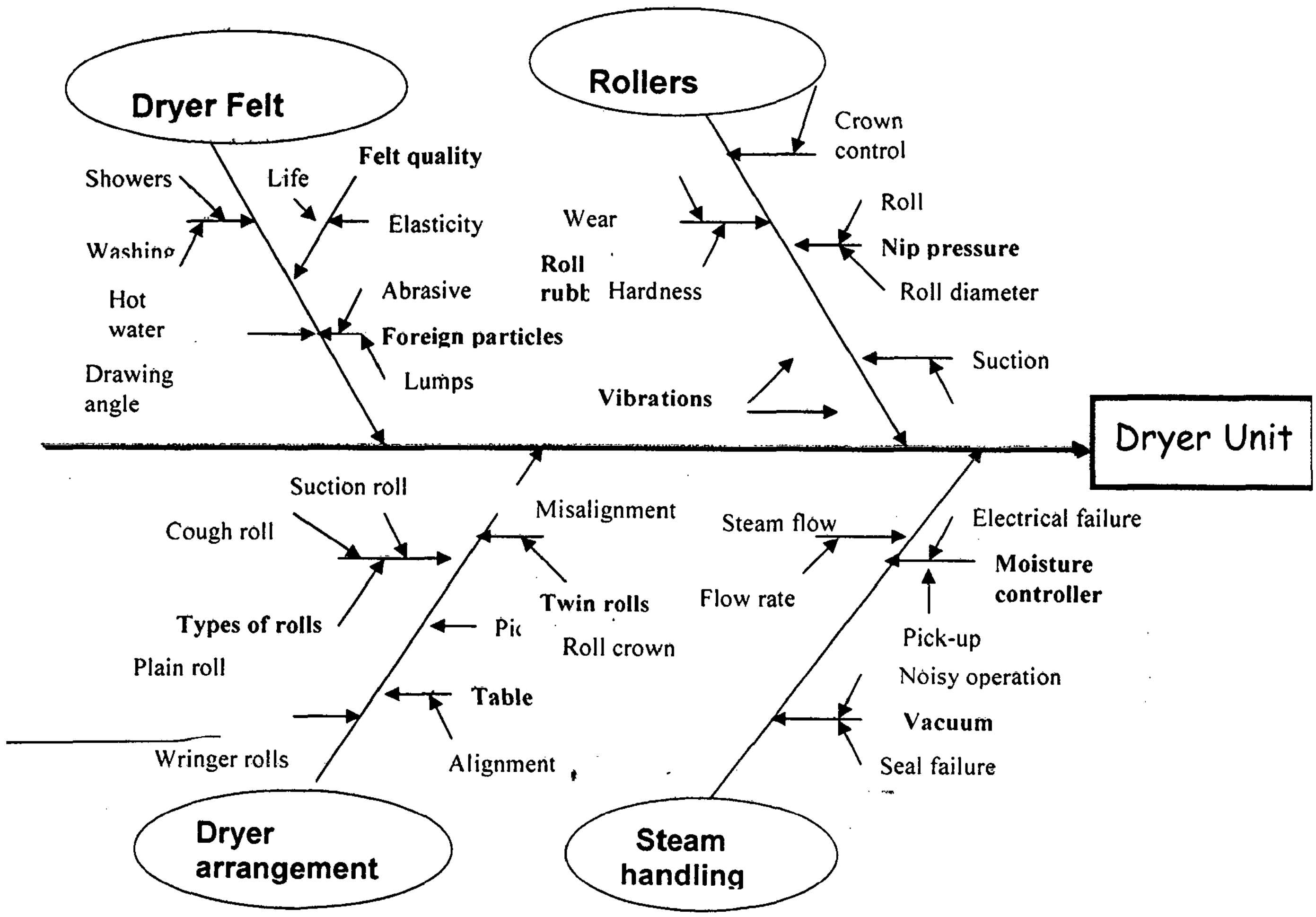
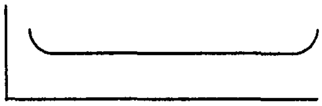
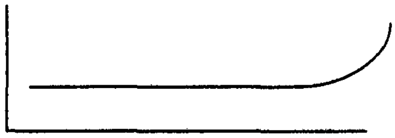
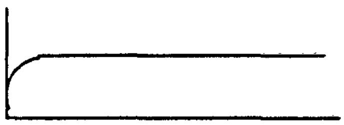
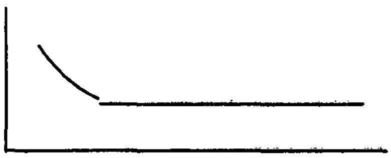


Figure 4.15 Root Cause Analysis [Dryer]

Table A-5(i) TPM losses

S.NO	Type of losses	Characteristics
(i)	*Downtime or breakdown*	These losses are due to sporadic/chronic failures. Sporadic failures occur when changes occur in some conditions (jigs/tools, work methods, and equipment's state). Chronic failures occur when there are some hidden defects in machinery/equipment.
(ii)	*Set-up and adjustment*	The losses incurred due to set up and adjustments. Setting up means a series of operations from the removal of jigs and fixtures to the end of production, clearing up and cleaning, through the preparation of jigs/tools and metal fixtures necessary for the next product, to their attachment, adjustment, trial processing, readjustment, measurement, production, and finally the production. For instance, exchanging of dies in presses and plastic injection molding machines.
iii)	*Minor/idling stoppage*	Minor and idling stoppage occurs when production is interrupted by a temporary malfunction or when a machine is idling: for instance, Idling and minor stoppages caused by the malfunctioning of sensors and blockages of work on chutes.
(iv)	*Reduced speed*	These type of losses occur when (i) There is a difference between designed speed and the actual speed. (ii) The design speed is lower than present technological standards or the desirable condition. For instance, even if a machine is operated at the desired speed, in many cases the speed may have to be reduced because of quality or mechanical problems.
(v)	*Start-up or reduced yield*	Start-up losses are defined as time losses (output decline) For instance, (i) Start-up after periodic repair. (ii) Start-up after suspension (long-time stoppage). (iii) Start-up after holidays.
(vi)	*Defect/rework losses*	Defect/rework losses are defined as volume losses due to defects and rework.

Table A-5(ii) Common Failure Pattern Observed by Various Components

Failure patterns	**Description / components**
 The bathtub curve infant mortality followed by a stable and wear out periods.	Components under this category exhibit constant failure rate (Planned maintenance at periodic intervals with emphasis on condition monitoring is the best way to deal with such failures. For instance, Electromechanical components.
 CFR followed by a pronounced wear out period	Under this category few early failures are followed by a longstable life before wear sets in and increases failure. The only remedy is monitoring [using VBM(c) or VBM (p) methods] to detect onset of the increasing failures.
 Gradually IFR	The failure rate of components/parts increases gradually because of deterioration for instance in case of hydraulic components (pumps, valves) because of contamination. The remedy is periodic preventive maintenance interventions.
 LFR (when component is new followed to a quick increase to a constant level)	The failures in this category are caused by human learning and reliability problems, for instance when instructions are not followed by production and maintenance personnel regarding the upkeep of equipment such as lubrication, oiling and eriodical inspections.
 Infant mortality followed by a constant or slowly IFR	The failures occur at an early stage and may be due to human errors reported because of inexperience, lack of knowledge regarding system function. Such failures can be reduced by administering proper training and setting guidelines or instructions for the use /operation of the system.

· CFR: Constant failure rate; IFR: Increasing failure rate; LFR: low failure rate; VBM(c): Vibration based monitoring, continuous and VBM (p): Vibration based monitoring, periodic

Table A-5(iii) Linear Regression Analysis for Selection of NHPPP Moc

For $\rho_1(t)$ $\qquad E[N(t)] = \dfrac{e^{\alpha_0}}{\alpha_1}\{e^{(\alpha_1 t)} - 1\}$ (i)

For $\rho_2(t)$ $\qquad E[N(t)] = \lambda t^{\beta}$ (ii)

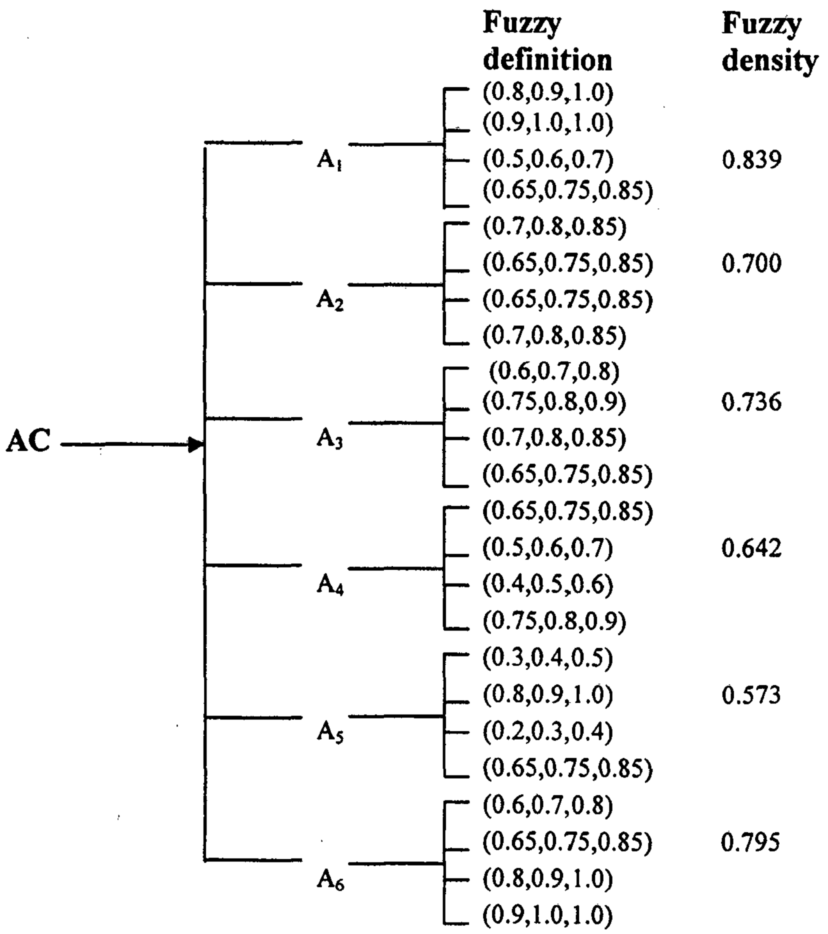
Considering that the observation period (0, t_0) is divided into k arbitrary intervals (0, a_1), (a_1, a_2), …, (a_{k-1}, t_0), an estimate of $\rho\ [1/2\,(a_{j-1}+a_j)]$, is given by

$$\rho[1/2(a_{j-1}+a_j)] = \frac{N(a_j) - N(a_{j-1})}{a_j - a_{j-1}} \qquad \text{(iii)}$$

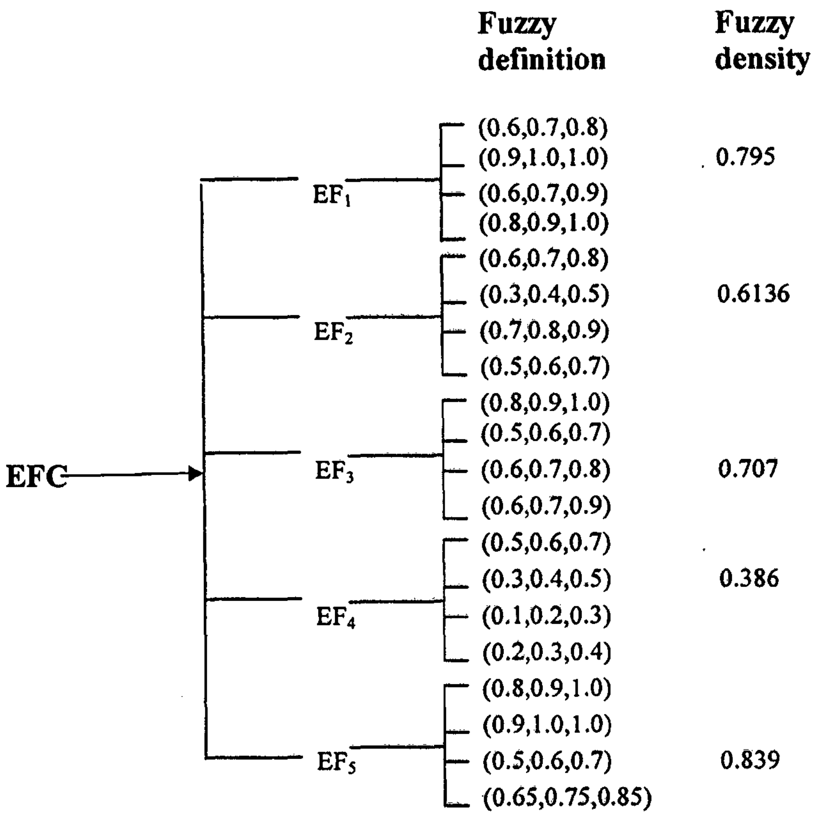
For j=1, 2, …, k, where a_0=0 and $a_k = t_0$.

Assuming b_j=1/2 ($a_{j-1}+a_j$), a plot of $\rho(b_j)\times b_j$ indicates the shape of the rate of occurrence failures, $\rho\ (t)$. The choice of k and a_j depends on the analyst. However, it is advisable to t different subdivisions of the observation interval in order to verify that the shape of the plot dc not depend on the chosen subdivision. If $\rho_1\ (t)$ is appropriate for $\rho\,(t)$, then the plot of $ln\,\rho\,(b_j)\times$ will show a straight line with slope α_1 and intercept. α_0 On the other hand, if $\rho_2\ (t)$ appropriate for $\rho\ (t)$, the plot of $ln\,\rho\ (b_j) \times \ln b_j$ will also show a straight line, but with slo $(\beta - 1)$ and intercept $ln\ \lambda + ln\ \beta$.

Appendix-A-6(i) Fuzzy Definition and Fuzzy Density Values for Quality Cost Items



(b) Appraisal costs



(c) External failure costs

IFC	Fuzzy definition	Fuzzy density
IF_1	(0.8,0.9,1.0)	
	(0.5,0.6,0.7)	
	(0.6,0.7,0.8)	0.707
	(0.6,0.7,0.9)	
IF_2	(0.6,0.7,0.8)	
	(0.75,0.8,0.9)	0.7369
	(0.7,0.8,0.85)	
	(0.65,0.75,0.85)	
IF_3	(0.5,0.6,0.7)	
	(0.3,0.4,0.5)	0.386
	(0.1,0.2,0.3)	
	(0.2,0.3,0.4)	
IF_4	(0.6,0.7,0.8)	
	(0.3,0.4,0.5)	0.6136
	(0.7,0.8,0.9)	
	(0.5,0.6,0.7)	
IF_5	(0.1,0.2,0.3)	
	(0.2,0.3,0.4)	0.363
	(0.3,0.4,0.5)	
	(0.4,0.5,0.6)	
IF_6	(0.6,0.7,0.8)	
	(0.9,1.0,1.0)	0.795
	(0.6,0.7,0.9)	
	(0.8,0.9,1.0)	
IF_7	(0.5,0.6,0.7)	
	(0.8,0.9,1.0)	0.636
	(0.4,0.5,0.6)	
	(0.7,0.8,0.9)	
IF_8	(0.8,0.9,1.0)	
	(0.7,0.8,0.9)	0.797
	(0.6,0.7,0.8)	
	(0.8,0.9,1.0)	

(d) Internal failure costs

A-7(i) Resource Allocation Results for System [Tables A-7(i)- A-7(viii)]

Tables A-7(i) Stage 1

$\lambda = 0.001$		$\lambda = 0.002$		$\lambda = 0.003$		$\lambda = 0.004$		$\lambda = 0.005$	
ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$
1	-1.90809	1	-1.91009	1	-1.91209	1	-1.91409	1	-1.91609
2	-1.29418	2	-1.29818	2	-1.30218	2	-1.30618	2	-1.31018
3	-0.965809	3	-0.97180	3	-0.97780	3	-0.98380	3	-0.98980
4	-0.753084	4	-0.76108	4	-0.76908	4	-0.77704	4	-0.78508
5	-0.602784	5	-0.61278	5	-0.62278	5	-0.63278	5	-0.64278
6	-0.491215	6	-0.50321	6	-0.51521	6	-0.52725	6	-0.53921
7	-0.405757	7	-0.41975	7	-0.43375	7	-0.44777	7	-0.46175
8	-0.338889	8	-0.35488	8	-0.37088	8	-0.38688	8	-0.40288
9	-0.28578	9	-0.30378	9	-0.32178	9	-0.33978	9	-0.35778
10	-0.243144	10	-0.26314	10	-0.28314	10	-0.30314	10	-0.32314
11	-0.208653	11	-0.23065	11	-0.25265	11	-0.27465	11	-0.29665
12	-0.180602	12	-0.20460	12	-0.22860	12	-0.25260	12	-0.27660
13	-0.157712	13	-0.18371	13	-0.20971	13	-0.23571	13	-0.26171
14	-0.13922	14	-0.16788	14	-0.19501	14	-0.22311	14	-0.25111
15	-0.123699	15	-0.15369	15	-0.18369	15	-0.21369	15	-0.24369
16	-0.111201	16	-0.14320	16	-0.17521	16	-0.20720	16	-0.23920
17	-0.101023	17	-0.13502	17	-0.16923	17	-0.20302	17	-0.23702
18	-0.092770	18	-0.12877	18	-0.16471	18	-0.20077	18	-0.23677
19	-0.086124	19	-0.12412	19	-0.16224	19	-0.20014	19	-0.23812
20	-0.080822	20	-0.12082	20	-0.16082	20	-0.20082		
21	-0.076647	21	-0.11864	21	-0.16064				
22	-0.073419	22	-0.11742	22	-0.16142				
23	-0.070991	23	-0.11699						
24	-0.069236	24	-0.11723						
25	-0.068050								
26	-0.067346								
27	-0.06705								
28	-0.067099								

Tables A-7(ii) Stage 2

$\lambda = 0.001$		$\lambda = 0.002$		$\lambda = 0.003$		$\lambda = 0.004$		$\lambda = 0.005$	
ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$
1	-2.5985	1	-2.65094	1	-2.6971	1	-2.73908	1	-2.77822
2	-1.94854	2	-2.00348	2	-2.0521	2	-2.09662	2	-2.13826
3	-1.58569	3	-1.64313	3	-1.6942	3	-1.74126	3	-1.78541
4	-1.34005	4	-1.39999	4	-1.4536	4	-1.50312	4	-1.54977
5	-1.15837	5	-1.22081	5	-1.2769	5	-1.32895	5	-1.37809
6	-1.01695	6	-1.08189	6	-1.1405	6	-1.19502	6	-1.24667
7	-0.903124	7	-0.97056	7	-1.0317	7	-1.08870	7	-1.14284
8	-0.809356	8	-0.87929	8	-0.94292	8	-1.00243	8	-1.05908
9	-0.730772	9	-0.80321	9	-0.86939	9	-0.931346	9	-0.990493
10	-0.664051	10	-0.73899	10	-0.80768	10	-0.872126	10	-0.933772
11	-0.606825	11	-0.68426	11	-0.75542	11	-0.822399	11	-0.886546
12	-0.557345	12	-0.63728	12	-0.71092	12	-0.78042	12	-0.847066
13	-0.514286	13	-0.59672	13	-0.67283	13	-0.74486	13	-0.814007
14	-0.476618	14	-0.56155	14	-0.64025	14	-0.714693	14	-0.786339
15	-0.443527	15	-0.53096	15	-0.61214	15	-0.689101	15	-0.763248
16	-0.414357	16	-0.50429	16	-0.58794	16	-0.667431	16	-0.744078
17	-0.388573	17	-0.48101	17	-0.56710	17	-0.649147	17	-0.728293
18	-0.365732	18	-0.46067	18	-0.54932	18	-0.633807	18	-0.715453
19	0.345467	19	-0.44290	19	-0.53406	19	-0.621041	19	-0.705187
20	-0.327465	20	-0.42740	20	-0.52106	20	-0.610539	20	-0.697185
21	-0.311462	21	-0.41390	21	-0.51005	21	-0.602037	21	-0.691183
22	-0.297232	22	-0.40217	22	-0.50089	22	-0.595307	22	-0.686953
23	-0.28458	23	-0.39202	23	-0.49377	23	-0.590154	23	-0.684300
24	-0.273336	24	-0.38327	24	-0.48693	24	-0.58641	24	-0.683056
25	-0.263352	25	-0.37579	25	-0.48199	25	-0.583927	25	-0.683073
26	-0.254501	26	-0.36944	26	-0.47807	26	-0.582575		
27	-0.246667	27	-0.36410	27	-0.47564	27	-0.582241		
28	-0.239750	28	-0.35969	28	-0.47347	28	-0.582825		
29	-0.233662	29	-0.35610	29	-0.47259				
30	-0.228324	30	-0.35326	30	-0.47121				
31	-0.223664	31	-0.35110	31	-0.47261				
32	-0.219621	32	-0.34956						
33	-0.216137	33	-0.34857						
34	-0.213161	34	-0.34810						
35	-0.210648	35	-0.34808						
36	-0.208558	36	-0.34849						
37	-0.206852								
38	-0.205496								
39	-0.204462								
40	-0.20372								
41	-0.203246								
42	-0.203017								
43	-0.203012								
44	-0.203213								

Tables A-7(iii) Stage 3

λ = 0.001		λ = 0.002		λ = 0.003		λ = 0.004		λ = 0.005	
ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$
1	-2.6195	1	-2.76608	1	-2.89141	1	-3.00323	1	-3.10555
2	-1.97357	2	-2.12165	2	-2.24848	2	-2.3618	2	-2.46561
3	-1.61459	3	-1.76417	3	-1.89254	3	-2.00732	3	-2.11263
4	-1.37266	4	-1.52374	4	-1.65357	4	-1.76989	4	-1.87671
5	-1.19455	5	-1.34713	5	-1.47846	5	-1.59628	5	-1.70459
6	-1.05654	6	-1.21062	6	-1.34345	6	-1.46277	6	-1.57258
7	-0.945978	7	-1.10156	7	-1.23589	7	-1.35671	7	-1.46802
8	-0.855322	8	-1.01241	8	-1.14823	8	-1.27055	8	-1.38337
9	-0.779704	9	-0.93828	9	-1.07561	9	-1.19943	9	-1.31375
10	-0.715804	10	-0.875881	10	-1.01471	10	-1.14003	10	-1.25585
11	-0.661254	11	-0.822831	11	-0.963163	11	-1.08998	11	-1.20735
12	-0.61431	12	-0.777388	12	-0.919219	12	-1.04754	12	-1.16635
13	-0.573649	13	-0.738226	13	-0.881557	13	-1.01138	13	-1.13169
14	-0.538243	14	-0.704321	14	-0.849151	14	-0.980472	14	-1.10229
15	-0.50728	15	-0.674857	15	-0.821189	15	-0.954009	15	-1.07732
16	-0.480108	16	-0.649186	16	-0.797017	16	-0.931337	16	-1.05615
17	-0.456195	17	-0.626773	17	-0.776104	17	-0.911924	17	-1.03824
18	-0.435102	18	-0.607181	18	-0.758011	18	-0.895331	18	-1.02315
19	-0.416463	19	-0.590041	19	-0.742372	19	-0.881192	19	-1.01051
20	-0.39997	20	-0.575047	20	-0.728878	20	-0.869199	20	-1.00001
21	-0.385362	21	-0.561939	21	-0.717277	21	-0.859091	21	-0.991406
22	-0.372415	22	-0.550493	22	-0.707324	22	-0.850644	22	-0.98446
23	-0.360939	23	-0.540517	23	-0.698848	23	-0.843668	23	-0.978984
24	-0.350768	24	-0.531845	24	-0.691676	24	-0.837997	24	-0.974812
25	-0.341756	25	-0.524334	25	-0.685665	25	-0.833485	25	-0.97185
26	-0.333779	26	-0.517857	26	-0.680688	26	-0.830008	26	-0.969824
27	-0.326727	27	-0.512304	27	-0.676636	27	-0.827456	27	-0.968771
28	-0.320502	28	-0.507579	28	-0.673411	28	0.825731	28	-0.968546
29	-0.315019	29	-0.503596	29	-0.670927	29	-0.824748	29	-0.969063
30	-0.310202	30	-0.500279	30	-0.669117	30	-0.824431		
31	-0.305984	31	-0.497561	31	-0.667893	31	-0.824713		
32	-0.302305	32	-0.495383	32	-0.667214				
33	-0.299113	33	-0.493695	33	-0.667021				
34	-0.296359	34	-0.492436	34	-0.667267				
35	-0.294001	35	-0.491578						
36	-0.292900	36	-0.491077						
37	-0.290323	37	-0.490922						
38	-0.288938	38	-0.491016						
39	-0.287819								
40	-0.286940								
41	-0.286278								
42	-0.285813								
43	-0.285528								
44	-0.285404								
45	-0.285428								

Tables A-7(iv) Stage 4

$\lambda = 0.001$		$\lambda = 0.002$		$\lambda = 0.003$		$\lambda = 0.004$		$\lambda = 0.005$	
ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$
1	-2.4896	1	-2.6976	1	-2.87622	1	-3.03613	1	-3.18274
2	-1.85585	2	-2.06635	2	-2.24747	2	-2.40988	2	-2.55899
3	-1.50864	3	-1.72163	3	-1.90526	3	-2.07017	3	-2.22178
4	-1.27807	4	-1.49357	4	-1.67969	4	-1.8471	4	-2.00121
5	-1.11091	5	-1.32891	5	-1.51753	5	-1.68744	5	-1.84405
6	-0.983449	6	-1.20395	6	-1.39507	6	-1.56748	6	-1.72659
7	-0.883039	7	-1.10604	7	-1.29966	7	-1.47457	7	-1.63618
8	-0.802141	8	-1.02764	8	-1.22376	8	-1.40117	8	-1.56528
9	-0.735895	9	-0.963891	9	-1.16251	9	-1.34242	9	-1.50904
10	-0.680987	10	-0.911483	10	-1.1126	10	-1.29501	10	-1.46413
11	-0.635059	11	-0.868055	11	-1.07168	11	-1.25659	11	-1.4282
12	-0.596374	12	-0.83187	12	-1.03799	12	-1.2254	12	-1.39952
13	-0.563618	13	-0.801614	13	-1.01024	13	-1.20014	13	-1.37676
14	-0.535773	14	-0.776269	14	-0.98739	14	-1.1798	14	-1.35891
15	-0.512037	15	-0.755033	15	-0.968654	15	-1.16356	15	-1.34518
16	-0.491768	16	-0.737264	16	-0.953385	16	-1.15079	16	-1.33491
17	-0.474444	17	-0.72244	17	-0.941061	17	-1.14097	17	-1.32759
18	-0.459637	18	-0.710133	18	-0.931255	18	-1.13366	18	-1.32278
19	-0.446993	19	-0.699989	19	-0.92361	19	-1.12852	19	-1.32013
20	-0.436213	20	-0.691709	20	-0.91783	20	-1.12524	20	-1.31936
21	-0.427049	21	-0.685045	21	-0.913666	21	-1.12358	21	-1.32019
22	-0.419288	22	-0.679784	22	-0.910905	22	-1.12331		
23	-0.41275	23	-0.675746	23	-0.909367	23	-1.12428		
24	-0.40728	24	-0.672776	24	-0.908897				
25	-0.402744	25	-0.67074	25	-0.909361				
26	-0.399028	26	-0.669524						
27	-0.396032	27	-0.669027						
28	-0.393669	28	-0.669164						
29	-0.391863								
30	-0.39055								
31	-0.38967								
32	-0.389174								
33	-0.389017								
34	-0.389159								

Tables A-7(v) Stage 5

$\lambda = 0.001$		$\lambda = 0.002$		$\lambda = 0.003$		$\lambda = 0.004$		$\lambda = 0.005$	
ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$
1	-2.26751	1	-2.54952	1	-2.79139	1	-3.00781	1	-3.20585
2	-1.65601	2	-1.94003	2	-2.18389	2	-2.40231	2	-2.60235
3	-1.32991	3	-1.61592	3	-1.86179	3	-2.08221	3	-2.28425
4	-1.11932	4	-1.40733	4	-1.6552	4	-1.87762	4	-2.08166
5	-0.971018	5	-1.26103	5	-1.5109	5	-1.73532	5	-1.94136
6	-0.861312	6	-1.15332	6	-1.40519	6	-1.63161	6	-1.83965
7	-0.777585	7	-1.0716	7	-1.32547	7	-1.55388	7	-1.76392
8	-0.712323	8	-1.00833	8	-1.2642	8	-1.49462	8	-1.70666
9	-0.660699	9	-0.95871	9	-1.21658	9	-1.44988	9	-1.66304
10	-0.619431	10	-0.91944	10	-1.17931	10	-1.41373	10	-1.62977
11	-0.586199	11	-0.88821	11	-1.15008	11	-1.3865	11	-1.60454
12	-0.559302	12	-0.863313	12	-1.12718	12	-1.3656	12	-1.58564
13	-0.537467	13	-0.843478	13	-1.10935	13	-1.34977	13	-1.57181
14	-0.519717	14	-0.827728	14	-1.0956	14	-1.33801	14	-1.56206
15	-0.50529	15	-0.815301	15	-1.08517	15	-1.32959	15	-1.55563
16	-0.493587	16	-0.805598	16	-1.07747	16	-1.32389	16	-1.55193
17	-0.484128	17	-0.798138	17	-1.07201	17	-1.32043	17	-1.55047
18	-0.476524	18	-0.792535	18	-1.0684	18	-1.31882	18	-1.55086
19	-0.470463	19	-0.788474	19	-1.06634	19	-1.31876		
20	-0.465687	20	-0.785697	20	-1.06557	20	-1.31998		
21	-0.461984	21	-0.783994	21	-1.06586				
22	-0.459179	22	-0.783197						
23	-0.457128	23	-0.783139						
24	-0.455711	24	-0.783721						
25	-0.454825								
26	-0.454388								
27	-0.454329								
28	-0.454589								

Tables A-7(vi) Stage 6

$\lambda = 0.001$		$\lambda = 0.002$		$\lambda = 0.003$		$\lambda = 0.004$		$\lambda = 0.005$	
ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$
1	-2.80535	1	-3.13617	1	-3.42059	1	-3.67579	1	-3.90949
2	-2.16312	2	-2.49593	2	-2.78235	2	-3.03955	2	-3.27525
3	-1.80772	3	-2.14253	3	-2.43096	3	-2.69015	3	-2.92786
4	-1.56927	4	-1.90608	4	-2.19651	4	-2.45771	4	-2.69741
5	-1.39453	5	-1.73334	5	-2.02577	5	-2.28897	5	-2.53067
6	-1.25979	6	-1.6006	6	-1.89503	6	-2.16022	6	-2.40393
7	-1.15239	7	-1.4952	7	-1.79163	7	-2.05882	7	-2.30453
8	-1.06479	8	-1.4096	8	-1.70803	8	-1.97722	8	-2.22493
9	-0.992128	9	-1.33894	9	-1.63937	9	-1.91056	9	-2.16027
10	-0.931082	10	-1.27989	10	-1.58232	10	-1.85551	10	-2.10722
11	-0.879289	11	-1.2301	11	-1.53453	11	-1.80972	11	-2.06343
12	-0.835004	12	-1.18781	12	-1.49424	12	-1.77144	12	-2.02714
13	-0.796906	13	-1.15172	13	-1.46014	13	-1.73934	13	-1.99704
14	-0.763972	14	-1.12078	14	-1.43121	14	-1.7124	14	-1.97211
15	-0.73539	15	-1.0942	15	-1.40663	15	-1.68982	15	-1.95153
16	-0.71051	16	-1.07132	16	-1.38575	16	-1.67094	16	-1.93465
17	-0.688804	17	-1.05161	17	-1.36804	17	-1.65524	17	-1.92094
18	-0.669835	18	-1.03464	18	-1.35307	18	-1.64227	18	-1.90997
19	-0.653238	19	-1.02005	19	-1.34048	19	-1.63167	19	-1.90138
20	-0.63871	20	-1.00752	20	-1.32995	20	-1.62314	20	-1.89485
21	-0.625991	21	-0.996801	21	-1.32123	21	-1.61642	21	-1.89013
22	-0.614862	22	-0.987672	22	-1.3141	22	-1.61129	22	-1.88777
23	-0.605132	23	-0.979942	23	-1.30837	23	-1.60756	23	-1.88527
24	-0.59664	24	-0.97345	24	-1.30388	24	-1.60507	24	-1.88478
25	-0.589243	25	-0.968053	25	-1.30048	25	-1.60367	25	-1.88538
26	-0.582818	26	-0.963628	26	-1.29806	26	-1.60325		
27	-0.577258	27	0.960069	27	-1.2965	27	-1.60369		
28	-0.572469	28	-0.957279	28	-1.29571				
29	-0.568368	29	-0.955178	29	-1.29561				
30	-0.564881	30	-0.953691	30	-1.29612				
31	-0.561943	31	-0.952753						
32	-0.559498	32	-0.952308						
33	-0.557494	33	-0.952304						
34	-0.555886	34	-0.952696						
35	-0.554633								
36	-0.5537								
37	-0.55305								
38	-0.552668								
39	-0.552514								
40	-0.552569								

Tables A-7(vii) Stage 7

$\lambda = 0.001$		$\lambda = 0.002$		$\lambda = 0.003$		$\lambda = 0.004$		$\lambda = 0.005$	
ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$
1	-3.05114	1	-3.45342	1	-3.79923	1	-4.10937	1	-4.3934
2	-2.40256	2	-2.80735	2	-3.15565	2	-3.4683	2	-3.75483
3	-2.04106	3	-2.44835	3	-2.79915	3	-3.11429	3	-3.40332
4	-1.79672	4	-2.20651	4	-2.55981	4	-2.87746	4	-3.16898
5	-1.61631	5	-2.0286	5	-2.3844	5	-2.70455	5	-2.99857
6	-1.47611	6	-1.8909	6	-2.2492	6	-2.57185	6	-2.86837
7	-1.36347	7	-1.78076	7	-2.14156	7	-2.46671	7	-2.76574
8	-1.27085	8	-1.69064	8	-2.05394	8	-2.38159	8	-2.68311
9	-1.19337	9	-1.61566	9	-1.98147	9	-2.31161	9	-2.61564
10	-1.12772	10	-1.55251	10	-1.92081	10	-2.25346	10	-2.55998
11	-1.07153	11	-1.49882	11	-1.86962	11	-2.20476	11	-2.51379
12	-1.02304	12	-1.45283	12	-1.82613	12	-2.16378	12	-2.4753
13	-0.980936	13	-1.41323	13	-1.78903	13	-2.12917	13	-2.4432
14	-0.944189	14	-1.37898	14	-1.75728	14	-2.09993	14	-2.41645
15	-0.911982	15	-1.34927	15	-1.73007	15	-2.07522	15	-2.39424
16	-0.883661	16	-1.32345	16	-1.70675	16	-2.0544	16	-2.37592
17	-0.858693	17	-1.30098	17	-1.68678	17	-2.03693	17	-2.36096
18	-0.836635	18	-1.28142	18	-1.66973	18	-2.02237	18	-2.3489
19	-0.817119	19	-1.26441	19	-1.65521	19	-2.01036	19	-2.33938
20	-0.799835	20	-1.24962	20	-1.64293	20	-2.00057	20	-2.3321
21	-0.784519	21	-1.23681	21	-1.63261	21	-1.99276	21	-2.32678
22	-0.770946	22	-1.22574	22	-1.62404	22	-1.98668	22	-2.32321
23	-0.758922	23	-1.21621	23	-1.61701	23	-1.98216	23	-2.32118
24	-0.748277	24	-1.20807	24	-1.61137	24	-1.97901	24	-2.32054
25	-0.738866	25	-1.20116	25	-1.60696	25	-1.97718	25	-2.32113
26	-0.73056	26	-1.19535	26	-1.60365	26	-1.97639		
27	-0.723246	27	-1.19054	27	-1.60134	27	-1.97648		
28	-0.716824	28	-1.18661	28	-1.59992				
29	-0.711208	29	-1.1835	29	-1.59938				
30	-0.706317	30	-1.18111	30	-1.59941				
31	-0.702083	31	-1.17937						
32	-0.698444	32	-1.17823						
33	-0.695344	33	-1.17763						
34	-0.692732	34	-1.17752						
35	-0.690565	35	-1.17786						
36	-0.688802								
37	-0.687405								
38	-0.686343								
39	-0.685586								
40	-0.685106								
41	-0.68488								
42	-0.684885								

Tables A-7(viii) Stage 8

$\lambda = 0.001$		$\lambda = 0.002$		$\lambda = 0.003$		$\lambda = 0.004$		$\lambda = 0.005$	
ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$	ε	$f(\varepsilon)$
1	-2.71773	1	-3.21237	1	3.63615	1	-4.01514	1	-4.36139
2	-2.09444	2	-2.59108	2	-3.01686	2	-3.39786	2	-3.74612
3	-1.7572	3	-2.25584	3	-2.68362	3	-3.06661	3	-3.41686
4	-1.5361	4	-2.03675	4	-2.46652	4	-2.85152	4	-3.20376
5	-1.37792	5	-1.88057	5	-2.31234	5	-2.69934	5	-3.05359
6	-1.25896	6	-1.7636	6	-2.19738	6	-2.58638	6	-2.94262
7	-1.16657	7	-1.67321	7	-2.10899	7	-2.49999	7	-2.85823
8	-1.09323	8	-1.60188	8	-2.03965	8	-2.43265	8	-2.79289
9	-1.03409	9	-1.54473	9	-1.98451	9	-2.37951	9	-2.74175
10	-0.98585	10	-1.49849	10	-1.94027	10	-2.33727	10	-2.70151
11	-0.94616	11	-1.4608	11	-1.90458	11	-2.30358	11	-2.66982
12	-0.91332	12	-1.42994	12	-1.87572	12	-2.27672	12	-2.64496
13	-0.885971	13	-1.40461	13	-1.85239	13	-2.25539	13	-2.62563
14	-0.863171	14	-1.38381	14	-1.83359	14	-2.23859	14	-2.61083
15	-0.844113	15	-1.36676	15	-1.81853	15	-2.22553	15	-2.59977
16	-0.828172	16	-1.35281	16	-1.80659	16	-2.21559	16	-2.59183
17	-0.814842	17	-1.34148	17	-1.79726	17	-2.20826	17	-2.58652
18	-0.803712	18	-1.33235	18	-1.79013	18	-2.20313	18	-2.58337
19	-0.794443	19	-1.32509	19	1.78486	19	-2.19986	19	-2.58211
20	-0.786755	20	-1.3194	20	-1.78117	20	-2.19817	20	-2.58242
21	-0.780414	21	-1.31506	21	-1.77883	21	-2.19783		
22	-0.775224	22	-1.31187	22	-1.77764	22	-2.19864		
23	-0.771018	23	-1.30966	23	-1.77744				
24	-0.767659	24	-1.3083	24	-1.77808				
25	-0.765025	25	-1.30767						
26	-0.763017	26	-1.30766						
27	-0.761548	27	-1.30819						
28	-0.760544								
29	-0.759942								
30	-0.759686								
31	-0.759731								

Appendix-A-7

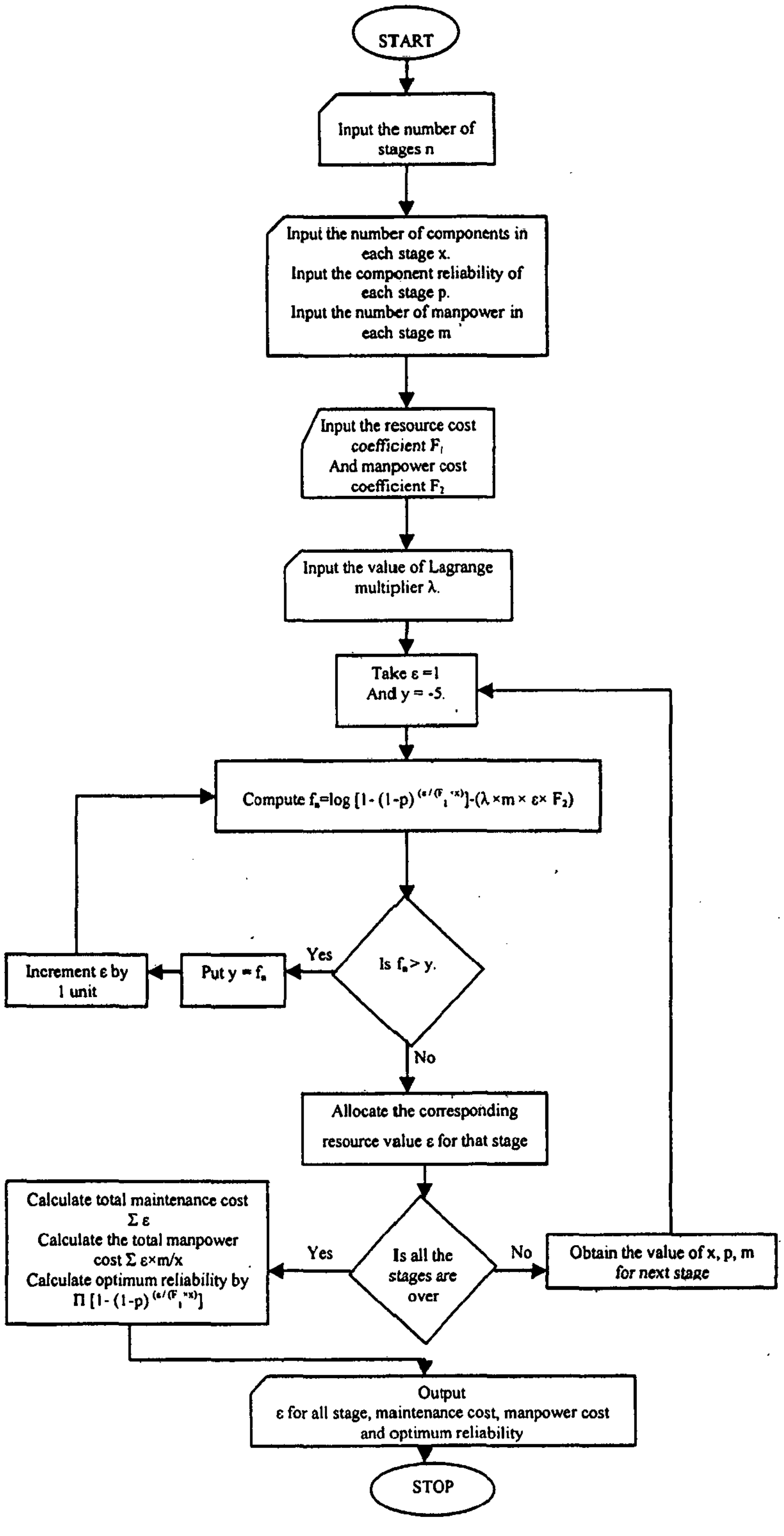


Figure A-7(i). Flowchart for Resource Allocation