Development of Advance Maintenance Planning and Resource Allocation System for Industrial Process

THESIS

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by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis, entitled **"Development of Advance Maintenance Planning and Resource Allocation System for Industrial Process"** in the fulfilment of the requirements for the award of the degree of Doctor of Philosophy and submitted in the Department of Mechanical Engineering of J. C. Bose University of Science & Technology, YMCA, Faridabad, is an authentic record of my own work carried out under the supervision of **Dr. Sanjeev Kumar**, Professor, Department of Mechanical Engineering, J. C. Bose University of Science & Technology, YMCA, Faridabad.

The matter presented in this thesis has not been submitted by me for the award of any degree of this or any other University/Institute.

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The results presented have not been submitted in part or in full to any other University/ Institute for the award of any degree or diploma.

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ABSTRACT

Continuous progression in technology leads to the complexity of industrial systems, hence making it more expensive to execute the system operations and maintenance. Thus, more attention is required to diminish the cost involved in production, operation and maintenance of the repairable systems. In the industrial systems, the said objectives can be easily achieved with the reliable system design and optimizing the maintenance as well as operational activities to ensure their maximum utilization. Thus, in huge complex process industries like sugar, paper, fertilizer, cement, chemical and food processing, reliable operations are of vital importance. This has made the task more challenging, as the maintenance engineers have to study, characterize, measure and analyse the behaviour and performance of systems to keep them in functioning state for a longer period of time to achieve high production along with huge profit. However, these systems are under the threat of random failures resulting into reduced or zero production. It is possible to bring back a failed system into its workable condition after its repair or replacement of some of its components. The factory operating conditions along with the policies adopted in the organization play a vital role in maintaining a system in operative condition for maximum duration of time.

A prior knowledge of system behaviour with the available repair facilities is a basic necessity to design a process. Analysis and modelling of such systems will be beneficial in evaluating the subsystem’s performance and the degree of interaction between the subsystems. A detailed system behavioural analysis along with a scientific maintenance planning will be of major help in this direction. To express the system upstate in quantitative terms, mathematical models of real existing systems have been developed that analyse their performance under actual operating conditions. The analysis will be help to predict the system behaviour in real working conditions and also will help the process designers to incorporate some useful changes in the system design (modification in the existing design).

The thesis work is mainly focused on process reorganization/modification, maintenance planning and resource allocation in a paper plant. Such process industries faces lots of issues like non-availability of raw materials, manpower, energy, machine, facilities, information technology, funds and unplanned maintenance that ultimately lead to loss in production and hence, loss in profit. Even after overcoming these constraints to the maximum possible extent, it is not possible to match the expected performance. Hence, in the process there is an urgent requirement to find and evaluate the instrument's behaviour under actual operating conditions. The behavioural analysis is must to generate the data bank regarding behaviour of equipment in the process. It will give a feedback to the process designer and helps him to improve the design and information to achieve high system availability. This analysis is only possible if some mathematical interrelationship in terms of known parameters is established with the equipment's working in the process. Then the behaviour of all equipments in the process is analysed and predicted under the real plant operative conditions.

Functioning of various operating systems and subsystems of the paper plant are explained with the help of schematic flow diagram. the steady state availability for various operating systems i.e. feeding, pulping, bleaching and washing, screening and paper making systems have been developed with the help of mathematical formulation based on Markov birth-death process using probabilistic approach to do the performance analysis of various operating systems of the paper plant in terms of the availability matrices which are based upon failure rate and repair rate. With the help of these availability matrices critical subsystems are identified. For evaluating the maintenance criticality of failure causes a new methodology based on cloud model and PROMETHEE II (Preference Ranking Organization Method for Enrichment of Evaluations) is proposed which will help the plant personnel to plan suitable maintenance strategies accordingly. .

In the end, Resource allocation for each stage has been carried out using dynamic programming method to solve the multi stage decision problem. Allocation of resources for each operating system of the paper plant has been worked out. Economic production charts are drawn to determine no loss/ no profit point beyond which the system should run to generate profit. Profit analysis for the plant has been carried out.

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NOTATIONS

Notations	Definitions
Ψ	Failure Rate
Φ	Repair Rate
A_{v1}	Steady state availability of feeding system
A_{v2}	Steady state availability of pulping system
A_{v3}	Steady state availability of bleaching and washing system
A_{v4}	Steady state availability of screening system
A_{v5}	Steady state availability of paper production system
$P_i(t)$	Probability that system is in the i^{th} state at time ‘t’
P_i	Steady state probability in the i^{th} state
Z	Cloud
E_p	Expectation
S_n	Entropy
S_e	Hyper Entropy
L	Linguistic term
q	Risk factors
$H(\tilde{R}^k)$	Uncertainty degree
$\lambda_k^{(1)}$	Primary Weight
$\lambda_k^{(2)}$	Secondary Weight
λ_k	Overall Weight
$G(\tilde{R}^k)$	Divergence degree
C	Overall Risk Index
W	Priority weight
β^+	Leaving outranking flow of failure causes
β^-	Entering outranking flow of failure causes
β	Net outranking flow of failure causes
F_o	Chance of failure occurrence
N_d	chance of non-detection
D_l	downtime length

S_{pc}	spare parts criticality
S_r	safety risk
R_1	Coefficient for component cost
R_2	Coefficient for manpower cost
P_j	System availability at stage j
c_j	Resource allocated at stage j
x_j	Number of components at stage j
m_n	Man power
A_v(opt.)	Optimum overall plant availability
$\in$	Total resources available
$\in_0$	Optimum Resource allocation
$f(\in)$	State function
$\pounds_L$	Lagrange’s multiplier

ABREVIATIONS

MTBF	Mean Time Between Failure
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
MTBM	Mean Time Between Maintenance
PM	Preventive Maintenance
RCM	Reliability Centred Maintenance
FMEA	Failure Mode and Effect Analysis
RAM	Reliability, Availability and Maintainability
MCDM	Multi-criteria Decision Making
RPN	Risk Priority Number
AHP	Analytic hierarchy Process
TOPSIS	Technique for order preference by similarity to ideal solution
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
ELECTRE	Elimination and Choice Expressing Reality
GRA	Grey relation analysis
DM	Decision makers
ICWA	Interval cloud weighted averaging
COS	Cost of Sales
EOS	Earning of Sales
B.E.P	Break Even Point

CHAPTER I

INTRODUCTION

1.1 INTRODUCTION

In these modern times of automatization, it involves a magnificent investment to set up a manufacturing plant. The continuance of these plants demands tremendous productivity with a great payback ratio. Hence, to accomplish the stated objectives of production, it is desired that the production unit is operative for the maximum period. But with time, the provided unit undergoes failure, which needs to be resumed to a functional state through service and maintenance. The reasons of these failures include human mistakes, improper maintenance or meagre inspection leads to slight inconvenience to a complete loss of service. The performance and endurance of a unit can be enhanced by proper designing and sincerely maintaining it during the service. Planning as well as scheduling of maintenance tasks plays a vital role in diminishing the production cost, enhancing the availability of production systems and in improvising the quality, which further leads to gain better performance and client satisfaction.

As regards, to reduce the system failures it is required to do a detailed analysis of RAM parameters i.e. Reliability, Availability and Maintainability. Importance of reliability as well as maintainability has been increased with the advancement of technology and flourishing complexity of systems. The same is the case with process industry, which makes use of highly expensive and specially designed equipments with inflexible environmental constraint. This all makes the job of a maintenance engineer more difficult as they have to analyse the performance of a unit more closely by studying, characterizing and measuring different parameters.

1.2 INTRODUCTION TO RAM CONCEPT

1.2.1 Reliability

Reliability is majorly related with the frequency as well as probability of failures. Repairable systems make use of Mean Time between Failures (MTBF) as a widely used measure to test reliability. The said measure for non-repairable systems is Mean Time to Failure (MTTF). It is also being used as a chance of success over a period. Under instrument maintenance, reliability is a vital factor as low instrument reliability means high maintenance. For great plant performance, instrument reliability is the major requirement because factors like quality, capacity and profitability of product depends solely on reliability. For a certain period the reliability of an element is calculated as:

$R(t) = e^{-\Psi t}$ where, Ψ is the mean failure rate.

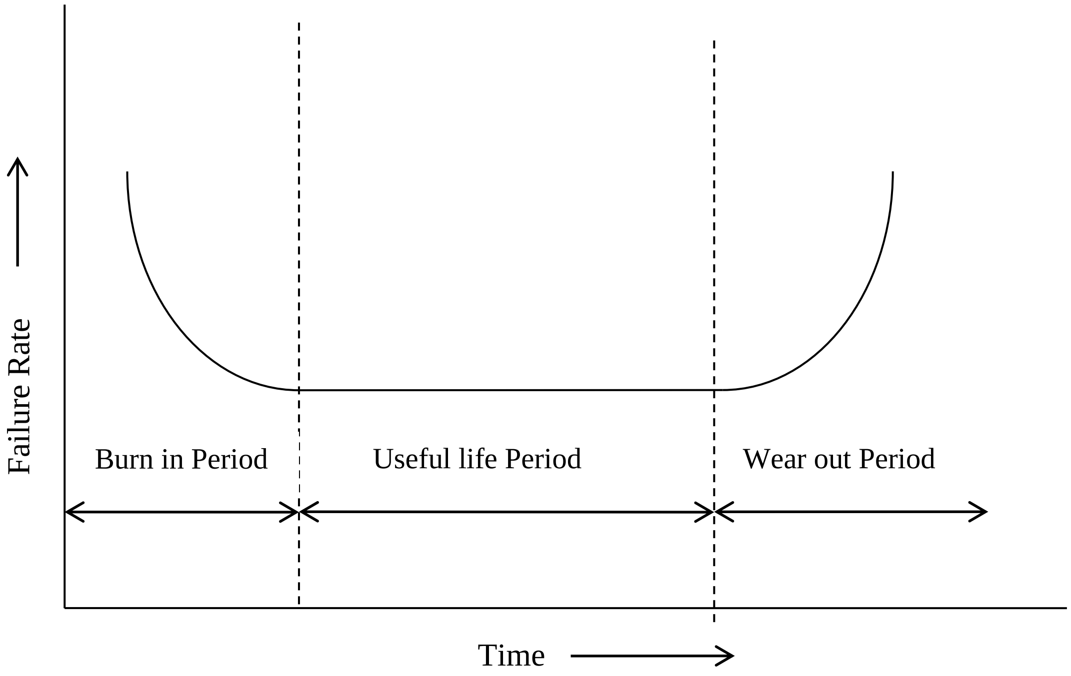


Figure 1.1 Bath-Tub Curve

In reliability studies of engineering system, it is assumed that items that depend on danger or time failure rate follow the bathtub shape as depicted in figure 1.1. There are three different regions in the bathtub curve: burn-in period, useful life period and wear out period.

The burn in region is also called as infant mortality period or debugging period. In this period failure arises due to many reasons such as improper installation, poor skills, cracks, defective parts, design and production defects etc. These failures can be diminished by acceptance sampling, different quality control approaches and burn in testing.

In the second period of bathtub curve the rate of failure is constant and the failures happen unpredictably. Some reasons of failures in this useful period are certain unavoidable failures, improper usage, inadequate design margins and human errors. The failures in this period can be diminished by integrating redundancies in the system.

The wear out period initiates when an item crosses the second i.e. the useful life period. In this period the risk rate increases and the failures occur due to a number of reasons such as friction, improper usage, aging, incorrect alignments, improper or insufficient preventive and repair measures, corrosion and restricted life components. The failures in wear out period can be diminished by substitution and incorporation of preventative procedures and policies for maintenance.

1.2.2 Maintainability

Maintainability of an item can be defined as its ability to be recovered or maintained in a particular condition. A skilled person is only able to maintain and repair the instruments using certain protocols and resources. Hence, it is right to state that maintainability is the process by which failures are prevented economically as well as effectively and is also measures the time period in which the system failure is restored using appropriate corrective measures. Mean Time to Repair (MTTR) is widely being used as a measure of maintainability by using different corrective measures. Maintenance comprises of operations to prevent and repair a failure while maintainability is a design variable.

Reliability, Maintainability and Availability are the terms that describe a system that can be repaired. Evolution of a running system can be observed by evaluation of said matrices at varied period of time. The measures of these matrices are condition based that can be actual, preventive and emergency maintenance actions taken that are being performed with a particular set of rules and regulations. The ultimate aim of all activities for maintenance is to make sure the functioning of a system at a reasonable cost. The traditional models used for reliability, maintainability and availability are very much clumsy and obstinate while the models that are based on latest techniques are much more promising and their application is increasing recently.

Maintainability can be influenced by various design features like exchangeability, complexity and availability of different components. Apart from these there are some environmental and operational factors that affect maintainability like monitoring, experience, skill sets, training, operating workforce, publication availability and protocol for examining, testing and calibration of failure. There are only few techniques available to measure the said factors in numeric terms. However, it is very much difficult to evaluate their specific effect on maintainability.

1.2.3 Availability

Huge Plant availability in an industrial system plays a vital role for industrial growth because profit gained is directly related to the volume of production that depends upon the unit performance. For higher system availability there should be appropriate maintenance management system that was being supported by sufficient resources like spare parts, machine and workforce. Therefore it is right to state that this is a cyclic event, better the availability of maintenance facilities, higher will be the system availability, greater will be the production rate and also greater will be the profit. In mathematical terms, availability can be described as probability of an equipment to be in an operational condition at any particular time. The availability of particular system can be measured with the combination of reliability as well as maintainability.

As per British Standards 4778, availability can be defined as capability of an item to carry out its desired functions at a particular time (under combined aspects of reliability, maintainability and maintenance). It can be described as probability of an equipment to be in an operational condition at a specific time. It is possible to quantify availability by knowing the time off of the instrument, whereas availability of any repairable system can be examined in terms of failures and repairs of the subsystems.

There are various ways to define availability:

1. Instantaneous Availability, $A_v(t)$: It can be defined as the probability that a unit is functional at a particular point of time. It is provided by anticipated up-time of the unit.

$$A_v(t) = E\left[Y(t)\right]$$

Where, Y (t) is an indicator variable

Y (t) =0; if the unit is in operating state at time t.

Y (t) =1; if the unit is in failed state at time t.

2. Average Uptime Availability, A_v (T): It can be defined as the portion of time in which the unit is available to be used in a particular interval (0, T).

$$A_v(t) = \frac{1}{T}\int_0^T A_v(T)dt$$

3. Steady State Availability, $A_v(\infty)$: It can be defined as the probability that a unit is functional for infinite period of time

$$A_v(\infty) = \lim_{T\to\infty} A_v(t) = \lim_{T\to\infty} \frac{1}{T}\int_0^T A_v(t)dt$$

4. Inherent Availability, A_{vi}: This can be defined as the portion of time in which the unit is functional by including only corrective maintenance downtime while exempting the ready time and down times for preventive maintenance, logistics and waiting etc.

$$A_{vi} = \frac{MTBF}{MTBF + MTTR}$$

5. Achieved Availability, A_{va}: It can be defined as the portion of the time in which the unit is functional by including both corrective as well as preventive maintenance down times and exempting ready times for logistics and waiting.

$$A_{va} = \frac{MTBM}{MTBM + M}$$

Where, MTBF= Mean Time Between Maintenance

M=Mean active maintenance down time

6. Operational Availability, A_{vo}: This can be defined as the probability that a unit would work satisfactorily when used under said conditions and in a particular environment (tools, workforce and protocols availability) at any particular time. It exempts ready time and down times for preventive maintenance, supply chain and administration etc. It is expressed as:

$$A_{vo} = \frac{MTBM}{MTBM + MDT}$$

Where, MTBM= Mean Time Between Maintenance

MDT=Mean Down Time

7. Mission Availability: It can be defined as the ability of a unit to be expressed by the probability that the same will be available in operational state for a mission according to a plant requirement.

1.3 MAINTENANCE: FACTS AND FIGURES

Manufacturing firms face great pressure to reduce their production costs continuously. One of the main expenditure items for these firms is maintenance cost which can reach 15-70% of production costs, varying according to the type of industry (Bevilacqua and Braglia, 2000). So, the role of maintenance is changing from a “necessary evil” to a “profit contributor” and towards a “partner” of companies to achieve world-class competitiveness (Waeyenbergh and Pintelon, 2002). Some of the important facts and figures directly or indirectly associated with engineering maintenance are given below (Dhillon, 2002) as:

- Each year over $300 billion are spent on plant maintenance and operations by U.S. industry and it is estimated that approximately 80% of this is spent to correct the chronic failure of machines, systems, and people.
- In 1970, a British Ministry of Technology Working Party report estimated that maintenance cost the United Kingdom (UK) was approximately £3000 million annually.
- Annually, the cost of manufacturing a military jet aircraft is around $1.6 million; approximately 11% of the total operating cost for an aircraft is spent on maintenance activities.
- The typical size of a plant maintenance group in a manufacturing organization varied from 5 to 10% of the total operating force: in 1969, 1 to 17 persons and in 1981, 1 to 12 persons.
- The U.S. Department of Defence is the steward of the world’s largest dedicated infrastructure, with a physical plant valued at approximately $570 billion on approximately 42,000 square miles of land, i.e., roughly the size of the state of Virginia.
- The operation and maintenance budget request of the U.S. Department of Defence for fiscal year 1997 was on the order of $79 billion.
- Annually, the U.S. Department of Defence spends around $12 billion for depot maintenance of weapon systems and equipment: Navy (59%), Air Force (27%), Army (13%), and others (1%).
- In 1968, it was estimated that better maintenance practices in U.K. could have saved approximately £300 million annually of lost production due to equipment unavailability.
- The amount spent on maintenance budget for Europe is around 1500 billion euros per year and for Sweden 20 billion euros per year.

1.4 RELIABILITY CENTRED MAINTENANCE (RCM)

In accordance with Electric Power Research Institute (EPRI), RCM is an organized consideration of a unit functions. It includes the ways in which functions can fail and a priority-based deliberation of safety and finance that identifies relevant and effective preventive maintenance (PM) duties. The main aim of RCM is to diminish the maintenance expense by concentrating on the most vital functions of the unit and preventing the unnecessary maintenance actions. It is relied on the hypothesis that the reliability of an instrument is a function of its design and the construct quality. RCM is an approach to develop an efficient preventive maintenance schedule. An efficient PM schedule will make sure that the innate reliability is accomplished. But, this cannot improvise the reliability of the unit and can be possible only through redesign or modification. A PM schedule must have a reduced estimated loss due to staff injury, environmental harm, production loss, and/or financial damage in order to be successful. When designing the PM schedule, always keep in mind that RCM would never be able to compensate for bad design, poor construction quality, or poor maintenance practises.

1.5 TOTAL PRODUCTIVE MAINTENANCE (TPM)

Total productive maintenance incorporates an enterprise-wide approach to unit, instrument or asset care which includes the lively involvement of all from upper management to employees on the ground to enhance instrument effectiveness by eradicating the six big losses such as Downtime loss, Set-up and adjustment loss, speed loss, diminished speed, Defect loss and diminished yield. In TPM the exercise of preventative maintenance is combined with total quality using involvement of employees. Engineers maintain their instruments by exercising 5S principles. They used to accumulate and decipher maintenance as well as operating data of the machines that helps them to identify signs of any degradation. Routine Checks for maintenance, slight adjustments, lubrication and slight component changes are some of the activities executed by the engineers. TPM improves the overall instrument effectiveness and the same is a vital indicator to measure TPM.

1.6. AVAILABILITY ISSUES IN PROCESS INDUSTRIES

Availability analysis is growing day by day in process plants. The process plants are huge and include complex engineering systems. This type of industry is capital concentrative and manufacturing is carried out on continuous basis. Hence, availability of production unit is very much important and crucial for smooth working of the unit. With this, the maintenance also becomes a vital fragment of such establishments as the stoppage is enormously costly. Therefore maintenance on regular basis needs to be done to make sure the maximum unit availability as well as reliability. There is an ultimate need to plan the maintenance schedules in accordance with the production schedules to minimize the stoppages and production loss. A detailed analysis on availability is essential for plant managers to improve performance of the units to achieve the aim of production. The decision on contractual deliveries can be taken after doing a detailed analysis of issues.

1.7 MARKOV PROCESS

A Markov model is used for the systems whose states are probability based. To analyse the availability of the system numerous approaches in the past have been used e.g. for very complex system Monte Carlo Simulation approach have been applied to analyse system availability, but its experimentation cost was too high. The Markovian probability based model was commonly used for the system availability analysis assuming exponential distribution for repair and failure rates due to mathematical complications.

A Markov process is a stochastic process where at some random time, the ensuing course of process is dependent only on the state at that time and independent upon the process at any other time. Markov models are basically the functions of two random variables, the state of the system and the time of observation. Availability studies essentially manage the discrete state, continuous time models. Such a model is represented by a typical element P_{ij} which denotes the transitions probability from state i to a mutually exclusive state j.

A set of Markov state equations can be set up to find the transitions probability from an initial state i to a final state j. Formulation of these set of equations turns out to be more complex for systems with numerous non-repairable components and multiple states. The circumstance gets more complicated if a transition from failed to the operating state for repairable systems is also to be taken into contemplations.

In past several approaches were suggested to determine the availability of the system with dependent failure and repair rates or standby system. An approach that functions admirably when repair and failure rates are constant requires the utilization of Markov probabilistic model. Markov graph are used to represent the Markov process which consists of nodes to represent the states and branches to represent transitional probabilities of the system.

The assumptions made in Markov models are:

- System at any given time is either in operating state or in the reduced/ failed state.
- The state of the system changes as time progresses.
- The transition of the system from one state to the other takes place instantaneously.
- Failure/repair rates over time are constant.

For one component system the expression for availability is derived as follows:

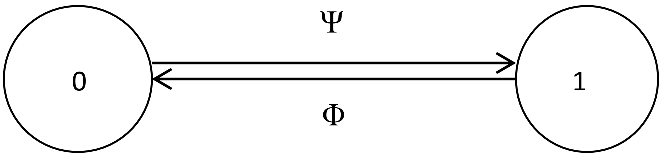


Figure 1.2 Two-State Representation of a System Consisting of One Component

Let, P_0 (t + dt) represents the probability of the system at time t+ dt in state 0 (good state), Ψ, Φ are the failure rates and repair rates respectively of the components. P_0 (t + dt) can be determined by summing the probability at state 0 at time t and did not fail during time (t, t + dt) to the probability of failed state (state 1) at time t and was taken to state 0 during (t, t+ dt). Thus,

$$P_0(t+dt) = P_0(t)(1-\Psi \mathrm{dt}) + P_1(t)\Phi \mathrm{dt} \tag{1.7.1}$$

Similarly P_1 (t + dt) represents the probability of the system at time t + dt in state 1, and can be calculated by summing the probability at state 0 at time t and failed during (t, t + dt) and the probability at state 1 at time t and the repair was not done during (t, d+ dt). Thus,

$$P_1(t+dt) = P_0(t)\Psi \mathrm{dt} + P_1(t)(1-\Phi)\mathrm{dt} \tag{1.7.2}$$

Equations (1.7.1) and (1.7.2) can also be written as:

$$\frac{dP_0(t)}{dt} = -\Psi P_0(t) + \Phi P_1(t) \tag{1.7.3}$$

$$\frac{dP_1(t)}{dt} = \Psi P_0(t) - \Phi P_1(t) \tag{1.7.4}$$

with initial conditions,

$P_0(0) = 1$,

$P_1(0) = 0$ at time $t = 0$,

To find the steady state solution the first derivative of P_0 and P_1 is put equal to zero. By putting $dP_0/dt = 0$ and $dP_1/dt = 0$ in equations (1.7.3) and (1.7.4), following equations are obtained

$$-\Psi P_0 + \Phi P_1 = 0 \quad (1.7.5)$$

$$\Psi P_0 - \Phi P_1 = 0 \quad (1.7.6)$$

Since the sum of the probabilities of mutually exclusive events is one, we have

$$P_0 + P_1 = 1 \quad (1.7.7)$$

1.8 DESCRIPTION OF AVAILABILITY MODEL AND PRESENT RESEARCH WORK

Availability model has been developed for a particular system of a paper plant using probabilistic method for stochastic modeling. Firstly, different differential equations are formulated using Markov process after drawing transitions diagram and then the obtained equations are solved recursively assuming steady state conditions. Using normalizing conditions steady state probabilities obtained are further solved i.e.

$\left(\sum_{i=0}^{n} P_i = 1\right)$, n=total number of states

Steady state availability (A_v) of that system can be obtained by summation of all 'm' operational state probabilities, i.e.

$$A_v = \sum_{j=0}^{m} P_j = P_0 + P_1 + \dots\dots\dots\dots\dots\dots + P_m$$

The developed availability model is basically a function of failure rates (Ψ_m) and repair rates (Φ_m), of various subsystems.

$$A_v = f\left(\Psi_m, \Phi_m\right)$$

where m = number of subsystems in a system.

In the present work, to evaluate the performance, availability models have been developed for various systems of a paper industry. Then these models have been analysed to find the most critical subsystem of various system of a paper plant. Then criticality analysis is performed using integrated cloud model and PROMETHEE II to rank the failure causes of various subsystems of paper plant which will allow the maintenance personal to select the best maintenance policy for the critical component to minimize the risk and cheapest corrective maintenance policy for the least critical component. In last, resource allocation and profit analysis for the paper plant is carried out which facilitate the management to run the plant at certain availability.

1.9. RESEARCH OBJECTIVE

The main objectives of the present work are as follows:

1. To understand the functioning of various operating systems and subsystems of selected industry.
2. Performance analysis of identified system of a selected industry.
3. To develop the maintenance planning system.
4. Develop a model for resource allocation.

1.10. ORGANIZATION OF THE THESIS

The chapter wise details of the thesis are as follows:

Chapter 1 discusses the introduction to reliability, availability and maintainability studies in general and process industries in particular. It describes the formulation of the problem and its relevance and a brief description of the methodology adopted followed by basic concepts, general terms and definition used in the work. Subsequently, the chapter discusses the objectives of the proposed study. At the end, it provides the organization of the thesis.

Chapter 2 is devoted to the literature survey where the contributions of the various academicians related to mechanical reliability, availability and maintainability, Markovian theory, common cause failure and steady state availability, various multi-criteria decisions making approach to perform maintenance criticality, resource allocation and profit analysis in process industries have been discussed. Research gaps are also identified after critical review of the literature.

Chapter 3 discusses the functioning of various operating systems and subsystems of the paper plant with the help of schematic flow diagram. In this chapter the steady state availability for various operating systems i.e. feeding, pulping, bleaching and washing, screening and paper making systems have been developed using probabilistic approach based on Markov birth-death process.

Chapter 4 deals with the performance analysis of various operating systems of the paper plant in terms of the availability matrices which are based upon failure rate and repair rate. The appropriate values of failure rates and repair rates for various subsystems are selected after deep study by continuous monitoring of failure/repair patterns, long discussions with highly skilled experienced plant personnel and consultation of maintenance log sheets and history cards. The effect of various parameters on system availability has been analysed.

Chapter 5 discusses a new methodology based on cloud model and PROMETHEE II (Preference Ranking Organization Method for Enrichment of Evaluations) for evaluating the maintenance criticality of failure causes. The proposed approach is based on more number of criteria (chance of failure occurrence, chance of non-detection, down time length, spare part criticality and safety risk) than the number of criteria of RPN evaluation in traditional FMEA technique. With the help of cloud model, objective weights of the decision makers are found, AHP is used to find the weights of the considered criteria and PROMETHEE II is used to rank the failure causes associated with its component. This will help the plant personnel to plan suitable maintenance strategies accordingly.

Chapter 6 discusses resource allocation and manpower planning. Resource allocation for each stage has been carried out using dynamic programming method to solve the multi stage decision problem. Allocation of resources for each operating system of the paper plant has been worked out. Economic production charts are drawn to determine no loss/ no profit point beyond which the system should run to generate profit. Profit analysis for the plant has been carried out.

Chapter 7 presents the summary, implications and limitations of the present research work.

Performance analysis for the systems in paper plant provide a basis for deciding the repair priorities and the feasible value of failure and repair rates for a certain level of availability in various subsystem. Maintenance planning definitely will help in maintaining the plant in upstate for maximum duration of time. Resource allocation and profit analysis gives an idea regarding the maintenance efforts needed and thus the profit achieved.

Towards the end, scope for future work and references are given.

CHAPTER II

LITERATURE REVIEW

2.1 HISTORICAL BACKGROUND

The history of engineering shows that failures may happen in any working unit and the same can be from different fields of engineering, for example Tacoma Bridge in USA distorted because of torsional vibrations and it happened in 1940, just after few months of its construction. In Portland 1943, the first welded tanker broke into two parts while lying afloat in still water of a dock. In 1985, massive destruction occurred due to gas leakage in Union Carbide, India and the accident in power reactor at Chernobyl USSR in 1986, explosion of space shuttle Challenger,1986 in mid-air are few worst examples of system failure. The importance of dependable instruments can be seen in daily routines i.e. washing machines, mixer, dryer and vehicles to the large multifaceted systems like railways and process industries. During World War II also, the need for high reliability as well as quality of system was also seen where 60% of the total instruments were found damaged and around 50% of the remaining instruments were not serviceable. It was also stated in 1949 that around 70% of the electronic instruments of navy were not in proper operating condition.

Despite of various difficulties, reliability engineering arose as a distinctive discipline of engineering in USA 1950. A group was also formed by Air force to study the situations and measures to increase the reliability and to diminish the maintenance of electronic instruments. In 1951, the navy and army did similar studies. An advisory group was formed by defence department in 1952 to synchronize the efforts of army, navy and air force on reliability of electronic instruments and accordingly a report was published in 1957. The conclusion of said report stated that reliability testing should be an integral part of new engineering units. The new instruments were tested for number of hours that included different level of temperatures, on and off switching and steady as well as vibratory conditions. The instrument testing was performed to find any designing defect at an initial stage and to correct the same before the onset of production. The defence accepted the said report and the same then became a law. Later on many new organisations have come into existence to promote reliability among producers and customers.

Recently there is a lot of burden on the production and process industries to exist in the competitive market; they need to fulfil the demand of quality products to the consumers. The malfunctioning of system leads to huge expenses due to manufacturing losses and delays. The process industry is a sort of complex system that can be arranged in either series or parallel or a combination of both. In these sorts of industries if any system fails for some instance can lead to production loss. There are number of causes of failure of a system such as improper designing, minimal strategic maintenance, improper coordination among the workers, unskilled employees and inadequate inventories. In order to deal with such situations, it is important to have a proper maintenance policy with proper goal in order to put the deteriorated unit into workable state before complete failure. This is one of the major reasons of increasing importance of availability issues in different industrial system during last some decades.

2.2 RELIABILITY, AVAILABILITY AND MAINTAINABILITY

With the complexity of systems, the penalties of their unpredictable behaviour became more severe in terms of money, energy, lives etc. The interest in measuring unit availability and the need to improvise the reliability of systems become very much crucial. In the past few decades, there has been a lot of development in measuring the availability and performance of process plants. Reliability as well as availability is the most vital performance measures for systems that can be repaired. The area of major concern for reliability is to improve the system availability and for it lots of research and articles are available. The features of reliability and maintainability can be used to deal with the availability allocation problems at element level. Hence it is right to state that reliability, availability and maintainability are the important measures to improve the current availability features.

The main purpose of analysis of system reliability and availability is to recognise the weakness of in a system and to measure the impact of component failures. Instrument’s performance depends on reliability as well as availability of the system used, working environment, maintenance effectiveness, operational process and technical skills of worker etc. Reliability and availability are interrelated but it is not necessary that the both are directly related. It is also possible to have an instrument that often breaks down for short period; in that case there is a reasonable level of availability present. Likewise, it is also possible that an instrument is highly dependable, but has got low availability because most of the times it is out of service for maintenance. It is very much important to improvise RAM aspects throughout the life of the instrument in order to meet its ultimate goals.

Reliability is a measure of performance of systems. Since 1960 numerous researchers has been attracted for Reliability engineering due to its critical importance in a variety of systems. Dhillon and Singh (1981), Zaho (1994), Adamyan and Dravid (2002) and Bhamare et al. (2008) performed availability analysis using Markovian approach by assuming exponential distribution for failure and repair rates. Kumar et al. (1988, 1989, 1991 and 2007), Bradley and Dawson (1998), Sharma and Garg (2011) developed Markov model for performance analysis and evaluation of urea fertilizer and paper plants. Gupta and Agarwal (1984), Gupta and Sharma (1993) performed the reliability analysis of a complex system with various modes of failures and only one repair type. Kumar et al. (1988) performed the reliability, availability and performance analysis for various systems of a paper industry. Kumar et al. (1993) developed the maintenance planning for various systems of fertilizer and thermal plants. Michelson (1998) performed the analysis in process industry and described reliability technology uses in the same. Reliability and availability analysis is performed by Singh et al. (1990) in fertilizer industry. Somani and Ritcey (1992) discussed reliability analysis for variable configuration systems. Kumar et al. (1992) performed the availability analysis system in sugar industry for crystallization unit. Dayal and Singh (1992) discussed reliability analysis in a fluctuating environment for a system. Singer (1990); Arora and Kumar (1997) performed the long term steady state availability analysis of steam and powder generation units of a thermal power plant. Singh and Mahajan (1999) used Laplace transformation method to determine the reliability and availability of a utensils manufacturing industry. Kumar et al. (1999) developed a stochastic model to perform the availability analysis of ammonia synthesis system in a fertilizer plant. Singh and Jain (2000) determined the reliability of repairable multi-component redundant system. Biswas and Sarkar (2000) developed a model for system with various imperfect repairs to determine its availability. Arora and Kumar (2000) determined the long term availability of a coal handling system. Rigdon et al. (2000), Gertsbakh (2000) and Lim et al. (2000) described the various methods for the reliability analysis of repairable systems. Blischke and Murthy (2003) identified that reliability and availability of any system is affected by various factors like design, manufacturing, operation, material, maintenance etc. Castro and Cavalca (2003) stated that availability of any system can be increased by either increasing the availability of every unit or by using redundant components. Watanabe et al. (2003) calculated the common cause failures through simulation. Tewari et al. (2003, 2005) dealt with development of decision support system for the refining system of a sugar plant. Yadav et al. (2003) and Dai et al. (2003) performed reliability and availability analysis for some complex systems. Ocon et al. (2004) and Murthy et al. (2004) proposed the reliability modelling and analysis using different modeling methods. Marquez et al. (2005) estimated reliability and availability of a cogeneration plant. Gupta et al. (2005a, 2005b, 2007) performed the long-term steady state availability and reliability of a cement manufacturing plant, butter oil processing plant and plastic-pipe manufacturing plant respectively. Singh et al. (2005) developed a model for an ash handling system to analyzed a three-unit standby system of water pumps. Tewari et al. (2000 and 2005) determined the availability for a sugar plant with independent failures and repairs rates. Marquez et al. (2007) formulated the redundancy allocation problem for maximizing the system availability under common cause failure. Zio et al. (2007) presented a Monte Carlo simulation model for evaluating the availability of a multi-state and multi output offshore installation. Ameri and Teri (2007) performed a transient availability and survivability analysis with identical components and repairman. Lisnianski (2007) performed reliability assessment for a multistate system with repair facility using extended block diagram method. Young et al. (2008) proposed a method to predict the availability of the system. Khanduja et al. (2008) studied the application of Markovian approach for the availability modeling and performance evaluation of various complex systems of the process industries. Gupta et al. (2008) and Khanduja et al. (2008a, 2008b) developed a stochastic model and decision support system for performance evaluation of a complex system. Barabady and Kumar (2008) stated that to reduce the maintenance cost, high reliability of system is desired. Rajiv et al. (2008) performed the availability analysis for a screening system of a paper plant. Sharma et al. (2008, 2009) proposed the performance modeling for different process industries using reliability and availability analysis. Kumar et al. (2008, 2009a, 2009b, 2010) developed a simulation model to evaluate the performance of various systems of a fertilizer plant. Gupta et al. (2009) discussed the reliability and steady state availability analysis of the ash handling subsystem of a steam thermal power plant. Garg et al. (2010) analyzed the availability of cattle feed plant. Garg et al. (2010) discussed about the availability and maintenance scheduling of a repairable blockboard manufacturing system. Krishan and Somasundaram (2011) suggested a method to improve reliability and MTTF for circular and linear systems. Shakuntla et al. (2011) developed a model for availability analysis of a pipe manufacturing industry by using supplementary variable technique. Gupta and Tewari (2011) performed the availability analysis of a thermal power plant. Yuan and Meng (2011) developed a reliability model for a repairable system consisting of two dissimilar units with one repairman only. Mathew et al. (2011) analyzed the reliability of a two-unit continuous casting plant. Sefidgaran et al. (2012) developed a reliability model for the power transformer with ONAF cooling. Savsar (2012) stated a model useful for design engineers and operational managers to analyze the performance of a system at the design or operational stages. Khanduja et al. (2012) demonstrated the steady state behaviour and maintenance planning of the bleaching system of a paper plant. Bhardwaj and Malik (2012) presented conventional fault tree analysis approach integrated with fuzzy theory to evaluate the reliability of a fire detector system. Yuge et al. (2013) presented two methods; one for calculating the steady state probability of a repairable fault tree with priority AND gates by Markov analysis and other for repeated basic events when the minimal cut sets are given. Modgil et al. (2013) developed performance model based on Markov birth-death process for shoe upper manufacturing unit and calculated time dependent system availability (TDSA) with long-run availability. Sharma and Khanduja (2013) developed a model for the availability analysis of the feeding system of a sugar mill. Jain and Preeti (2013) analyzed a repairable robot safety system composed of standby robot units and inbuilt safety. Chen et al. (2013) dealt with the preventive maintenance scheduling problem of reusable rocket engine. Ardakan and Hamadani (2014) considered the mixed-integer non-linear optimization-redundancy allocation problem to determine simultaneous reliability and redundancy level of components. Ahmed et al. (2014) performed availability analysis of a processing unit using Markov approach. Doostparast et al. (2014) planned a reliability based periodic preventive maintenance (PM) for a system with deteriorating components. Gowid et al. (2014) presented the reliability model based on the time-dependent Markov approach for a LNG production plant. Shahrzad et al. (2014) developed a dynamic model for the availability assessment of multi-state weighted k-out-of-n systems. Sharma and Vishwakarma (2014) computed the availability of feeding system and it is optimized by applying genetic algorithm technique. Reliability analysis is performed for different system using Markovian approach by various authors; butter manufacturing system in a dairy plant by Gupta et al. (2005), two non-identical parallel repairable unit by Kakkar et al. (2015), urea synthesis system of a fertilizer plant by Aggarwal et al. (2015), condensate system of thermal power plant gas and steam power plant of combined cycle power plant by Sabouhi et al. (2016), and sugar manufacturing plant by Garg (2015), Kumar and Saini (2018). Pandey et al. (2018) also performed reliability analysis to enhance the system availability by identifying the critical subsystem by finding risk priority number (RPN) for better maintenance planning. Using supplementary variable technique; Kadiyan and Kumar (2017) performed performance analysis of a sugar industry and Kumari et al. (2019) performed performance analysis of milk plant. Availability analysis is performed for various systems by different authors; fertilizer plant by Kumar et al. (2009), steam generating system in thermal power plant by Tewari et al. (2012), shoe manufacturing unit by Modgil et al. (2013), A-pan crystallization system sugar industries by Dahiya et al. (2019), condensate system of thermal power plant by Gupta (2019), butter oil processing plant by Singhal and Sharma (2019). Reliability, availability, maintainability and dependability (RAMD) analysis is also performed for various system by various researchers; Saini and Kumar (2019) evaporation system of sugar industries, Choudhary et al. (2019) to improve availability of cement industry to reduce maintenance time, Tsarouhas (2019) to upgrade the maintenance management of milk industry.

2.3 MAINTENANCE POLICY SELECTION

In specialized resources, risk is measured in terms of likelihood of failure occurrence and expected outcomes such as failure (Kaplan and Garrick, 1981). Hence, firms execute maintenance strategies as a method for moderating the risks. According to Pintelon and Puyvelde, (2013) maintenance strategy is a sequence of actions applied to maximize the reliability and availability of the equipment to manufacture desired quality and quantity products. Thus the entire manufacturer wants a maintenance system in which expenditure on maintenance is minimum but the reliability of the system is maximum. In any case, less maintenance will reduce the expenditure cost on maintenance but may result in frequent machine breakdown (Pourjavad et al., 2013).

According to Zaim et al., (2012), failure of the system due to inadequate equipment maintenance prompts increment in the manufacturing cost, delay in delivery plan, loss of benefit, loss of chance. Moore & Starr, (2006) stated that it causes inherent losses to the organization due to unsatisfied customers. Grievink et al., (1993) reported that in the initial starting stage of the industry maintenance costs are estimated to be 2-6% of capital costs and according to Bevilacqua and Braglia, (2000) due to lack of maintenance activities, its cost may consumes 15 to 70% of total production cost depending upon the industry. Ilangkumaran and Kumanan, (2009) illustrated that maintenance cost for heavy process industries lies well over 15% of the total production cost and minimization of this percentage may help in improving profitability. Also penalty costs are associated if the demands are not met in time. In order to avoid these situations, it is necessary to adopt an appropriate maintenance strategy i.e. corrective maintenance (Wang et al., 2014), time-based maintenance (Jonge et al., 2015), reliability centred maintenance (RCM) (Thawkar et al., 2018) and condition-based maintenance (Khatab et al., 2018) including preventive maintenance (PM) (Ebrahimi et al., 2018) depending upon the criticality of the system in order to repair or replace the deteriorated system before failure. Apart from failure-related costs, sometimes failure of the system possess some indefinable risks. An essential worry in such manner is the need of evaluating the risks related with equipment failure before planning and conveying suitable mitigation policies (Chemweno et al., 2015). The selection of appropriate maintenance policies is critical and complex in maintenance management as it involves safety, cost, added value, feasibility and also it is very hard to measure and quantify the output of maintenance (Mechefske and Wang, 2003).

Deciding the best maintenance policy is not an easy matter as the maintenance program must combine technical requirements with the management strategy. A good maintenance program must define maintenance strategies for different facilities. The failure mode of every component must be studied in order to assess the best maintenance solution, in accordance with its failure pattern, impact and its cost on the whole system. This information helps the maintenance personnel to decide the best suited maintenance action and to assign the different priorities to various plant components and machines.

To decide an appropriate maintenance strategy, it is necessary to find what the root causes of failure are, what its mode is and what are its effect, which according to Stamatis (2003), can be done through failure mode and effect analysis (FMEA). It is a standout tool for carrying criticality analysis for process industry with criticalness being measured by assessing Risk Priority Number (RPN) which is a product of likelihood of failure occurrence, severity and likelihood of non-detection and used by many researchers in many industrial applications such as; coal handling system (Panchal and Kumar, 2017) and diesel engine turbocharger (Xu et al., 2002).

The traditional FMEA employed in the industry has been censured as it is having several problems being addressed by numerous authors (Straker, 1995; Sankar and Prabhu, 2001; Liu et al., 2011; Kutluand Ekmekçioğlu, 2012). The problems identified by these authors are that (i) this technique take into account only three attributes as discussed above in prioritising risk whereas many other important attributes are not considered, (ii) various combination of three decision criteria acquiescent the same RPN value though the apparent criticalness may be absolutely different (iii) non consideration of interrelations among the various failure modes and effects. These make the traditional FMEA unsuitable and in order to reduce these problems and enhance its effectiveness, various Multi-Criteria Decision Making (MCDM) techniques have been applied in the literature.

2.4 MULTI-CRITERIA DECISION MAKING

A review on multi-criteria decision analysis is given by Kumar et al. (2015) and Jamwal et al. (2020). Analytic hierarchy Process (AHP) is one of the most widely used MCDM approach to rank the alternatives by finding the priority weights of the criteria (Saaty, 1980). Triantaphyllou et al. (1997) used the AHP in which he considered reliability, availability, cost and reparability as the four maintenance criteria. Bevilacqua and Braglia (2000) applied AHP technique for the selection of maintenance strategy in an oil refinery plant selection by considering economic, applicability and costs, safety, etc as the evaluation criteria. Emblemsvag and Tonning, (2003) employed AHP to find an appropriate maintenance strategy for weapon system of Norwegian Army. Bertolini and Bevilacqua (2006) proposed a hybrid AHP and goal programming based model along with traditional FMEA criteria for maintenance strategy selection taking into account the cost and labour constraints. Sachdeva et al. (2008) utilized the AHP approach for computing the ranking of various components/failure on the basis of seven evaluation criteria. Cascales & Lamata, (2009) proposed the use of an AHP as a potential decision-making method in the selection of a parts cleaning system for diesel engine maintenance. Gupta et al. (2011) applied the AHP method to evaluate the priority of product metrics for sustainable manufacturing. Bahadir and Bahadir, (2015) applied AHP method to select the e-textile structure manufacturing process.

TOPSIS (Technique for order preference by similarity to ideal solution) method is linear weighting technique which was originally proposed in its crisp version by Hwang and Yoon (1981) to select the best option with a limited number of criteria. Deng et al (2000) presented a modified weighted TOPSIS method to ensure a meaningful interpretation of the evaluation result. Sachdeva et al. (2009) proposed the TOPSIS method to formulate the priority ranking by considering maintainability, safety and cost along with traditional FMEA for risk assessment. Zhou & Lu (2012) presented the drawbacks of TOPSIS stating the failure to calculate dynamic weights of the evaluation criteria and used fuzzy TOPSIS for risk evaluation.

Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) and Elimination and Choice Expressing Reality (ELECTRE) are an outranking method which was developed by Roy (1990) and Brans et al. (1986). ELECTRE method takes uncertainty and vagueness into consideration which are inherent in data obtained by predictions and estimations. Brito & de Almeida (2009) ranked the risks associated with the natural gas pipelines based on multi-attribute utility theory. Brito et al. (2010) assessed the risk in natural gas pipelines through an integrated ELECTRE method and model utility theory. Cavalcante and Almeida (2007) developed a model that permits more rational planning for preventive maintenance by controlling failures in the specific context of equipment breakdown using PROMETHEE. Abdelhadi (2018) used PROMETHEE for maintenance scheduling. Sen et al. (2015) applied PROMETHEE II for selection of robot for industrial purpose. PROMETHEE method has been widely used widely to solve various MCDM problems such as airport location selection by Sennaroglu and Celebi (2018), service quality evaluation by Tuzkaya et al. (2019), and emergency response assessment by Nassereddine et al. (2019). Different MCDM with their application, strengths and weakness is mentioned is mentioned in the Table 2.1.

Table 2.1 Different MCDM approaches with their application, strengths and weakness

Methods	Application area	Strengths	Weakness
Analytical hierarchy process (AHP) (Saaty 1980; Ishizaka and Labib (2009)	1. Resource management 2. Corporate policy and strategy 3. Public policy 4. Energy Planning 5. Logistics & transportation engineering	1. Adaptable 2. Doesn't involve complex mathematics 3. Based on hierarchical structure and thus each criteria can be better focussed and transparent	1. Interdependency between objectives and alternatives leads to hazardous results. 2. Involvement of more decision maker can make the problem more complicate while assigning weights. 3. Demands data collected based on experience
Analytic Network Process (ANP) (Saaty and Vargas 2013)	1. Project Partnering 2. Process modelling 3. Clinical applications 4. Solid waste management 5. Evaluation of technologies 6. Selection and prioritisation purposes.	1. This technique can be used to simplify complex problems. 2. It can be used for prioritisation purposes. 3. It included both tangible and intangible factors. 4. It uses the quantitative description of subjective judgement. 5. It allows feedback and dependence in the hierarchy.	1. If there are a large number of factors then it leads to an unwieldy model. 2. It heavily relies on the experience and judgement of experts.
Best Worst Method	1. Supplier development	1. Needs fewer comparison data as	There is a limitation of 9 point

(BWM) (Rezaei 2015)	2. Evaluation of strategies 3. Selection purposes 4. Prioritising the barriers and enablers.	compared to other MCDM techniques. 2. Can be applied to different MCDM problems with both qualitative and quantitative criteria. 3. Easy to understand and easy to apply as compared to other MCDM.	comparison scale. E.g. if a criterion is 12 times important than other than there is no option for scale.
Decision-making trial and evaluation laboratory (DEMATEL) (Wu and Lee 2007)	1. Evaluating success factors. 2. Find the casual relationship between factors. 3. Finding the critical factors.	1. It can analyse the mutual influences between the factors effectively. 2. It helps to visualise the relationship between the factors with the help of IRM. 3. It can be used to rank the alternatives as well as it helps to find out the critical evaluation criteria.	1. Ranking of alternatives is done based on the independent relationship among the alternatives. 2. Relative weights of experts are not considered in personal judgements.
Multi attribute utility theory (MAUT) (Li and Mathiyazhagan, 2018)	1. City planning 2. Economic policy 3. Government policy	1. Accounts for any difference in any criteria 2. Simultaneously compute preference order for all alternatives 3. Dynamically updates value changes due to any impact.	1. Difficult to have precise input from decision maker. 2. Outcome of the decision criteria is uncertain.

Elimination and Choice Translating Reality (ELECTRE) (Govindan and Jepsen, 2016)	1. Energy management 2. Financial management 3. Business management 4. Information technology & communication 5. Logistics & transportation engineering	1. Deals with both quantitative and qualitative features of criteria. 2. Final results are validated with reasons 3. Deals with heterogeneous scales	1. Less versatile 2. Demands good understanding of objective specially when dealing with quantitative features.
Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) (Lai et al. 1994)	1. Logistics 2. Water resource management 3. Energy management 4. Chemical engineering	1. Works with fundamental ranking 2. Makes full use of allocated information 3. The information need not be independent.	1. Basically works on the basis of Euclidian distance and so doesn't consider any difference between negative and positive values. 2. The attribute values should be monotonically increasing or decreasing
VlseKriterijumskaOptimizacija I Kompromisno Resenje(VIKOR) (Opricovic and Tzeng 2007)	1. Mechanical Engineering 2. Manufacturing engineering 3. Energy Policy 4. Business Management 5. Medicine and health	1. An updated version of TOPSIS 2. Calculates ration of positive and negative ideal solution thereby removing the impact	1. Difficulty when conflicting situation arises. 2. Need modification while dealing with some terse data as it become difficult to model a real time model.

Preference ranking organisation method (PROMETHEE) (Sen et al. 2015)	1. Manufacturing engineering 2. Risk analysis 3. Industrial engineering	1. It incorporates fuzzy and uncertain information. 2. It deals with both quantitative and qualitative information. 3. It involves group-level decisions.	1. The major limitation is that it cannot structure the objective properly. 2. It is complicated so the users are only limited to experts. 3. It depends on the decision-makers to assign the weights.

To use the positives of different techniques, limited literature is available which integrates the different techniques in order to develop a hybrid technique. Hybrid technique takes the advantages of integrated approaches. Shyjith et al. (2008) proposed an integrated AHP and TOPSIS to find an efficient ranking of alternatives for maintenance strategy selection. Zhou & Lu (2012) developed a hybrid model of fuzzy AHP and TOPSIS for evaluating the risk of dynamic alliance. Pourjavad et al. (2013) proposed integrated AHP-TOPSIS approach for the selection of best maintenance policy in mining industry. Aktas and Kabak (2019), Irfan et al. (2019) used AHP-TOPSIS to; evaluate the location site for solar energy plant, selection of material in the construction industry respectively. Singh and Singh (2018) used fuzzy AHP-TOPSIS to find the ranking of alternative routes in multicriteria decision situation. Chatterjee et al. (2011) applied Vlse Kriterijumska Optimizacija Kompromisno Resenje (VIKOR) and ELimination and Et Choice Translating Reality (ELECTRE) an outranking method for supplier selection. Mohsen and Fereshteh (2017) applied fuzzy VIKOR to rank and prioritize the failure causes of geothermal power plant. Feng et al. (2013) proposed model based on integrated VIKOR and PROMETHEE II for equilibrium design.

Lo and Liu (2018) proposed a novel approach for FMEA based risk assessment using best worse method and grey relation analysis (GRA) in an electronics company. According to Li et al. (2009) Cloud model is an approach incorporating randomness with fuzziness. Due to its distinguished capability of handling uncertainty, various researchers have used this approach in various applications. Liu et al. (2015) performed ranking of failure modes of C-arm of x-ray machine using combination of cloud model and GRA. Wang et al. (2015) solved MCDM problems using cloud model. Zhao and Li (2015) developed a model that integrates cloud computing and fuzzy method to perform the risk analysis in power construction sector. Shi et al. (2017) selected best healthcare waste treatment advances by considering three decision makers using an integrated cloud model and MABAC (multi attributive border approximation area comparison method). Wang et al. (2017) developed an integrated cloud model and qualitative flexible multiple criteria method to an auto manufacturer industry. Using integrating cloud model theory and PROMETHEE II approach; Liu et al. (2017) performed the FMEA of healthcare delivery system by incorporating 8 failure causes and Liu (2019) performed FMEA of emergency department. Wang et al. (2018) performed robot selection for automobile industry using cloud TODIM approach. Liu et al. (2018) performed risk analysis of scraper arm control system and Lei et al. (2019) performed risk analysis using of metro vehicle by integrating cloud model and TOPSIS approach. Failure causes of a steam valve system is identified by using Cloud model and extended TOPSIS by Li et al. (2019).Hu et al. (2019) performed risk analysis of health care department by ranking the failure causes using cloud model and GRA-TOPSIS approach. Huang et al. (2019) performed the risk analysis of enterprise architecture and information system by using probabilistic linguistic term sets to handle the intrinsic ambiguity and TODIM approach to rank the failure modes. Li et al. (2019) performed risk assessment of CNC machine using cloud model and best-worst method. Liu et al (2019) performed risk ranking of identified failure causes in a process industry using cloud model and extended GRA to overcome the limitation of traditional FMEA. Zhu et al. (2020) obtained the risk priority of failure modes in water gasification system using modified PROMETHEE under linguistic neutrosophic context.

2.5 RESOURCE ALLOCATION

In the past from literature it has been noticed that there are various methods to improve the availability of the system such as reducing complexity of system (Bemment et al. 2018) , proper maintenance planning (Jagtap et al. 2020), structural redundancy (Peiravi et al. 2020) and using enough safety measures (Guo et al. 2017).

From an industry perspective, resource allocation refers to the arrangement for utilizing available resources, to accomplish the predetermined objectives. It is the way towards allotting the available resources to the different sections of an association. In past, researcher has carried lot of work in the area of resource allocation for process industries. Misra (1971) performed redundancy allocation problem using dynamic programming. Joglekar and Hamburg (1987) explained resource allocation model for research and development under normally distributed benefit. Segelod (2002) explained the resource allocation, its determinants and trends in few industries Pang and Chang (1989) solved a problem to efficiently allocate the components so as to minimize the maximum weighted deviation from target demands of the boards.

Shooman (1970), Dinesh and Knezevic (1997 and 1998) suggested various tools for resource allocation like gradient methods, nonlinear programming, dynamic programming, mixed integer and integer programming. Kumar and Pandey (1993a and 1993b) performed resource allocation in paper industry and urea fertilizer plant respectively. Rowse (1994) performed efficient allocation of non-conventional nonrenewable resources. Knezevic (1995) developed a maintenance resources allocation model for complex systems. Li (1995) maximized reliability of the system and minimizes resource consumption using dynamic programming. Brown and McCarragher (1999) discussed the maintenance resource allocation using decentralized cooperative control. Xie et al. (2000) discussed optimum resource allocation using fault tree analysis. A simulation model for multi project resource allocation suggested was suggestd by Ghomi and Ashjari (2002).

Zayed (2004) performed resource allocation for concrete batch plant and Leus and Herroelen (2004) discussed the importance of resource allocation in project planning. Marseguerra et al. (2005) optimized the resource allocation for a multicomponent system using Genetic Algorithm. Dai and Wang (2006) proposed Genetic Algorithm as a tool to effectively solve a problem for the grid service allocation. Castro and Cavalca (2006) presented a maintenance resources optimization model of an engineering system assembled in a series configuration. An intelligent resource allocation model was developed by Wang and Lin (2007) using Genetic Algorithm with fuzzy inference. Lin and Gen (2007) solved a multi objective resource allocation problem using Genetic Algorithm. Yeddanapudi (2008) proposed a method to allocate available resources to distribution system. Cook et al. (2009) performed the resource allocation of a complex system with aging components.

Gupta (2011) examined the resource allocation problem in a thermal power plant. Lu et al. (2013) performed allocation of new data for improving the reliability of the system. Sharma and Sharma (2012) performed resource allocation to optimize reliability, availability, maintainability and cost decisions in a process plant. Komal (2017) performed resource allocation for a paper production system. Liu et al. (2018) performed resource allocation of manpower, budget, time etc. using Kriging model for improving reliability assessment of non-repairable multi-state system.

2.6 SUMMARY

Based upon intensive literature review as discussed above, it has been observed that very limited research work has been done and available on the performance evaluation and resource allocation of Paper plant. Further, most of the researchers have confined their work to the development and analysis of only theoretical mathematical models, which are of little practical significance. Although, a few researchers have developed real models for actual plant conditions but not provided any solid frame work for performance analysis. Presently, Paper plant area has great potential to be studied out and a lot of research work can be done. Therefore, sincere efforts have been made in the present work to develop the availability models based on real situation for the various systems of paper plant. Some performance evaluating systems for the existing conditions in a Paper plant have been analyzed and then accordingly adequate maintenance resources have been allocated to each system of the plant. Performance evaluation of various systems of Paper plant has been made to help the maintenance managers, to use failure/repair data and the availability models and hence, to support their decision making regarding the maintenance work.

With reference to the above literature analysis efforts have been made to overcome the limitations of traditional FMEA but still little attention has been paid to the vagueness and randomness inherent in the group based FMEA decision makers. For this reason an integrated approach based on cloud model and extended PROMETHEE in which firstly using cloud model the failure causes are defined in terms of linguistic evaluators which are transformed into interval cloud matrix and then to group cloud matrix by taking into account the overall weights of the decision maker. To calculate the overall weights of the decision makers firstly primary weights are calculated using uncertainty degree and then secondary weights using divergence degree. By doing this we can avoid the imprecise subjective assigning of weights to the decision maker. Secondly, an extended PROMETHEE is used to rank the failure causes by using the concept of net outranking flow calculated based on leaving and entering flow. Finally the proposed methodology is applied to rank the failure causes of various subsystems to illustrate its effectiveness and also it will allow the maintenance personnel to select the best maintenance policy.

Thus, performance evaluation, criticality analysis and resource allocation of various systems of the Paper plant concerned is of immense importance, to help the plant managers for the futuristic maintenance planning and respective appropriate decisions, so that the goal of maximum production and high profitability may be achieved.

CHAPTER III

DEVELOPMENT OF PERFORMANCE MODELS

3.1. INTRODUCTION

To evaluate the performance of process industry i.e. paper production plant situated in northern part of India (producing 200 tons of paper per day) the reliability and availability analysis was carried out. A paper production plant has many functional units such as (i) feeding (ii) pulp preparation (iii) bleaching and washing (iv) screening and (v) preparation of paper (forming, press and dryer units). For the production of paper the raw material (softwood, hardwood and bamboo) is chopped into small pieces of approximately uniform size and transported using compressed air to the store for temporary storage. Conveyors in the feeding system carry the chips from the store to the digesters, where these are cooked using $NaOH+Na_2S$ with steam pressure of 8.5 Kg/cm^2 at around 180^0C temperature. The chips when cooked are referred to as ‘pulp’. The pulp is then transported to storage tanks from where it is further processed through fibrelizier and refiner. After that the pulp is bleached and washed with water in stages to remove chemicals. For the production of white paper bleaching is done and for producing brown paper bleaching is skipped. In bleaching chlorine gas is passed through the pulp in the tank. The washed pulp obtained in last stage of washing, is stored in a surge tank. In the next stage of processing, screening processes are carried out. The white pulp so obtained is passed through screens to separate odd and oversized particles. The pulp is then made to pass through cleaners which separate heavy material from the pulp. Then the pulp is sent to the head box of the paper machine comprising of three section viz. forming, press and dryer. In the forming section of the paper machine, the suction box having five pumps dewaters the pulp by vacuum action. The paper in the form of sheets produced by rolling presses is sent to the press and dryer sections to reduce the moisture content by means of heat and vapour transfer to smooth/iron out any irregularities. Finally, the rolled-dried sheet is sent for packaging. A schematic diagram of the various processes in a paper production plant is shown in Figure 3.1. For higher productivity, it is essential that each subsystem of paper production plant should run failure free for long duration with full capacity and efficiency called ideal condition. In real situation, it is noticed that the operating systems are always subjected to random failures depending upon the working conditions and the maintenance strategies. The efforts are made in this chapter to develop interrelationship among the various parameters and analyze the system behaviour in real situation. For this purpose, transition diagrams (Figures 3.7-3.11) are drawn for each system of paper production plant and performance models i.e. measure of steady state availability are developed.

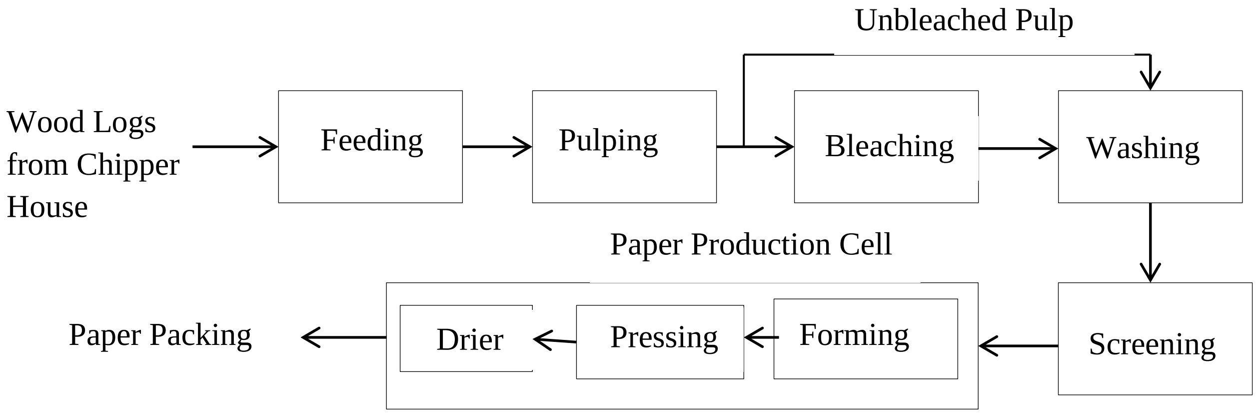


Figure 3.1: Block Diagram of Paper Plant

3.2. ASSUMPTIONS

The assumptions used in developing the performance models for the various operating systems of paper plant are

1. Failure/repair rates over time are constant and autonomous from each other.
2. A repaired system is equivalent to a new one with respect to performance wise, for a definite period.
3. Appropriate repair facilities are available.
4. If any component fails immediately it is replaced by stand subsystem if there is one which is of the same nature and capacity as that of active systems.
5. Failure/repair of the system follows exponential distribution.
6. System at any given time is either in operating state or in the reduced/ failed state.

3.3 NOTATIONS

The various notations associated with the transition diagrams (figures 3.7-3.11) are given in Table 3.1. Based on assumptions and notations, transition diagrams

Table 3.1. Notations used in the Analysis of Paper Plant

State	**Feeding System**	**Pulping System**	**Bleaching and Washing System**	**Screening System**	**Paper Production System**
Block Diagram	Figure 3.2	Figure 3.3	Figure 3.4	Figure 3.5	Figure 3.6
Transition Diagram	Figure 3.7	Figure 3.8	Figure 3.9	Figure 3.10	Figure 3.11
Full Capacity (without Standby)	A_1-A_3	B_1-B_5	C_1-C_6	D_1-D_4	E_1-E_7
Full Capacity (with standby)	A_3^1	B_2^1	C_5^1, C_5^2,C_6^1,C_6^2	D_3^1,D_4^1	E_3^1,E_3^2
Reduced Capacity	A_2^1	B_3^1, B_5^1			
Failed State	a_1 to a_3	b_1 to b_5	c_1 to c_6	d_1 to d_4	e_1 to e_7
Failure Rates	Ψ_1 to Ψ_3	Ψ_4 to Ψ_8	Ψ_9 to Ψ_{14}	Ψ_{15} to Ψ_{18}	Ψ_{19} to Ψ_{25}
Repair Rates	Φ_1 to Φ_3	Φ_4 to Φ_8	Φ_9 to Φ_{14}	Φ_{15} to Φ_{18}	Φ_{19} to Φ_{25}
Probability of Full Capacity (without standby)	P_0	P_0	P_0	P_0	P_0
Probability of Full Capacity (with standby)	P_1	P_1	P_1 to P_8	P_1 to P_3	P_1, P_2
Probability of Reduced Capacity	P_2	P_2 to P_7			
Probability of Failed State	P_3 to P_6	P_8 to P_{35}	P_9 to P_{50}	P_4 to P_{15}	P_3 to P_{21}

for various operating systems are drawn. These diagrams give the visual representation of the various states of the system at any instant of time.

3.4. DESCRIPTION OF PAPER PLANT

This paper plant is divided into the following independent systems:

1. Feeding System
2. Pulping System
3. Bleaching and Washing System
4. Screening System
5. Paper Making System

3.4.1 Feeding System

The feeding system comprises of three subsystems (figure 3.2), which are as follows:

1. **Subsystem A_1:** It consists of a blower whose failure causes total failure of the framework and its purpose is to push the wooden chips with the help of compressed air from chipper to storage unit.

2. **Subsystem A_2:** This consists of conveyor subsystem whose purpose is to lift the wooden chips from storage unit up to the height of digester if failure occurs to this subsystem, feeder subsystem A_3 becomes active which feeds the chips to digester but at a reduced speed causing production loss.

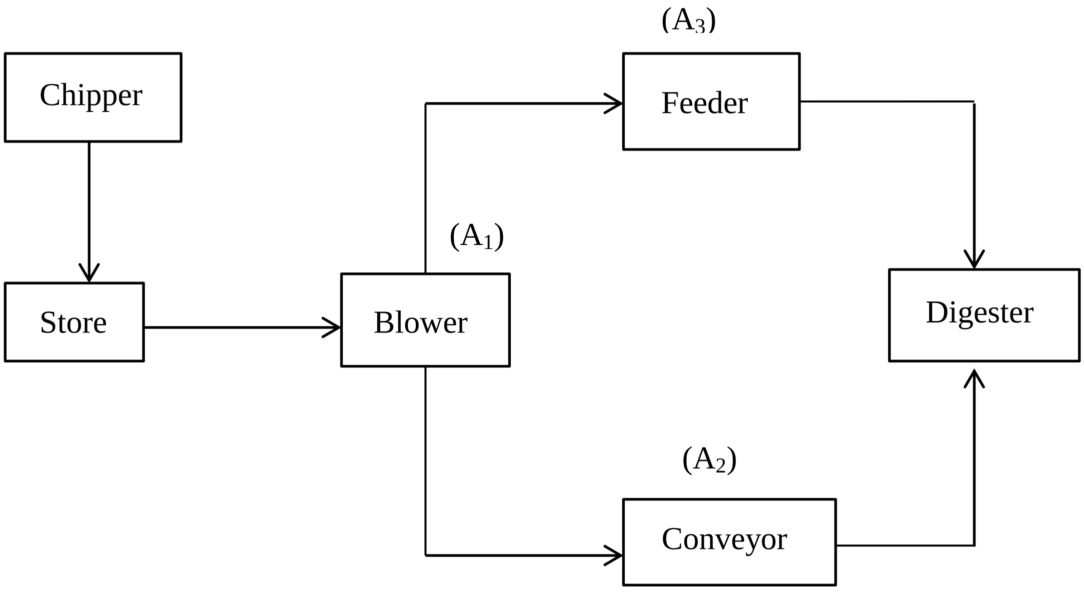


Figure 3.2 Schematic diagram of Feeding System

3. **Subsystem A_3:** It consists of feeder which remains in standby mode with subsystem A_2 and becomes operative when either subsystem A_2 fails or when there is extra demand of chips.

3.4.2 Pulping System:

The Pulping system comprises of five subsystems (figure 3.3), which are as follows:

1. **Subsystem B_1:** It consists of a digester whose failure causes total failure of the frame work. Within the digester wooden chips are blended with white alcohol (NaOH) and cooked for a few hours utilizing dry and saturated steam.
2. **Subsystem B_2:** This subsystem consists of pumps in two pairs out of which one is in standby mode which becomes operative when other unit of pump fails and its function is to move the pulp in between the units.
3. **Subsystem B_3:** It consists of two knotters whose function is to remove knots from the cooked pulp and the framework fails if the both the unit fails, but this results in reduced framework capacity.
4. **Subsystem B_4:** This subsystem consists of three stage decker frame work whose function is to remove black alcohol from the pulp to the most extreme degree and the frameworks fails if any of the washing system fails as failure of any washing system results in reduced quality of the paper which is not acceptable as objective is to get high quality paper
5. **Subsystem B_5:** It consists of two openers whose function is to separate fibres from the pulp by combing action and the framework fails only if the both the unit fails, but this results in reduced framework capacity.

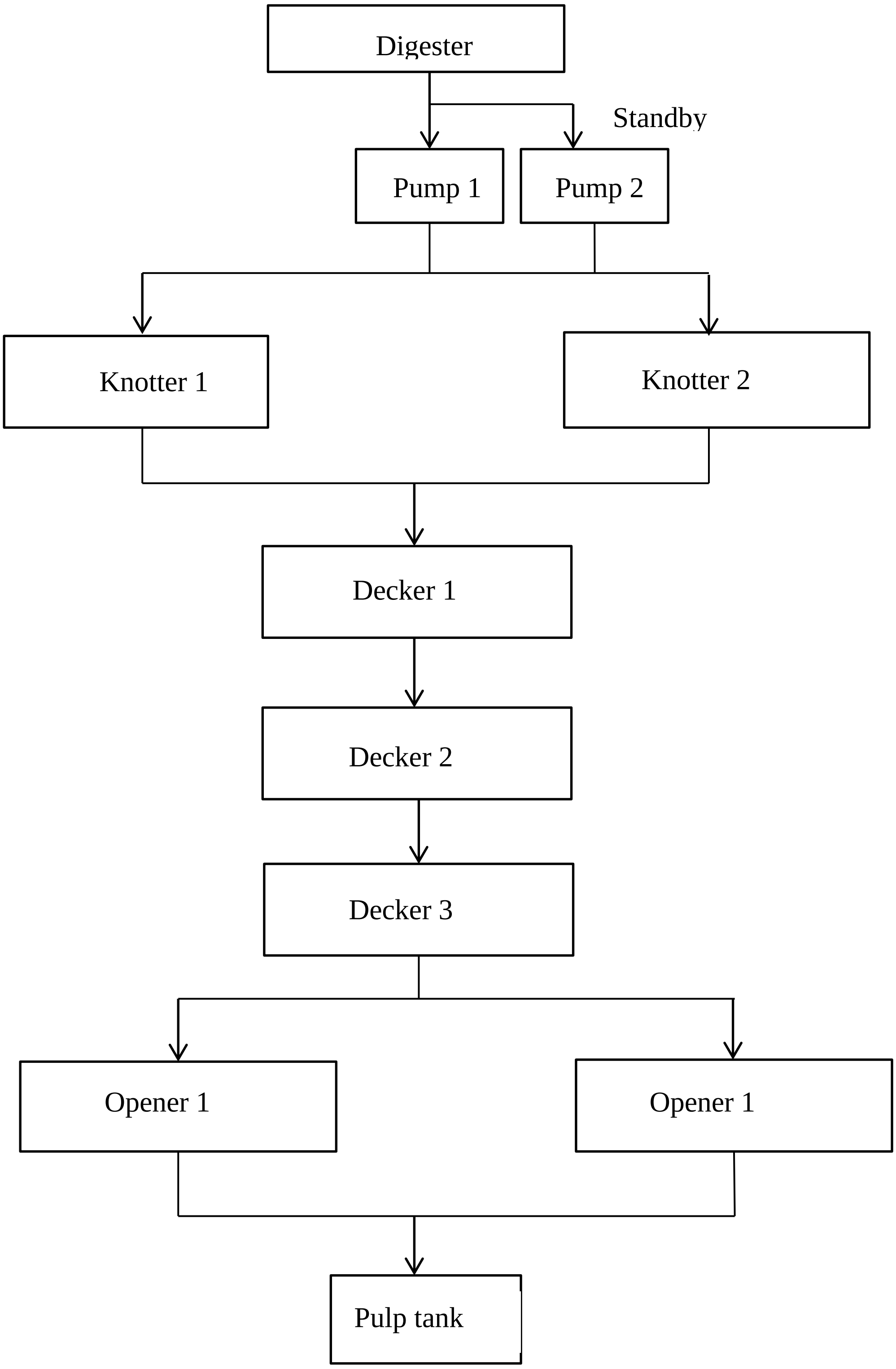


Figure 3.3 Schematic Diagram of Pulping System

3.4.3 Bleaching and Washing System

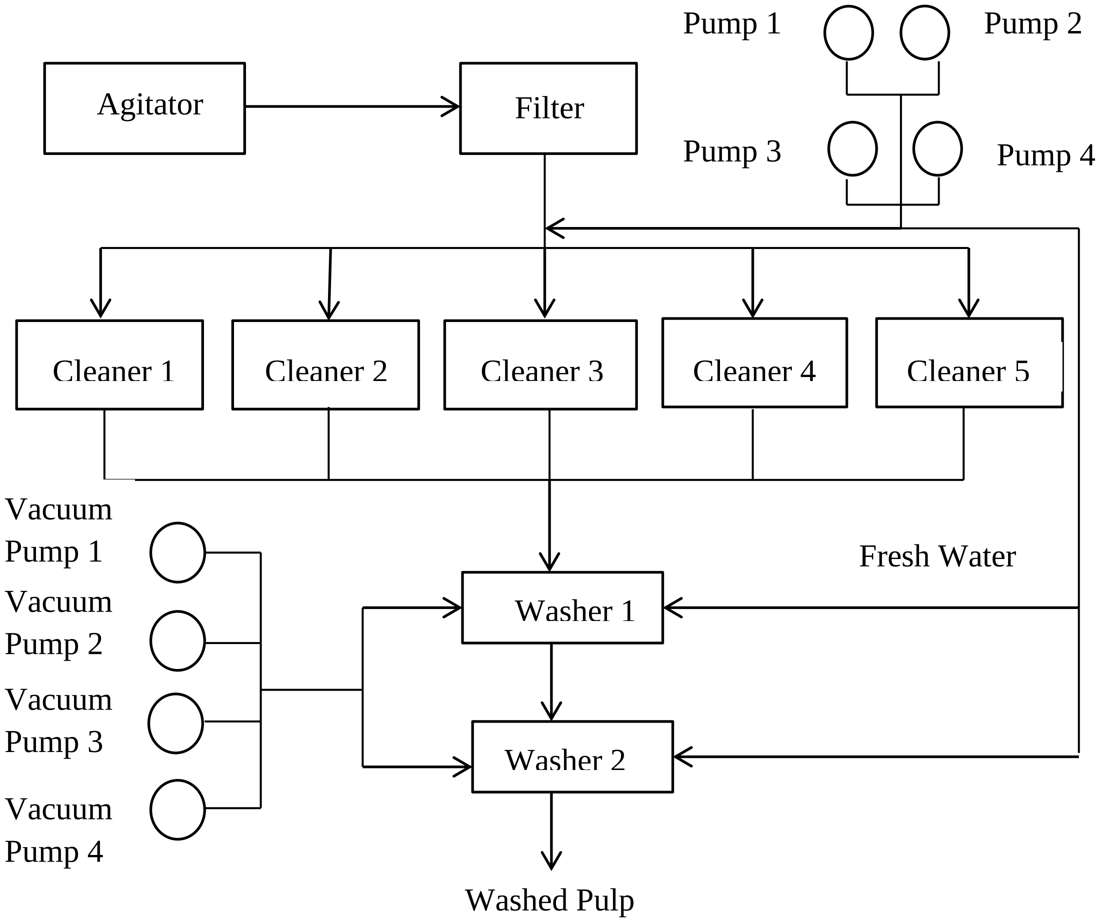


Figure 3.4 Schematic Diagram of Bleaching and washing System

The bleaching and washing system comprises of six subsystems (figure 3.4), which are as follows:

1. **Subsystem C_1:** Failure of agitator cause complete failure of the system, where chlorine at a controlled rate is mixed with the pulp for a few hours.
2. **Subsystem C_2:** The pulp is then passed over a filter to get chlorine-free white pulp and also failure of filter cause complete failure of the system.
3. **Subsystem C_3:** The pulp is then washed through five cleaners in which water is sprayed on the pulp and mixed with the pulp by a rotating blade in it to carry away the blackness of the pulp and system failure occurs if any cleaner fails as the objective is to produce quality paper.
4. **Subsystem C_4:** The mixture is then passed through a series of washers, where clean water is sprayed and the pulp is separated from the mixture through suction. System failure occurs if any washer fails.

5. **Subsystem C_5:** Four vacuum pumps are there in the system; at least two of them should be working at any time to keep the system in working.
6. **Subsystem C_6:** Four centrifugal pumps are used to supply water to cleaners and washers, system failure occurs if more than two pump fails.

3.4.4 Screening System

The screening system comprises of four subsystems (figure 3.5), which are as follows:

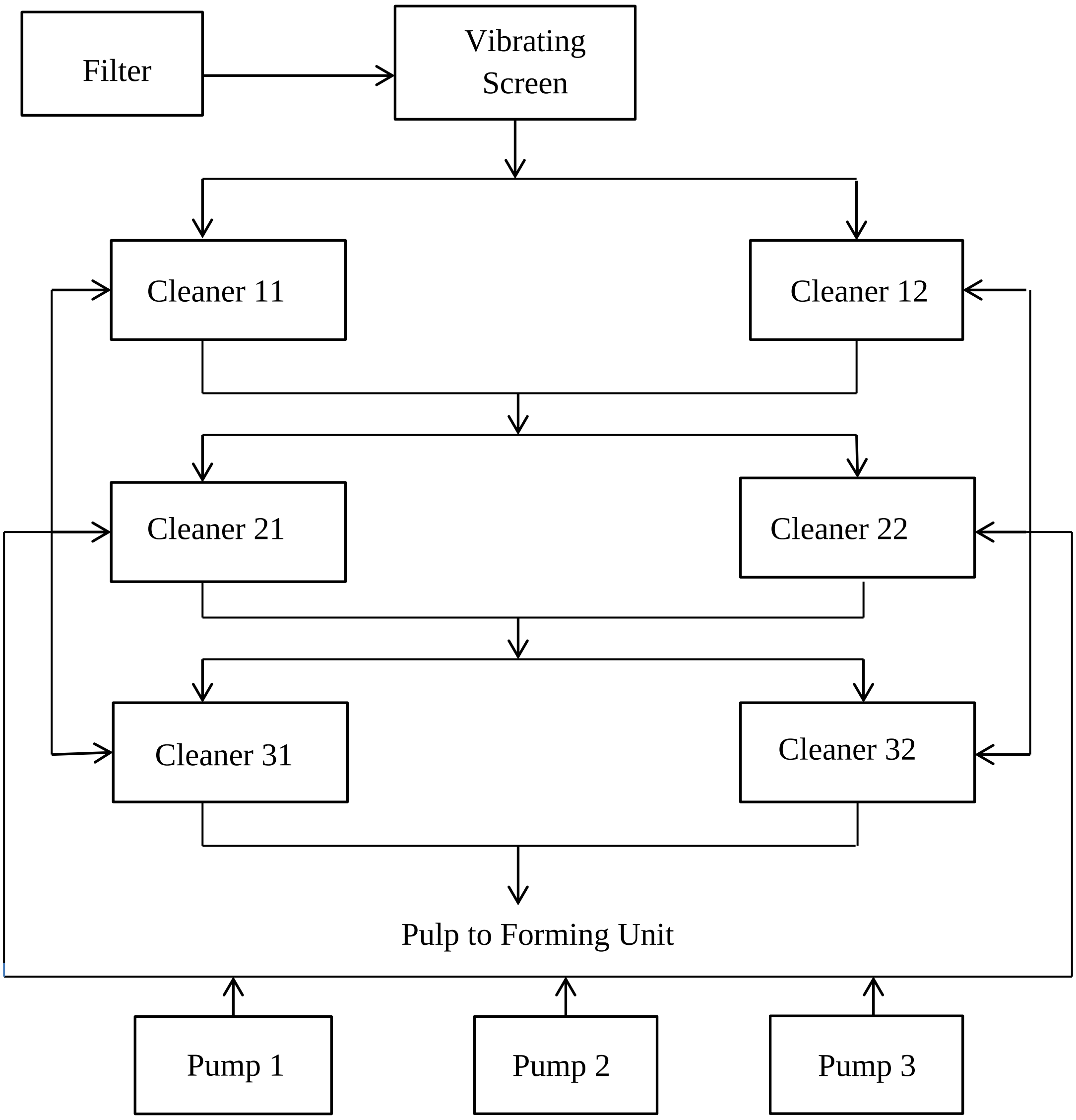


Figure 3.5 Schematic Diagram of Screening System

1. **Subsystem D_1:** It consists of a filter whose failure causes total failure of the framework and its purpose is to drain black liquor from the cooked pulp.

2. **Subsystem D_2**: This subsystem consists of screener whose purpose is to remove oversized, uncooked and odd shaped fibres from pulp through straining action. Its failure cause complete failure of the system.

3. **Subsystem D_3:** It consists of three sets of dual cleaner. Water is mixed here with pulp to cleanse by centrifugal action. The failure of more than one dual cleaner will cause the system to fail.

4. **Subsystem D_4:** This subsystem consists of three centrifugal pump to supply water to cleaner and failure of more than one will cause the system to fail.

3.4.5 Paper Production System

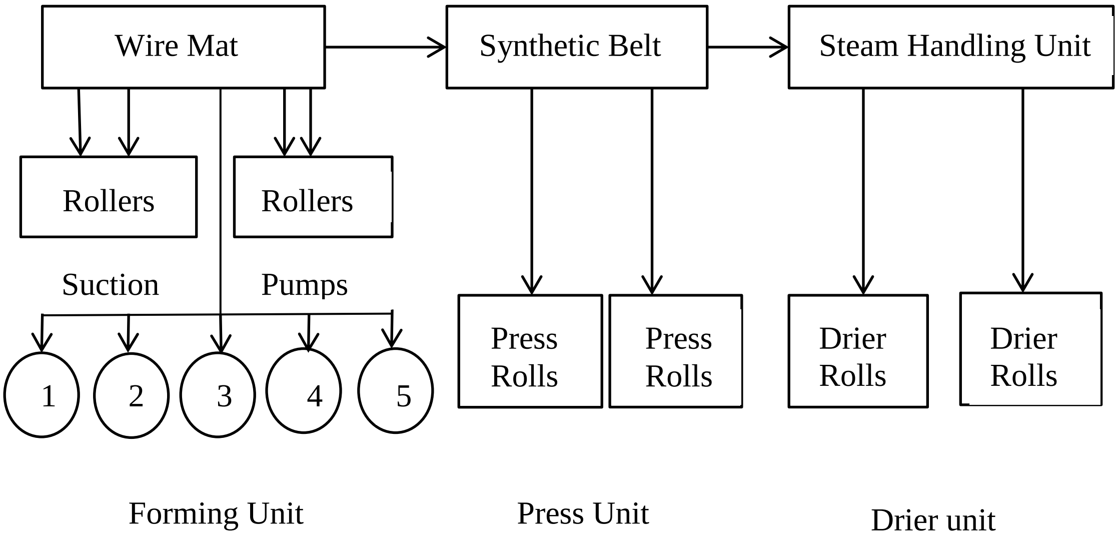


Figure 3.6 Schematic Diagram of Paper Production System

Forming unit: The function of the forming unit is to carry metred quantity of the pulp for further processing. It consists of head box, wire mat, suction box and a number of rollers. Cooked pulp after processing through number of stages is fed to head box of paper machine from where (in controlled proportion) it is made to flow over the wire mat running over the rollers. Head box delivers stock (pulp +water) in controlled quantity to moving wire mat, supported by series of table & wire rolls. The suction box having five pumps dewaters the pulp through vacuum action. Three pumps out of five pumps should keep on working to keep the system working. The chances of failure of head box are assumed be negligible.

Press Unit: The main function of the unit is to reduce the moisture content of the paper by pressing the pulp under the rolls received from forming unit of machine. It consists of synthetic belt, upper and bottom rollers as the main components. The unit receives wet paper sheet from forming unit on to the synthetic belt, which is further carried through press rolls thereby reducing the moisture content to almost 50-60 %.

Drier Unit: Its function is to further dry the paper sheet by heating and thus vaporizing the moisture content to zero level. The system consists of steam-heated rolls (dryer), in stages, and the steam is supplied from steam handling systems. The rolls are heated with superheated steam and remove the moisture content of the paper rolled over them completely.

3.5 PERFORMANCE MODELING OF OPERATING SYSTEMS OF PAPER PLANT

Referring to the transition diagrams (Figures 3.7-3.11), Chapman Kolmogorov differential equations are developed for each operating system of the paper plant. These performance models (availability expressions) are used for evaluating the performance of various operating systems of a paper plant. The differential equations are developed using Markov birth-death process. In birth process, there is one step change in the probability function in forward direction due to failures of the components. While due to repairs of the components, there is one backward change in the probability function like death process.

3.5.1 Performance Modeling of Feeding System

Following differential equations are developed by using Markovian birth-death process based on probabilistic method associated with the feeding unit of a paper plant.

$$\left(\frac{d}{dt}+\sum_{i=1}^{3}\Psi_i\right)P_0(t)=\Phi_1P_4(t)+\Phi_2P_2(t)+\Phi_3P_1(t) \tag{3.5.1}$$

$$\left(\frac{d}{dt}+2\Phi_3+2\Psi_2+\Psi_1\right)P_1(t)=\Psi_3P_0(t)+\Phi_2P_3(t)+\Phi_2P_2(t)+\Phi_1P_6(t)+\Psi_2P_2(t) \tag{3.5.2}$$

$$\left(\frac{d}{dt}+\Psi_1+2\Phi_2+2\Psi_3\right)P_2(t)=\Psi_2P_0(t)+\Phi_3P_1(t)+\Phi_3P_3(t)+\Psi_2P_1(t)+\Phi_1P_5(t) \tag{3.5.3}$$

$$\left(\frac{d}{dt}+\Phi_1\right)P_i(t)=\Psi_1P_j(t) \tag{3.5.4}$$

Where $i=4,5,6$ and $j=0,1,2$ respectively

$$\left(\frac{d}{dt}+\Phi_2+\Phi_3\right)P_3(t)=\Psi_3P_2(t)+\Psi_2P_1(t) \tag{3.5.5}$$

With the initial condition at time $t = 0$

$$P_i(t) = 1 \text{ for } i = 0\text{; otherwise } P_i(t) = 0 \tag{3.5.6}$$

Long run steady state availability of the feeding unit of a paper plant is obtained by putting $\frac{d}{dt} = 0 \; at \; t \to \infty$ into differential equations, following equations are obtained

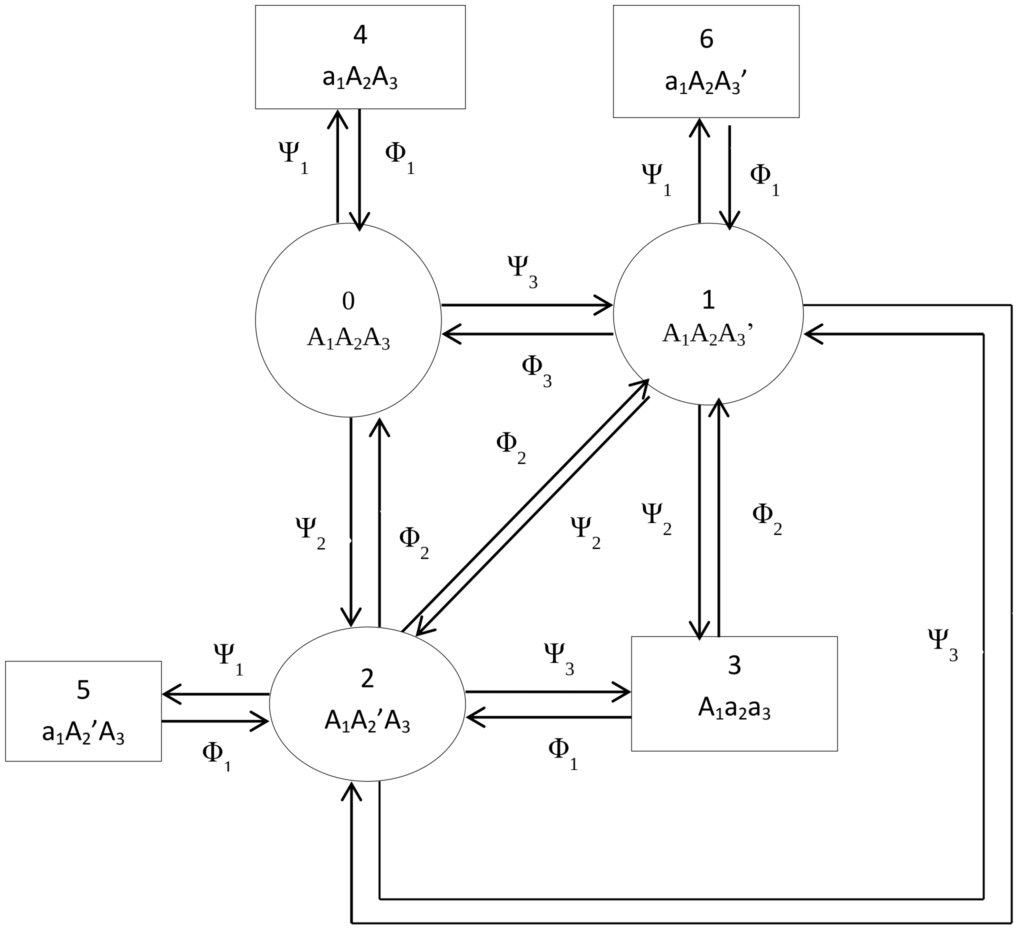


Figure 3.7 Transition Diagram of Feeding System

$$\Phi_1 P_i = \Psi_1 P_j$$

Where $i = 4, 5, 6$ and $j = 0, 1, 2$ respectively

$$(\Phi_2 + \Phi_3) P_3 = \Psi_2 P_1 + \Psi_3 P_2 \tag{3.5.7}$$

By using back substitution following equations are obtained

$$\left(\Psi_2 + \Psi_3\right) P_0 = \Phi_3 P_1 + \Phi_2 P_2 \tag{3.5.8}$$

$$\left(\Psi_2 + \Psi_3\right) P_0 + \Psi_2 P_2 = \Psi_3 P_2 + \Phi_2 P_2 \tag{3.5.9}$$

The likelihood of full operating capacity P_0 is obtained by using normalising condition which states that sum of probabilities of working, reduced and failed states is equal to one.

$$\sum_{i=0}^{6} P_i = 1 \tag{3.5.10}$$

$$\left(1+\frac{\Psi_1}{\Phi_1}\right)P_0+\left(1+\frac{\Psi_2}{\Phi_3+\Phi_2}+\frac{\Psi_1}{\Phi_1}\right)P_1+\left(1+\frac{\Psi_1}{\Phi_1}+\frac{\Psi_3}{\Phi_3+\Phi_2}\right)P_2=1 \tag{3.5.11}$$

So the long run steady state availability can be obtained by summation of probabilities of subunits working under full capacity and reduced capacity.

$$A_{v1}=\sum_{i=0}^{2} P_i = P_0+P_1+P_2 \tag{3.5.12}$$

With the help of this stochastic model developed and using equation 3.5.12 long term steady availability can be obtained for feeding system.

3.5.2 Performance Modelling of Pulping System

Following differential equations are developed by using Markovian birth-death process based on probabilistic method associated with the pulping unit of a paper plant.

$$\left(\frac{d}{dt}+\sum_{i=4}^{8}\Psi_i\right)P_0(t)=\Phi_5P_1(t)+\Phi_6P_2(t)+\Phi_7P_8(t)+\Phi_8P_3(t)+\Phi_4P_9(t) \tag{3.5.13}$$

$$\left(\frac{d}{dt}+\sum_{i=4}^{8}\Psi_i+\Phi_5\right)P_1(t)=\Phi_4P_{10}(t)+\Phi_5P_{11}+\Phi_6P_5(t)+\Phi_7P_{12}(t)+\Phi_8P_4(t)+\Phi_5P_0(t) \tag{3.5.14}$$

$$\left(\frac{d}{dt}+\sum_{i=4}^{8}\Psi_i+\Phi_6\right)P_2(t)=\Phi_4P_{13}(t)+\Phi_5P_5(t)+\sum_{i=6}^{7}\Phi_iP_{i+8}(t)+\Phi_8P_6(t)+\Psi_6P_0(t) \tag{3.5.15}$$

$$\left(\frac{d}{dt}+\sum_{i=4}^{8}\Psi_i+\Phi_8\right)P_3(t)=\Phi_4P_{16}(t)+\Phi_5P_4(t)+\Phi_6P_6(t)+\sum_{i=7}^{8}\Phi_iP_{i+10}(t)+\Psi_8P_0(t) \tag{3.5.16}$$

$$\left(\frac{d}{dt}+\sum_{i=4}^{8}\Psi_i+\Phi_8+\Phi_5\right)P_4(t)=\sum_{i=4}^{5}\Phi_iP_{i+15}(t)+\Phi_6P_7(t)+\sum_{i=7}^{8}\Phi_iP_{i+14}(t)+\Psi_5P_3(t)+\Psi_8P_1(t) \tag{3.5.17}$$

$$\left(\frac{d}{dt}+\sum_{i=4}^{8}\Psi_i+\Phi_5+\Phi_6\right)P_5(t)=\sum_{i=4}^{8}\Phi_iP_{i+19}(t)+\Psi_6P_1(t)+\Psi_5P_2(t) \tag{3.5.18}$$

$$\left(\frac{d}{dt}+\sum_{i=4}^{8}\Psi_i+\Phi_6+\Phi_8\right)P_6(t)=\Phi_4P_{27}(t)+\Phi_5P_7(t)+\sum_{i=6}^{8}\Phi_iP_{i+22}(t)+\Psi_6P_3(t)+\Psi_8P_2(t) \quad (3.5.19)$$

$$\left(\frac{d}{dt}+\sum_{i=4}^{8}\Psi_i+\Phi_5+\Phi_6+\Phi_8\right)P_7(t)=\sum_{i=4}^{8}\Phi_iP_{i+27}(t)+\Psi_6P_4(t)+\Psi_5P_6(t)+\Psi_8P_5(t) \quad (3.5.20)$$

$$\left(\frac{d}{dt}+\Phi_4\right)P_i(t)=\Psi_4P_j(t) \quad (3.5.21)$$

Where $i=9,10,13,16,19,23,27,33$ and $j=0,1,2,3,4,5,6,7$ respectively

$$\left(\frac{d}{dt}+\Phi_5\right)P_i(t)=\Psi_5P_j(t) \quad (3.5.22)$$

Where $i=11,20,24,34$ and $j=1,4,5,7$ respectively

$$\left(\frac{d}{dt}+\Phi_6\right)P_i(t)=\Psi_6P_j(t) \quad (3.5.23)$$

Where $i=14,25,28,35$ and $j=2,5,6,7$ respectively

$$\left(\frac{d}{dt}+\Phi_7\right)P_i(t)=\Psi_7P_j(t) \quad (3.5.24)$$

Where $i=8,12,15,17,21,26,29,32$ and $j=0,1,2,3,4,5,6,7$ respectively

$$\left(\frac{d}{dt}+\Phi_8\right)P_i(t)=\Psi_8P_j(t) \quad (3.5.25)$$

Where $i=18,22,30,31$ and $j=3,4,6,7$ respectively

With the initial condition at time t=0

$P_i(t) = 1\ for\ i = 0; otherwise\ P_i(t) = 0$

Long run steady state availability of the pulping unit of a paper plant is obtained by putting $\frac{d}{dt} = 0\ at\ t \to \infty$ into differential equations, following equations are obtained

$$\Phi_4P_i=\Psi_4P_j \quad (3.5.26)$$

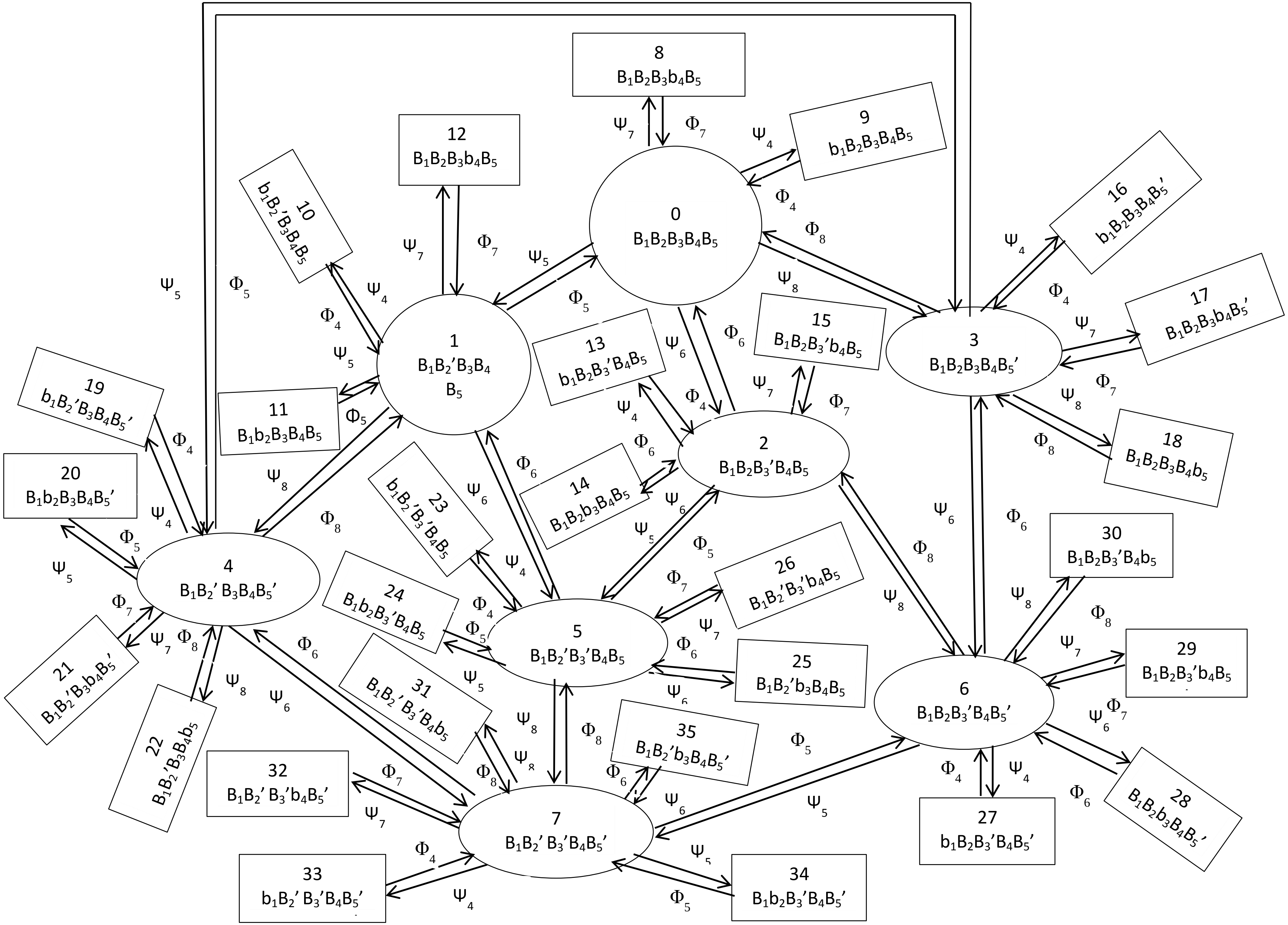
Where $i=9,10,13,16,19,23,27,33$ and $j=0,1,2,3,4,5,6,7$ respectively

$$\Phi_5P_i=\Psi_5P_j \quad (3.5.27)$$

Where $i=11,20,24,34$ and $j=1,4,5,7$ respectively

$$\Phi_6P_i=\Psi_6P_j \quad (3.5.28)$$

Where $i=14,25,28,35$ and $j=2,5,6,7$ respectively



0
$B_1B_2B_3B_4B_5$
1
$B_1B_2'B_3B_4B_5$
2
$B_1B_2B_3'B_4B_5$
3
$B_1B_2B_3B_4B_5'$
4
$B_1B_2'B_3B_4B_5'$
5
$B_1B_2'B_3'B_4B_5$
6
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$b_1B_2'B_3B_4B_5$
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$B_1b_2B_3B_4B_5$
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$B_1B_2'B_3'b_4B_5'$
33
$b_1B_2'B_3'B_4B_5'$
34
$B_1b_2B_3'B_4B_5'$
35
$B_1B_2'b_3B_4B_5'$
Ψ_7
Φ_7
Ψ_4
Φ_4
Φ_8
Ψ_8
Ψ_5
Φ_5
Ψ_6
Φ_6

Figure 3.7 Transition Diagram of Pulping Unit.

$$\Phi_7 P_i = \Psi_7 P_j \tag{3.5.29}$$

Where $i = 8,12,15,17,21,26,29,32$ and $j = 0,1,2,3,4,5,6,7$ respectively

$$\Phi_8 P_i = \Psi_8 P_j \tag{3.5.30}$$

Where $i = 18,22,30,31$ and $j = 3,4,6,7$ respectively

By using back substitution following equations are obtained

$$\left(\Psi_5 + \Psi_6 + \Psi_8\right) P_0 = \Phi_5 P_1 + \Phi_6 P_2 + \Phi_8 P_3 \tag{3.5.31}$$

$$\left(\Psi_6 + \Psi_8 + \Phi_5\right) P_1 = \Psi_5 P_0 + \Phi_8 P_4 + \Phi_6 P_5 \tag{3.5.32}$$

$$\left(\Psi_5 + \Psi_8 + \Phi_6\right) P_2 = \Psi_6 P_0 + \Phi_5 P_5 + \Phi_8 P_6 \tag{3.5.33}$$

$$\left(\Psi_5 + \Psi_6 + \Phi_8\right) P_3 = \Psi_8 P_0 + \Phi_5 P_4 + \Phi_6 P_6 \tag{3.5.34}$$

$$\left(\Psi_6 + \Phi_5 + \Phi_8\right) P_4 = \Psi_8 P_1 + \Psi_5 P_3 + \Phi_6 P_7 \tag{3.5.35}$$

$$\left(\Psi_8 + \Phi_5 + \Phi_6\right) P_5 = \Psi_6 P_1 + \Psi_5 P_2 + \Phi_8 P_7 \tag{3.5.36}$$

$$\left(\Psi_5 + \Phi_6 + \Phi_8\right) P_6 = \Psi_6 P_3 + \Psi_8 P_2 + \Phi_5 P_7 \tag{3.5.37}$$

$$\left(\Phi_5 + \Phi_6 + \Phi_8\right) P_7 = \Psi_6 P_4 + \Psi_5 P_6 + \Psi_8 P_5 \tag{3.5.38}$$

The likelihood of full operating capacity P_0 is obtained by using normalising condition which states that sum of probabilities of working, reduced and failed states is equal to one.

$$\sum_{i=0}^{35} P_i = 1 \tag{3.5.39}$$

So the long run steady state availability can be obtained by summation of probabilities of subunits working under full capacity and reduced capacity.

$$A_{v2} = \sum_{i=0}^{7} P_i = P_0 + P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 \tag{3.5.40}$$

With the help of this stochastic model developed and using equation 3.5.40, long term steady state availability can be obtained for pulping system.

3.5.3 Performance Modeling of Bleaching and Washing System

Following differential equations are developed by using Markovian birth-death process based on probabilistic method associated with the bleaching and washing system of a paper plant.

$$\left(\frac{d}{dt}+\sum_{i=9}^{14}\Psi_i\right)P_0(t)=\Phi_9P_4(t)+\sum_{i=10}^{12}\left(\Phi_iP_i(t)\right)+\Phi_{13}P_1(t)+\Phi_{14}P_2(t) \tag{3.5.41}$$

$$\left(\frac{d}{dt}+\sum_{i=9}^{14}\left(\Psi_i+\Phi_{13}\right)\right)P_1(t)=\sum_{i=9}^{12}\left(\Phi_iP_{i+4}(t)\right)+\Phi_{13}P_4(t)+\Phi_{14}P_3(t)+\Psi_{13}P_0(t) \tag{3.5.42}$$

$$\left(\frac{d}{dt}+\sum_{i=9}^{14}\left(\Psi_i+\Phi_{14}\right)\right)P_2(t)=\sum_{i=9}^{12}\left(\Phi_iP_{i+8}(t)\right)+\Phi_{13}P_3(t)+\Phi_{14}P_5(t)+\Psi_{14}P_0(t) \tag{3.5.43}$$

$$\left(\frac{d}{dt}+\sum_{i=9}^{14}\left(\Psi_i+\Phi_{13}\right)\right)P_4(t)=\sum_{i=9}^{12}\left(\Phi_iP_{i+16}(t)\right)+\Phi_{13}P_4(t)+\Phi_{14}P_3(t)+\Psi_{13}P_0(t) \tag{3.5.44}$$

$$\left(\frac{d}{dt}+\sum_{i=9}^{14}\left(\Psi_i+\Phi_{14}\right)\right)P_5(t)=\sum_{i=9}^{12}\left(\Phi_iP_{i+21}(t)\right)+\Phi_{13}P_7(t)+\Phi_{14}P_{34}(t)+\Psi_{14}P_2(t) \tag{3.5.45}$$

$$\left(\frac{d}{dt}+\sum_{i=9}^{14}\left(\Psi_i+\Phi_{13}\right)\right)P_6(t)=\sum_{i=9}^{13}\left(\Phi_iP_{i+26}(t)\right)+\Phi_{14}P_4(t)+\Psi_{13}P_3(t) \tag{3.5.46}$$

$$\left(\frac{d}{dt}+\sum_{i=9}^{14}\left(\Psi_i+\Phi_{13}\right)\right)P_7(t)=\sum_{i=9}^{12}\left(\Phi_iP_{i+31}(t)\right)+\Phi_{13}P_8(t)+\Phi_{14}P_{44}(t)+\Psi_{13}P_5(t) \tag{3.5.47}$$

$$\left(\frac{d}{dt}+\sum_{i=9}^{14}\left(\Psi_i+\Phi_{13}+\Phi_{14}\right)\right)P_8(t)=\sum_{i=9}^{13}\left(\Phi_iP_{i+36}(t)\right)+\Phi_{14}P_{50}(t)+\Psi_{13}P_7(t)+\Psi_{14}P_6(t) \tag{3.5.48}$$

$$\left(\frac{d}{dt}+\Phi_9\right)P_i(t)=\Psi_9P_j(t) \tag{3.5.49}$$

Where $i=9,13,17,21,25,30,35,40,45$ and $j=0,1,2,3,4,5,6,7,8$ respectively

$$\left(\frac{d}{dt}+\Phi_{10}\right)P_i(t)=\Psi_{10}P_j(t) \tag{3.5.50}$$

Where $i=10,14,18,22,26,31,36,41,46$ and $j=0,1,2,3,4,5,6,7,8$ respectively

$$\left(\frac{d}{dt}+\Phi_{11}\right)P_i(t)=\Psi_{11}P_j(t) \tag{3.5.51}$$

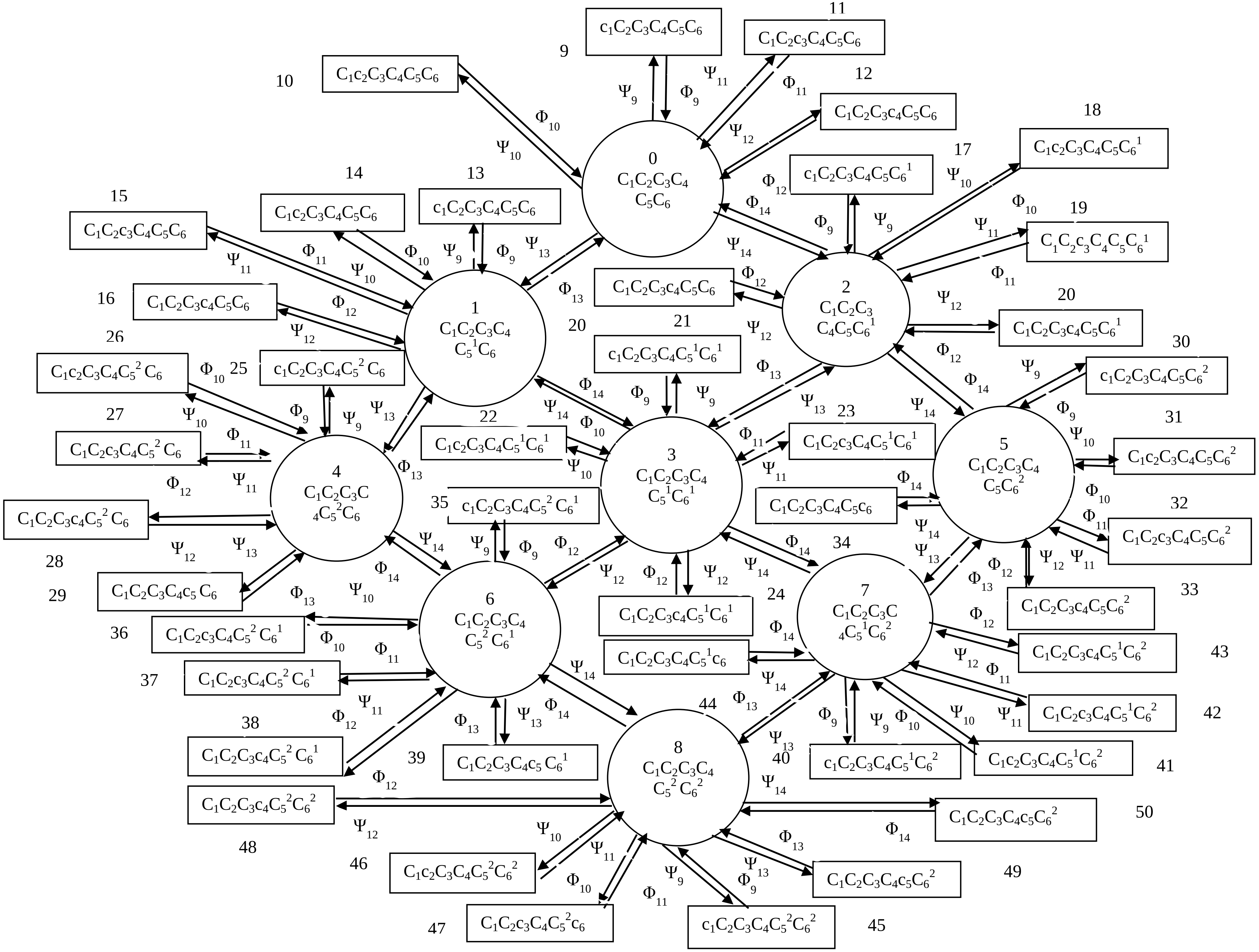
Where $i=11,15,19,23,27,32,37,42,47$ and $j=0,1,2,3,4,5,6,7,8$ respectively

$$\left(\frac{d}{dt}+\Phi_{12}\right)P_i(t)=\Psi_{12}P_j(t) \tag{3.5.52}$$

Where $i=12,16,20,24,28,33,38,43,48$ and $j=0,1,2,3,4,5,6,7,8$ respectively

$$\left(\frac{d}{dt}+\Phi_{13}\right)P_i(t)=\Psi_{13}P_j(t) \tag{3.5.53}$$

Where $i=29,39,49$ and $j=4,6,8$ respectively


0 $C_1C_2C_3C_4C_5C_6$
1 $C_1C_2C_3C_4C_5^1C_6$
2 $C_1C_2C_3C_4C_5C_6^1$
3 $C_1C_2C_3C_4C_5^1C_6^1$
4 $C_1C_2C_3C_4C_5^2C_6$
5 $C_1C_2C_3C_4C_5C_6^2$
6 $C_1C_2C_3C_4C_5^2C_6^1$
7 $C_1C_2C_3C_4C_5^1C_6^2$
8 $C_1C_2C_3C_4C_5^2C_6^2$
9 $c_1C_2C_3C_4C_5C_6$
10 $C_1c_2C_3C_4C_5C_6$
11 $C_1C_2c_3C_4C_5C_6$
12 $C_1C_2C_3c_4C_5C_6$
13 $c_1C_2C_3C_4C_5C_6$
14 $C_1c_2C_3C_4C_5C_6$
15 $C_1C_2c_3C_4C_5C_6$
16 $C_1C_2C_3c_4C_5C_6$
17 $c_1C_2C_3C_4C_5C_6^1$
18 $C_1c_2C_3C_4C_5C_6^1$
19 $C_1C_2c_3C_4C_5C_6^1$
20 $C_1C_2C_3c_4C_5C_6^1$
20 $C_1C_2C_3c_4C_5C_6$
21 $c_1C_2C_3C_4C_5^1C_6^1$
22 $C_1c_2C_3C_4C_5^1C_6^1$
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24 $C_1C_2C_3c_4C_5^1C_6^1$
$C_1C_2C_3C_4C_5c_6$
$C_1C_2C_3C_4C_5^1c_6$
25 $c_1C_2C_3C_4C_5^2C_6$
26 $C_1c_2C_3C_4C_5^2C_6$
27 $C_1C_2c_3C_4C_5^2C_6$
28 $C_1C_2C_3c_4C_5^2C_6$
29 $C_1C_2C_3C_4c_5C_6$
30 $c_1C_2C_3C_4C_5C_6^2$
31 $C_1c_2C_3C_4C_5C_6^2$
32 $C_1C_2c_3C_4C_5C_6^2$
33 $C_1C_2C_3c_4C_5C_6^2$
34
35 $c_1C_2C_3C_4C_5^2C_6^1$
36 $C_1C_2c_3C_4C_5^2C_6^1$
37 $C_1C_2c_3C_4C_5^2C_6^1$
38 $C_1C_2C_3c_4C_5^2C_6^1$
39 $C_1C_2C_3C_4c_5C_6^1$
40 $c_1C_2C_3C_4C_5^1C_6^2$
41 $C_1c_2C_3C_4C_5^1C_6^2$
42 $C_1C_2c_3C_4C_5^1C_6^2$
43 $C_1C_2C_3c_4C_5^1C_6^2$
44
45 $c_1C_2C_3C_4C_5^2C_6^2$
46 $C_1c_2C_3C_4C_5^2C_6^2$
47 $C_1C_2c_3C_4C_5^2c_6$
48 $C_1C_2C_3c_4C_5^2C_6^2$
49 $C_1C_2C_3C_4c_5C_6^2$
50 $C_1C_2C_3C_4c_5C_6^2$
Φ_9 Ψ_9 Φ_{10} Ψ_{10} Φ_{11} Ψ_{11} Φ_{12} Ψ_{12} Φ_{13} Ψ_{13} Φ_{14} Ψ_{14}

Figure 3.8: Transition diagram of Bleaching and Washing unit.

$$\left(\frac{d}{dt}+\Phi_{14}\right)P_i(t)=\Psi_{14}P_j(t) \tag{3.5.54}$$

Where $i=34,44,50$ and $j=5,7,8$ respectively

With the initial condition at time $t=0$

$P_i(t)=1$ for $i=0$; otherwise $P_i(t)=0$

Long run steady state availability of the bleaching and washing system obtained by putting $\frac{d}{dt}=0\ at\ t\to\infty$ into differential equations, following equations are obtained

$$\Phi_9P_i=\Psi_9P_j \tag{3.5.55}$$

Where $i=9,13,17,21,25,30,35,40,45$ and $j=0,1,2,3,4,5,6,7,8$ respectively

$$\Phi_{10}P_i=\Psi_{10}P_j \tag{3.5.56}$$

Where $i=10,14,18,22,26,31,36,41,46$ and $j=0,1,2,3,4,5,6,7,8$ respectively

$$\Phi_{11}P_i=\Psi_{11}P_j \tag{3.5.57}$$

Where $i=11,15,19,23,27,32,37,42,47$ and $j=0,1,2,3,4,5,6,7,8$ respectively

$$\Phi_{12}P_i=\Psi_{12}P_j \tag{3.5.58}$$

Where $i=12,16,20,24,28,33,38,43,48$ and $j=0,1,2,3,4,5,6,7,8$ respectively

$$\Phi_{13}P_i=\Psi_{13}P_j \tag{3.5.59}$$

Where $i=29,39,49$ and $j=4,6,8$ respectively

$$\Phi_{14}P_i=\Psi_{14}P_j \tag{3.5.60}$$

Where $i=34,44,50$ and $j=5,7,8$ respectively

By using back substitution following equations are obtained

$$\left(\Psi_{13}+\Psi_{14}\right)P_0-\Phi_{13}P_1-\Phi_{14}P_2=0 \tag{3.5.61}$$

$$\Psi_{13}P_0-\left(\Psi_{13}+\Psi_{14}+\Phi_{13}\right)P_1+\Phi_{14}P_3+\Phi_{13}P_4=0 \tag{3.5.62}$$

$$\Psi_{14}P_0-\left(\Psi_{13}+\Psi_{14}+\Phi_{14}\right)P_2+\Phi_{13}P_3+\Phi_{14}P_5=0 \tag{3.5.63}$$

$$\Psi_{14}P_1+\Psi_{13}P_2-\left(\Psi_{13}+\Psi_{14}+\Phi_{13}+\Phi_{14}\right)P_3+\Phi_{13}P_6+\Phi_{14}P_7=0 \tag{3.5.64}$$

$$\Psi_{13}P_1-\left(\Psi_{14}+\Phi_{13}\right)P_4+\Phi_{14}P_6=0 \tag{3.5.65}$$

$$\Psi_{14}P_2-\left(\Psi_{13}+\Phi_{14}\right)P_5+\Phi_{13}P_7=0 \tag{3.5.66}$$

$$\Psi_{13}P_3+\Phi_{14}P_4-(\Psi_{14}+\Phi_{13})P_6=0 \tag{3.5.67}$$

$$\Psi_{13}P_5 - \left(\Psi_{13} + \Phi_{13}\right)P_7 + \Phi_{13}P_8 = 0 \tag{3.5.68}$$

$$\Psi_{14}P_6 + \Psi_{13}P_7 - \left(\Phi_{13} + \Phi_{14}\right)P_8 = 0 \tag{3.5.69}$$

The likelihood of full operating capacity P$_0$ is obtained by using normalising condition which states that sum of probabilities of working, reduced and failed states is equal to one.

$$\sum_{i=0}^{50} P_i = 1 \tag{3.5.70}$$

$$\left(1+\frac{\Psi_9}{\Phi_9}+\frac{\Psi_{10}}{\Phi_{10}}+\frac{\Psi_{11}}{\Phi_{11}}+\frac{\Psi_{12}}{\Phi_{12}}\right)(P_0+P_1+P_2+P_3)+\left(1+\frac{\Psi_9}{\Phi_9}+\frac{\Psi_{10}}{\Phi_{10}}+\frac{\Psi_{11}}{\Phi_{11}}+\frac{\Psi_{12}}{\Phi_{12}}+\frac{\psi_{13}}{\varphi_{13}}\right)(P_4+P_6)+$$
$$\left(1+\frac{\Psi_9}{\Phi_9}+\frac{\Psi_{10}}{\Phi_{10}}+\frac{\Psi_{11}}{\Phi_{11}}+\frac{\Psi_{12}}{\Phi_{12}}+\frac{\Psi_{14}}{\Phi_{14}}\right)(P_5+P_7)+\left(1+\frac{\Psi_9}{\Phi_9}+\frac{\Psi_{10}}{\Phi_{10}}+\frac{\Psi_{11}}{\Phi_{11}}+\frac{\Psi_{12}}{\Phi_{12}}+\frac{\Psi_{13}}{\Phi_{13}}+\frac{\Psi_{14}}{\Phi_{14}}\right)P_8 = 1 \tag{3.5.71}$$

So the long run steady state availability can be obtained by summation of probabilities of subunits working under full capacity and reduced capacity.

$$A_{v3} = \sum_{i=0}^{8} P_i = P_0 + P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 \tag{3.5.72}$$

3.5.4 Performance Modelling of Screening System

Following differential equations are developed by using Markovian birth-death process based on probabilistic method associated with the screening unit of a paper plant.

$$\left(\frac{d}{dt}+\sum_{i=15}^{18}\Psi_i\right)P_0(t) = \Phi_{15}P_4(t)+\Phi_{17}P_1(t)+\Phi_{16}P_5(t)+\Phi_{18}P_2(t) \tag{3.5.73}$$

$$\left(\frac{d}{dt}+\sum_{i=15}^{18}\Psi_i+\Phi_{17}\right)P_1(t) = \sum_{i=15}^{17}\Phi_i P_{i-9}(t)+\Phi_{18}P_3(t)+\Psi_{17}P_0(t) \tag{3.5.74}$$

$$\left(\frac{d}{dt}+\sum_{i=15}^{18}\Psi_i+\Phi_{18}\right)P_2(t) = \sum_{i=15}^{16}\Phi_i P_{i-6}(t)+\Phi_{17}P_3(t)+\Phi_{18}P_{11}(t)+\Psi_{18}P_0(t) \tag{3.5.75}$$

$$\left(\frac{d}{dt}+\sum_{i=15}^{18}\Psi_i+\Phi_{17}+\Phi_{18}\right)P_3(t) = \sum_{i=15}^{18}\Phi_i P_{i-3}(t)+\Psi_{17}P_2(t)+\Psi_{18}P_1(t) \tag{3.5.76}$$

$$\left(\frac{d}{dt}+\Phi_{15}\right)P_i(t) = \Psi_{15}P_j(t) \tag{3.5.77}$$

Where $i = 4, 6, 9, 12$ and $j = 0, 1, 2, 3$ respectively

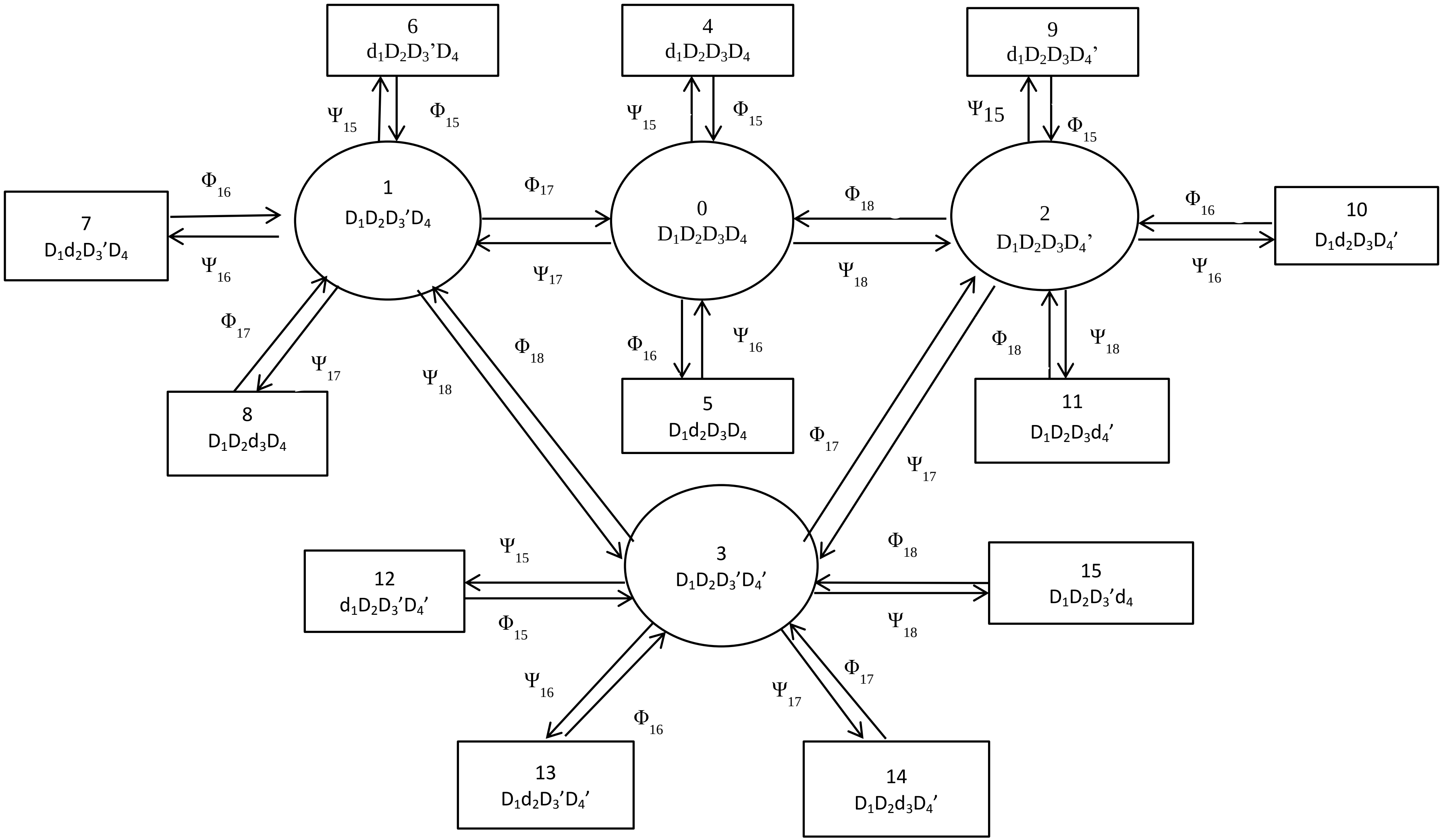


Figure 3.9 Transition Diagram for Screening System

$$\left(\frac{d}{dt}+\Phi_{16}\right)P_i\left(t\right)=\Psi_{16}P_j\left(t\right) \tag{3.5.78}$$

Where $i=5,7,10,13$ and $j=0,1,2,3$ respectively

$$\left(\frac{d}{dt}+\Phi_{17}\right)P_i\left(t\right)=\Psi_{17}P_j\left(t\right) \tag{3.5.79}$$

Where $i=8,14$ and $j=1,3$ respectively

$$\left(\frac{d}{dt}+\Phi_{18}\right)P_i\left(t\right)=\Psi_{18}P_j\left(t\right) \tag{3.5.80}$$

Where $i=11,15$ and $j=2,3$ respectively

With the initial condition at time $t=0$

$P_i(t)=1$ for $i=0$; otherwise $P_i(t)=0$

Long run steady state availability of the screening unit of a paper plant is obtained by putting $\frac{d}{dt}=0\ at\ t\rightarrow\infty$ into differential equations, following equations are obtained

$$\Phi_{15}P_i=\Psi_{15}P_j \tag{3.5.81}$$

Where $i=4,6,9,12$ and $j=0,1,2,3$ respectively

$$\Phi_{16}P_i=\Psi_{16}P_j \tag{3.5.82}$$

Where $i=5,7,10,13$ and $j=0,1,2,3$ respectively

$$\Phi_{17}P_i=\Psi_{17}P_j \tag{3.5.83}$$

Where $i=8,14$ and $j=1,3$ respectively

$$\Phi_{18}P_i=\Psi_{18}P_j \tag{3.5.84}$$

Where $i=11,15$ and $j=2,3$ respectively

By using back substitution following equations are obtained

$$\left(\Psi_{17}+\Psi_{18}\right)P_0=\Phi_{17}P_1+\Phi_{18}P_2 \tag{3.5.85}$$

$$\left(\Psi_{18}+\Phi_{17}\right)P_1=\Psi_{17}P_0+\Phi_{18}P_3 \tag{3.5.86}$$

$$\left(\Psi_{17}+\Psi_{18}+\Phi_{16}\right)P_2=\Psi_{18}P_0+\Phi_{17}P_3 \tag{3.5.87}$$

$$\left(\Phi_{17}+\Phi_{18}\right)P_3=\Psi_{17}P_2+\Psi_{18}P_1 \tag{3.5.88}$$

The likelihood of full operating capacity P_0 is obtained by using normalising condition which states that sum of probabilities of working, reduced and failed states is equal to one.

$$\sum_{i=0}^{15} P_i = 1 \qquad (3.5.89)$$

So the long run steady state availability can be obtained by summation of probabilities of subunits working under full capacity and reduced capacity.

$$A_{v4} = \sum_{i=0}^{3} P_i = P_0 + P_1 + P_2 + P_3 \qquad (3.5.90)$$

3.5.5 Performance Modelling of Paper Making System

Following differential equations are developed by using Markovian birth-death process based on probabilistic method associated with the paper production system of a paper plant.

$$\left(\frac{d}{dt} + \sum_{i=19}^{25} \Psi_i\right) P_0(t) = \sum_{i=19}^{20} \left(\Phi_i P_{i-16}(t)\right) + \sum_{i=22}^{25} \left(\Phi_i P_{i-17}(t)\right) + \Phi_{21} P_1(t) \qquad (3.5.91)$$

$$\left(\frac{d}{dt} + \sum_{i=19}^{25} \left(\Psi_i + \Phi_{21}\right)\right) P_1(t) = \sum_{i=19}^{20} \left(\Phi_i P_{i-10}(t)\right) + \sum_{i=22}^{25} \left(\Phi_i P_{i-11}(t)\right) + \Phi_{21} P_2(t) + \Psi_{21} P_0 \qquad (3.5.92)$$

$$\left(\frac{d}{dt} + \sum_{i=19}^{25} \left(\Psi_i + \Phi_{21}\right)\right) P_2(t) = \sum_{i=19}^{25} \left(\Phi_i P_{i-4}(t)\right) + \Psi_{21} P_1 \qquad (3.5.93)$$

$$\left(\frac{d}{dt} + \Phi_{19}\right) P_i(t) = \Psi_{19} P_j(t) \qquad (3.5.94)$$

Where $i = 3,9,15$ and $j = 0,1,2$ respectively

$$\left(\frac{d}{dt} + \Phi_{20}\right) P_i(t) = \Psi_{20} P_j(t) \qquad (3.5.95)$$

Where $i = 4,10,16$ and $j = 0,1,2$ respectively

$$\left(\frac{d}{dt} + \Phi_{21}\right) P_i(t) = \Psi_{21} P_j(t) \qquad (3.5.96)$$

Where $i = 17$ and $j = 2$ respectively

$$\left(\frac{d}{dt} + \Phi_{22}\right) P_i(t) = \Psi_{22} P_j(t) \qquad (3.5.97)$$

Where $i = 5,11,18$ and $j = 0,1,2$ respectively

$$\left(\frac{d}{dt} + \Phi_{23}\right) P_i(t) = \Psi_{23} P_j(t) \qquad (3.5.98)$$

Where $i = 6,12,19$ and $j = 0,1,2$ respectively

$$\left(\frac{d}{dt} + \Phi_{24}\right) P_i(t) = \Psi_{24} P_j(t) \qquad (3.5.99)$$

Where $i = 7,13,20$ and $j = 0,1,2$ respectively

$$\left(\frac{d}{dt} + \Phi_{25}\right) P_i\left(t\right) = \Psi_{25} P_j\left(t\right) \tag{3.5.100}$$

Where $i = 8,14,21$ and $j = 0,1,2$ respectively

With the initial condition at time $t = 0$

$P_i(t) = 1$ for $i = 0$; otherwise $P_i(t) = 0$

Long run steady state availability of the paper production system of paper plant is obtained by putting $\frac{d}{dt} = 0\ at\ t \to \infty$ into differential equations, following equations are obtained

$$\Phi_{19} P_i = \Psi_{19} P_j \tag{3.5.101}$$

Where $i = 3,9,15$ and $j = 0,1,2$ respectively

$$\Phi_{20} P_i = \Psi_{20} P_j \tag{3.5.102}$$

Where $i = 4,10,16$ and $j = 0,1,2$ respectively

$$\Phi_{21} P_i = \Psi_{21} P_j \tag{3.5.103}$$

Where $i = 17$ and $j = 2$ respectively

$$\Phi_{22} P_i = \Psi_{22} P_j \tag{3.5.104}$$

Where $i = 5,11,18$ and $j = 0,1,2$ respectively

$$\Phi_{23} P_i = \Psi_{23} P_j \tag{3.5.105}$$

Where $i = 6,12,19$ and $j = 0,1,2$ respectively

$$\Phi_{24} P_i = \Psi_{24} P_j \tag{3.5.106}$$

Where $i = 7,13,20$ and $j = 0,1,2$ respectively

$$\Phi_{25} P_i = \Psi_{25} P_j \tag{3.5.107}$$

Where $i = 8,14,21$ and $j = 0,1,2$ respectively

By using back substitution following equations are obtained

$$\Psi_{21} P_0 - \left(\Psi_{21} + \Phi_{21}\right) P_1 + \Phi_{21} P_2 = 0 \tag{3.5.108}$$

$$\Psi_{21} P_1 - \Phi_{21} P_2 = 0 \tag{3.5.109}$$

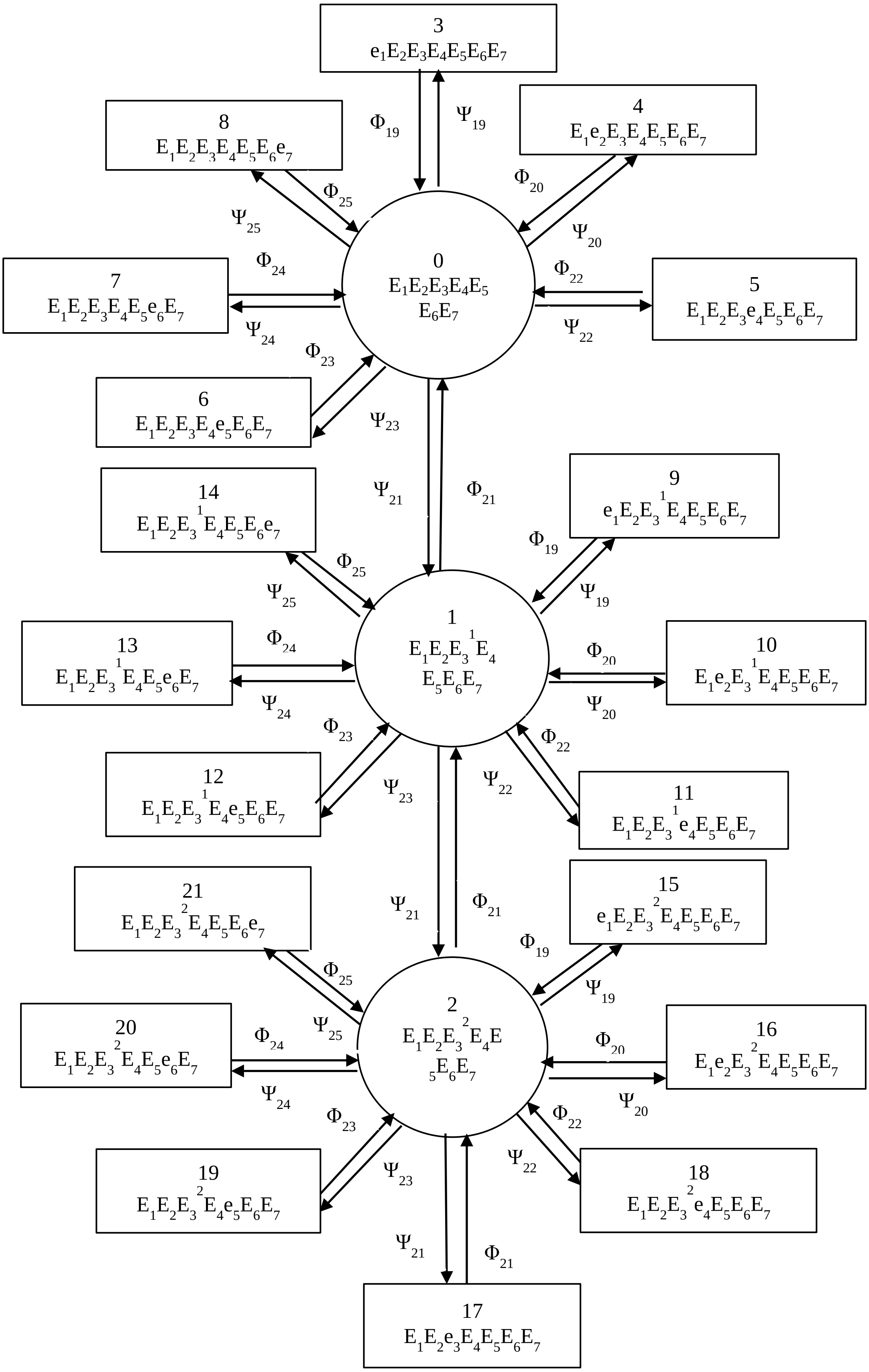


Figure 3.10 Transition Diagram of Paper Making System

The likelihood of full operating capacity P_0 is obtained by using normalising condition which states that sum of probabilities of working, reduced and failed states is equal to one.

$$\sum_{i=0}^{21} P_i = 1 \tag{3.5.110}$$

$$\left(1+\frac{\Psi_{19}}{\Phi_{19}}+\frac{\Psi_{20}}{\Phi_{20}}+\frac{\Psi_{22}}{\Phi_{22}}+\frac{\Psi_{23}}{\Phi_{23}}+\frac{\Psi_{24}}{\Phi_{24}}+\frac{\Psi_{25}}{\Phi_{25}}\right)\left(P_0+P_1\right)+\left(1+\frac{\Psi_{19}}{\Phi_{19}}+\frac{\Psi_{20}}{\Phi_{20}}+\frac{\Psi_{21}}{\Phi_{21}}+\frac{\Psi_{22}}{\Phi_{22}}+\frac{\Psi_{23}}{\Phi_{23}}+\frac{\Psi_{24}}{\Phi_{24}}+\frac{\Psi_{25}}{\Phi_{25}}\right)P_2 = 1 \tag{3.5.111}$$

So the long run steady state availability can be obtained by summation of probabilities of subunits working under full capacity and reduced capacity.

$$A_{v5} = \sum_{i=0}^{2} P_i = P_0 + P_1 + P_2 \tag{3.5.112}$$

CHAPTER IV

PERFORMANCE EVALUATION AND ANALYSIS

4.1 INTRODUCTION

The performance analysis of various systems of a paper plant is mostly affected by the failure rates and repair rates of each subsystem. The failure rates of various subsystems are assumed to follow exponential distribution for the simplicity of performance analysis. These system parameters ensure the high performance i.e. measure of availability of the various systems of paper plant. The performance model includes failure rates (Ψ_i) and the repair rates (Φ_i).

The appropriate values of failure and repair rates are taken after a long stay, deep study and long discussions with highly skilled and experienced plant personnel. During stay, continuous monitoring of failure/repair patterns, consultation of maintenance log sheets and history cards and recording of maintenance strategies in different situations are done. However, to reduce the ambiguity in the selection of failure and repair rates, the study is conducted in paper plant located in northern region of India and feasible range of failure and repair rates of various subsystems are selected for the computation purpose Table 4.1.

For each subsystem, a desired level of outcome is planned and indicated in each developed availability matrix. This level is maintained in the subsequent matrices and the applicable states/strategies are also indicated. Tables 4.2 to 4.26 shows availability matrices for various subsystem of a paper plant.

Table 4.1 Ranges of Failure and Repair Rates of Various Subsystems of a Paper Plant

Failure Rates (Ψ_i)	**Repair Rates (Φ_i)**
Ψ_1=0.005-0.009	Φ_1=0.08-0.12
Ψ_2=0.03-0.05	Φ_2=0.3-0.6
Ψ_3=0.011-0.015	Φ_3=0.125-0.25
Ψ_4=0.001-0.005	Φ_4=0.04-0.08
Ψ_5= Ψ_{18}=0.002-0.006	Φ_5=0.3-0.7
Ψ_6=0.008-0.012	Φ_6=0.12-0.32
Ψ_7=0.003-0.007	Φ_7=0.2-0.6
Ψ_8=0.01-0.02	Φ_8=0.1-0.5

Ψ_9=0.0028-0.004	Φ_9= Φ_{12}=0.2-0.3
Ψ_{10}=0.0025-0.0039	Φ_{10}=0.25-0.39
Ψ_{11}=0.005-0.008	Φ_{11}=0.4-0.7
Ψ_{12}=0.002-0.003	Φ_{13}=0.6-0.9
Ψ_{13}= Ψ_{14}=0.0037-0.0055	Φ_{14}=0.3-0.5
Ψ_{15}=0.002-0.004	Φ_{15}=0.25-0.45
Ψ_{16}=0.007-0.011	Φ_{16}=0.1-0.3
Ψ_{17}=0.004-0.008	Φ_{17}=0.45-0.65
Ψ_{19}=0.0045-0.32	Φ_{18}=0.6-0.8
Ψ_{20}= Ψ_{24}=0.0036-0.0054	Φ_{19}=0.07-0.1
Ψ_{21}= Ψ_{22}=0.0009-0.0013	Φ_{20}= Φ_{24}=0.14-0.22
Ψ_{23}=0.0045-0.0065	Φ_{21}=0.35-0.55
Ψ_{25}=0.003-0.005	Φ_{22}=0.054-0.083
	Φ_{23}=0.16-0.24
	Φ_{25}=0.24-0.4

4.2 PERFORMANCE ANALYSIS OF VARIOUS SYSTEMS OF PAPER PLANT

Performance Analysis of a paper plant is primarily influenced by each system’s failure and repair rates that are presumed to follow exponential distribution for the effortlessness of performance and availability analysis. These system parameters make sure that the paper unit is highly available. This model of performance evaluation incorporates every attainable state, that is, failure occurrence Ψ_i and therefore the identity of all avenues of intervention, that is, repair priorities Φ_i. For multiple combinations of failure and repair rates, the different availability levels are figured out. Based on examination, one can choose most effective combination (Ψ_i ,Φ_i) that is, optimal maintenance strategies.

4.2.1 Performance Analysis of Feeding system

Table 4.2 and Figure 4.1 demonstrate the impact of blower repair and failure rates on feeding system availability. As blower repair rates (Φ_1) rises from 0.08 to 0.12, the long run availability of the frame work only improves by 1.98%. In the same way as the blower failure rate (Ψ_1) rises from 0.005 to 0.009, the framework long run availability reduces by 4.55%.

Table 4.2 Availability Matrix for Blower Subsystem of Feeding System

Φ_1	Ψ_1					Constant Values
	0.005	0.006	0.007	0.008	0.009	
0.08	0.940041	0.929123	0.918456	0.908031	0.897841	Ψ_2=0.040, Φ_2=0.45 Ψ_3=0.013, Φ_3=0.187
0.09	0.946218	0.936373	0.926731	0.917286	0.908031	
0.1	0.951215	0.942255	0.933460	0.924827	0.916352	
0.11	0.955349	0.947123	0.939038	0.931089	0.923274	
0.12	0.958819	0.951218	0.943737	0.936373	0.929123	

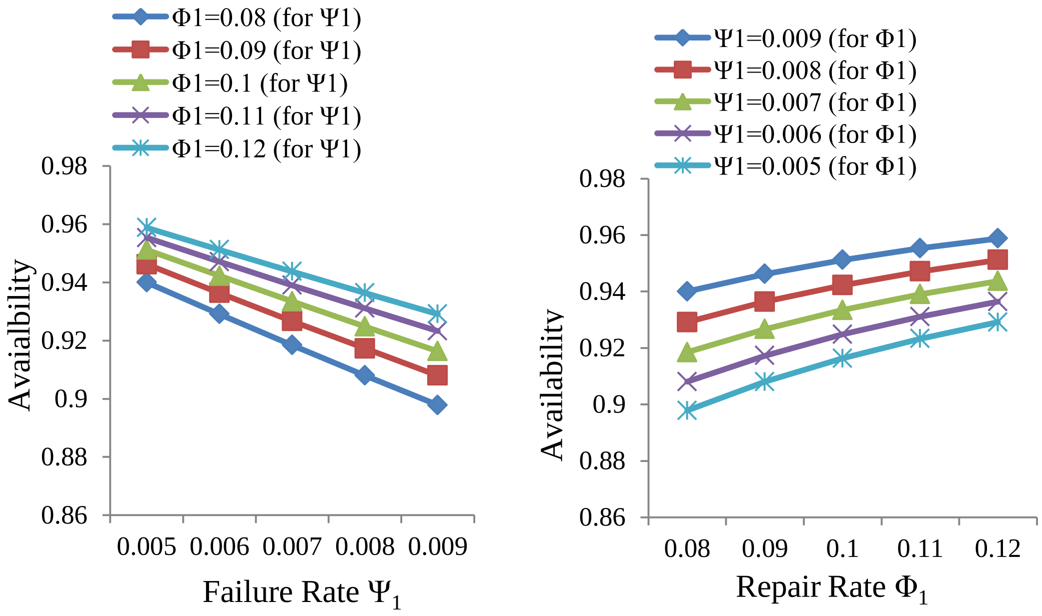


Figure 4.1(a) (b) Impact of Blower Failure and Repair Rate on Feeding System Availability

Table 4.3 and Figure 4.2 demonstrate the impact of conveyor repair and failure rates on feeding system availability. As conveyor repair rates (Φ_2) rises from 0.3 to 0.6, the long run availability of the framework improves by 0.217%. In the same way as the conveyor failure rate (Ψ_2) rises from 0.03 to 0.05, the framework long run availability reduces by 0.052%.

Table 4.4 and Figure 4.3 demonstrate the impact of feeder repair and failure rates on feeding system availability. As feeder repair rates (Φ_3) rises from 0.125 to 0.25, the long run availability of the framework only improves by 0.023%. In the same way as the feeder failure rate (Ψ_3) rises from 0.011 to 0.015, the framework long run availability reduces by 0.087%.

Table 4.3 Availability Matrix for Conveyor Subsystem of Feeding System

Φ_2	Ψ_2					Constant Values
	0.03	0.035	0.040	0.045	0.05	
0.3	0.931389	0.931128	0.930967	0.93093	0.930902	Ψ_1=0.007, Φ_1=0.10 Ψ_3=0.013,Φ_3=0.187
0.375	0.932254	0.932037	0.931885	0.931814	0.931763	
0.45	0.932794	0.932607	0.932464	0.932378	0.932362	
0.525	0.933154	0.93299	0.932857	0.932765	0.932722	
0.6	0.933409	0.933262	0.933138	0.933043	0.932986	

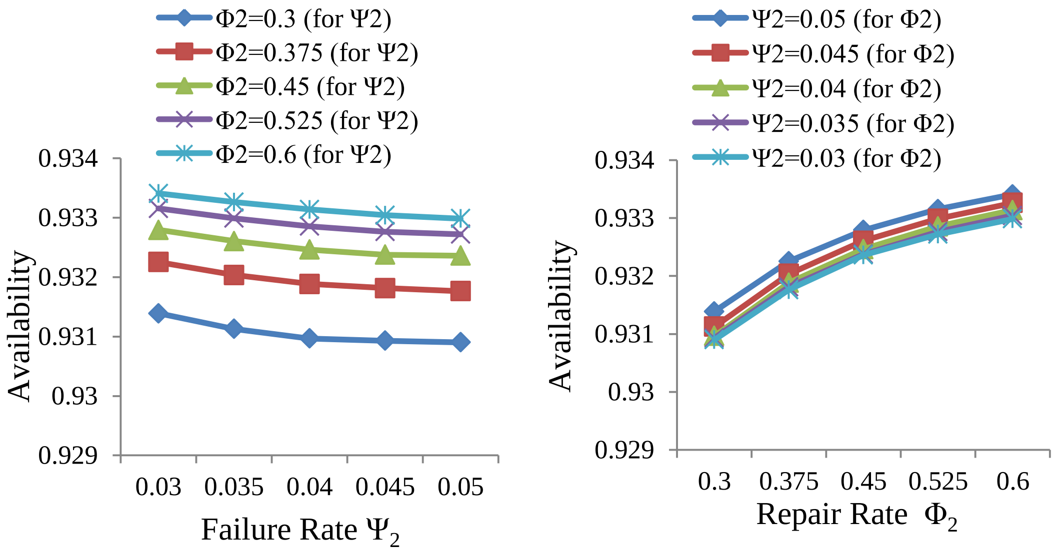


Figure 4.2(a) (b) Impact of Conveyor Failure and Repair Rate on Feeding System Availability

Table 4.4 Availability Matrix for Feeder Subsystem of Feeding System

Φ_3	Ψ_3					Constant Values
	0.011	0.012	0.013	0.014	0.015	
0.125	0.932722	0.932524	0.932323	0.932111	0.931906	Ψ_1=0.007, Φ_1=0.10 Ψ_2=0.04, Φ_2=0.45
0.156	0.932763	0.932578	0.932389	0.932195	0.931998	
0.187	0.932818	0.932643	0.932464	0.932281	0.932095	
0.219	0.932879	0.932713	0.932544	0.93237	0.932194	
0.25	0.932938	0.93278	0.932619	0.932454	0.932285	

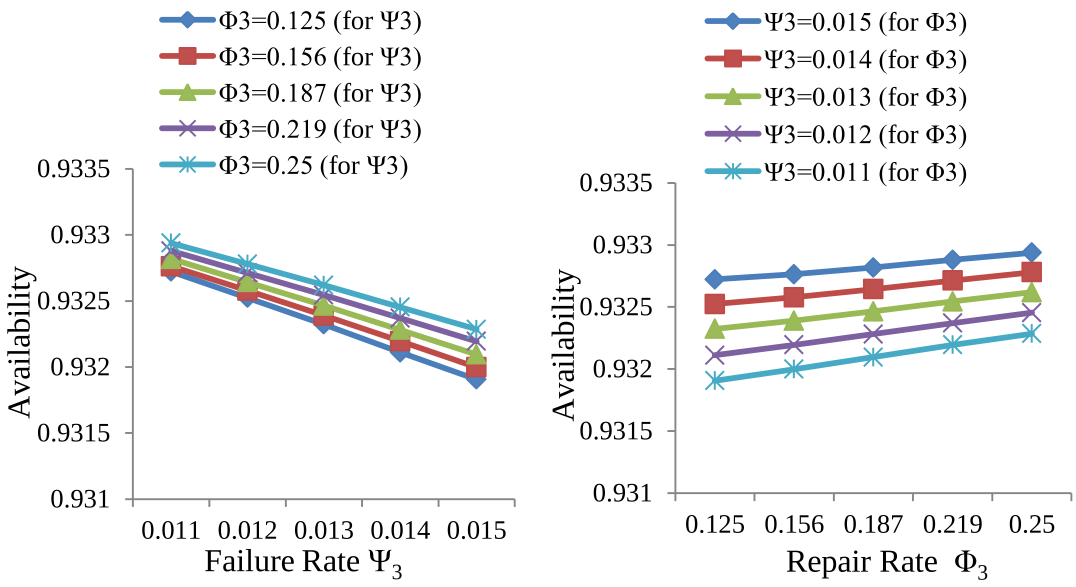


Figure 4.3(a) (b) Impact of Feeder Failure and Repair Rate on Feeding System Availability

4.2.2 Performance Analysis of the Pulping system

Table 4.5 and Figure 4.4 demonstrate the impact of digester repair and failure rates on pulping unit availability. As digester repair rates (Φ_4) rise from 0.04 to 0.08, the long run availability of the frame work only improves by 1%. In the same way as the digester failure rate (Ψ_4) rises from 0.001 to 0.005, the framework long run availability reduces by 6.7%.

Table 4.6 and Figure 4.5 demonstrate the impact of pump repair and failure rates on pulping unit availability. As pump repair rates (Φ_5) rises from 0.3 to 0.7, the long run availability of the framework only improves by 0.03%.In the same way as the pump failure rate (Ψ_5) rises from 0.002 to 0.006, the framework long run availability reduces by 0.02 %.

Table 4.5 Availability Matrix for Digester Subsystem of Pulping System

Φ_4	Ψ_4					Constant Values
	0.001	0.002	0.003	0.004	0.005	
0.04	0.957176	0.934853	0.913442	0.893041	0.87134	Ψ_5=0.003, Φ_5=0.4
0.05	0.961783	0.943635	0.926174	0.909269	0.892164	Ψ_6=0.009,Φ_6=0.17
0.06	0.964835	0.949617	0.934853	0.920424	0.905712	Ψ_7=0.004, Φ_7=0.3
0.07	0.967088	0.953911	0.941049	0.928649	0.914241	Ψ_8=0.125, Φ_8=0.2
0.08	0.969002	0.958005	0.947123	0.935847	0.924317	

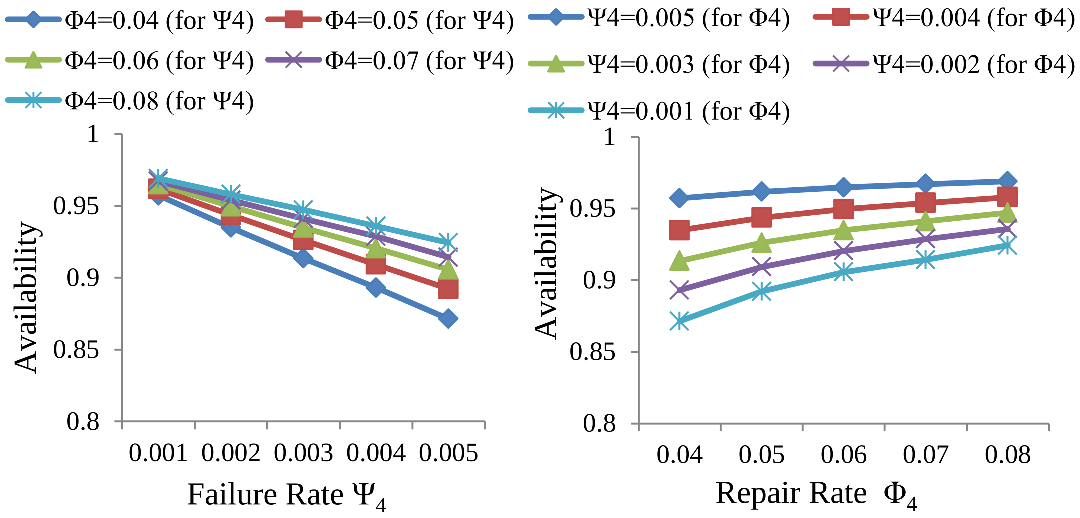


Figure 4.4(a) (b) Impact of Digester Failure and Repair Rate on Pulping System Availability

Table 4.6 Availability Matrix for Pump Subsystem of Pulping System

Φ_5	Ψ_5					Constant Values
	0.002	0.003	0.004	0.005	0.006	
0.3	0.943651	0.943606	0.943552	0.943457	0.943374	Ψ_4=0.002,Φ_4=0.05
0.4	0.943662	0.943635	0.943606	0.943562	0.943518	Ψ_6=0.009,Φ_6=0.17
0.5	0.943674	0.943657	0.943632	0.943600	0.943575	Ψ_7=0.004, Φ_7=0.3
0.6	0.943679	0.943666	0.943649	0.943627	0.94361	Ψ_8=0.125, Φ_8=0.2
0.7	0.943683	0.943674	0.943659	0.94364	0.943621	

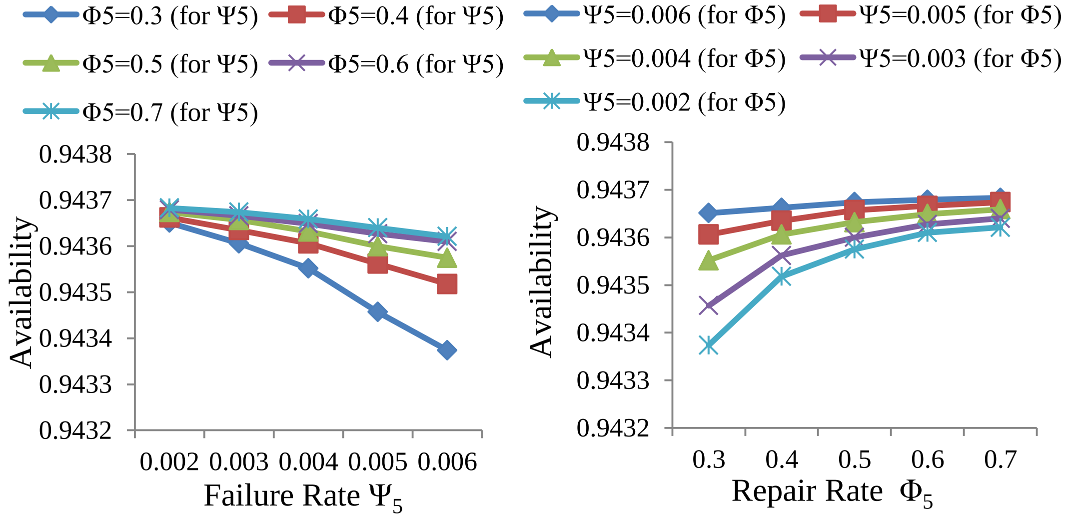


Figure 4.5(a) (b) Impact of Pump Failure and Repair Rate on Pulping System Availability

Table 4.7 and Figure 4.6 demonstrate the impact of knotter repair and failure rates on pulping unit availability. As knotter repair rates (Φ_6) rises from 0.12 to 0.32, the long run availability of the framework only improves by 0.3%.In the same way as the knotter failure rate (Ψ_6) rises from 0.008 to 0.012, the framework long run availability reduces by 0.4%.

Table 4.7 Availability Matrix for Knotter Subsystem of Pulping System

Φ_6	Ψ_6					Constant Values
	0.008	0.009	0.010	0.011	0.012	
0.12	0.941989	0.940967	0.939843	0.938618	0.937308	Ψ_4=0.002,Φ_4=0.05
0.17	0.944014	0.943499	0.942928	0.942305	0.941625	Ψ_5=0.003, Φ_5=0.4
0.22	0.944822	0.944513	0.944169	0.943793	0.943389	Ψ_7=0.004, Φ_7=0.3
0.27	0.945224	0.945018	0.944789	0.944537	0.944537	Ψ_8=0.125, Φ_8=0.2
0.32	0.945606	0.945503	0.945401	0.945299	0.945197	

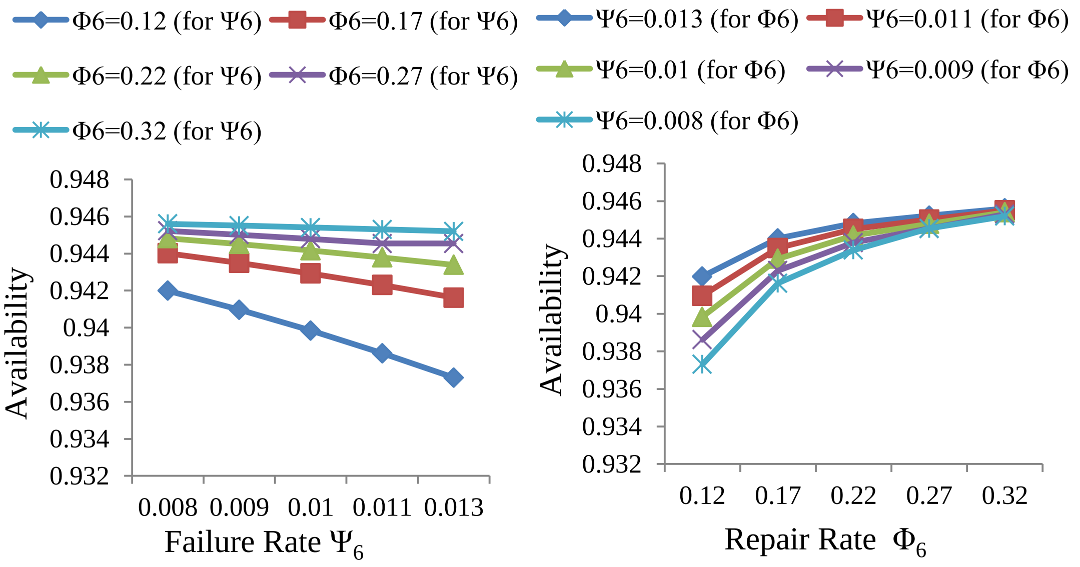


Figure 4.6(a) (b) Impact of Knotter Failure and Repair Rate on Pulping System Availability

Table 4.8 and Figure 4.7 demonstrate the impact of washing repair and failure rates on pulping unit availability. As washing system repair rates (Φ_7) rises from 0.2 to 0.6, the long run availability of the framework only improves by 0.8%. In the same way as the washing system failure rate (Ψ_7) rises from 0.003 to 0.007, the framework long run availability reduces by 1.4%.

Table 4.8 Availability Matrix for Washer Subsystem of Pulping System

Φ_7	Ψ_7					Constant Values
	0.003	0.004	0.005	0.006	0.007	
0.2	0.943679	0.939247	0.934857	0.930508	0.926159	Ψ_4=0.002,Φ_4=0.05
0.3	0.948153	0.945166	0.942197	0.939247	0.936288	Ψ_5=0.003, Φ_5=0.4
0.4	0.950406	0.948153	0.945911	0.943679	0.941438	Ψ_6=0.009,Φ_6=0.17
0.5	0.951763	0.949954	0.948153	0.946358	0.944558	Ψ_8=0.125, Φ_8=0.2
0.6	0.952441	0.950854	0.949274	0.947697	0.946112	

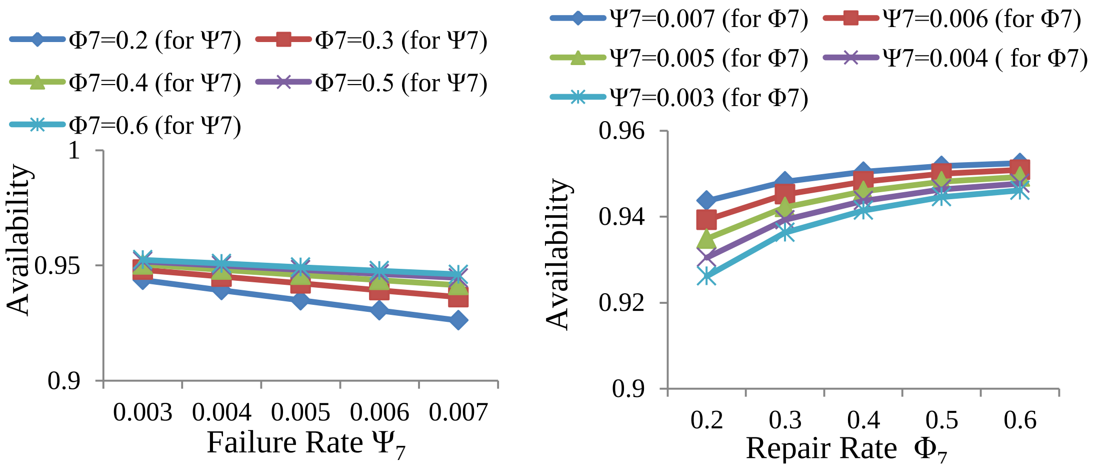


Figure 4.7(a) (b) Impact of Washer Failure and Repair Rate on Pulping System Availability

Table 4.9 and Figure 4.8 demonstrate the impact of opener repair and failure rates on pulping unit availability. As opener repair rates (Φ_8) irises from 0.1 to 0.5, the long run availability of the framework only improves by 0.2%. In the same way as the opener failure rate (Ψ_8) rises from 0.01 to 0.02, the framework long run availability reduces by 0.5%.

Table 4.9 Availability Matrix for Opener Subsystem of Pulping System

Φ_8	Ψ_8					Constant Values
	0.01	0.0125	0.015	0.0175	0.02	
0.1	0.944575	0.943284	0.941726	0.939910	0.936601	Ψ_4=0.002,Φ_4=0.05
0.2	0.945791	0.945166	0.944410	0.943527	0.942644	Ψ_5=0.003, Φ_5=0.4
0.3	0.946185	0.945777	0.945283	0.944705	0.944127	Ψ_6=0.009,Φ_6=0.17
0.4	0.946378	0.946076	0.945710	0.945282	0.944854	Ψ_7=0.004, Φ_7=0.3
0.5	0.946481	0.946266	0.94591	0.945675	0.945319	

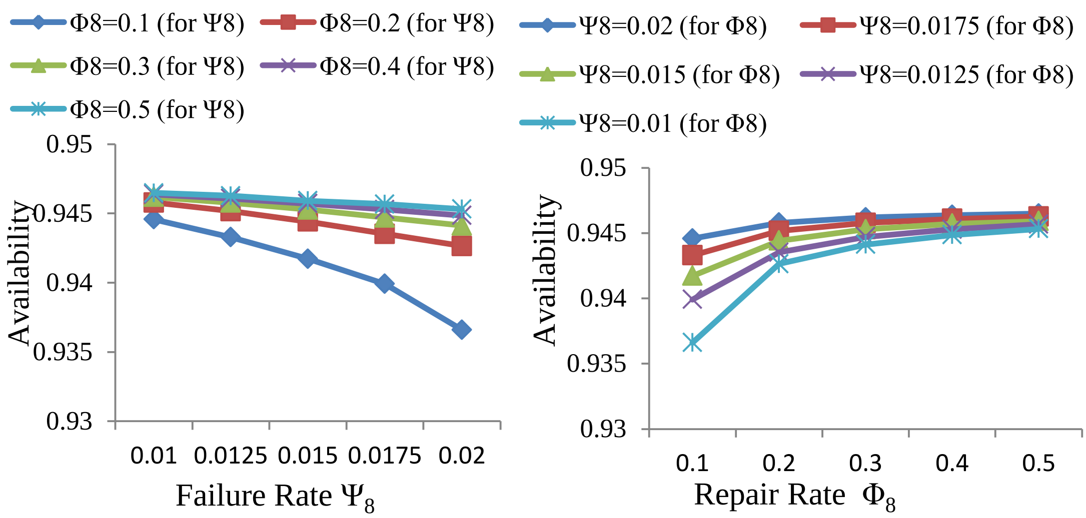


Figure 4.8(a) (b) Impact of Opener Failure and Repair Rate on Pulping System Availability

4.2.3 Performance Analysis of Bleaching and Washing System

Table 4.10 and Figure 4.9 demonstrate the impact of agitator repair and failure rates on bleaching and washing system availability. As bleaching and washing repair rates (Φ_9) rises from 0.2 to 0.3, the long run availability of the frame work only improves by 0.447 %. In the same way as the bleaching and washing failure rate (Ψ_9) rises from 0.0028 to 0.004, the framework long run availability reduces by 0.575 %.

Table 4.10 Availability Matrix for Agitator Subsystem of Bleaching and Washing system

Φ_9	Ψ_9					Constant Values
	0.0028	0.0031	0.0034	0.0037	0.004	
0.2	0.9562	0.9548	0.9535	0.9521	0.9507	Ψ_{10}=0.0032,Φ_{10}=0.32
0.225	0.9576	0.9564	0.9552	0.954	0.9527	Ψ_{11}=0.0065,Φ_{11}=0.55
0.25	0.9588	0.9577	0.9566	0.9555	0.9544	Ψ_{12}=0.0025,Φ_{12}=0.25
0.275	0.9597	0.9587	0.9577	0.9567	0.9557	Ψ_{13}=0.0035,Φ_{13}=0.75
0.3	0.9605	0.9596	0.9586	0.9577	0.9568	Ψ_{14}=0.0046,Φ_{14}=0.4

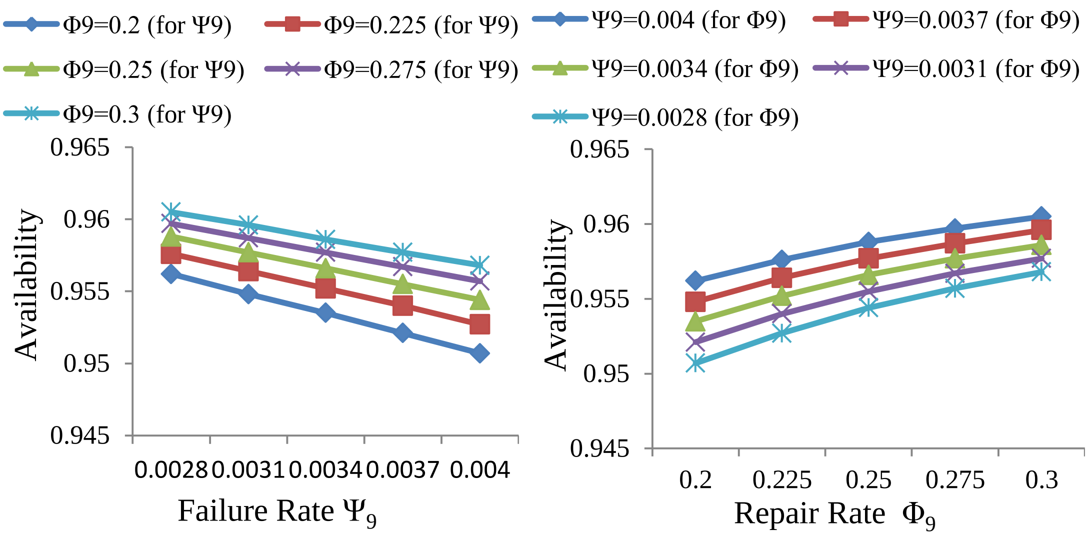


Figure 4.9(a) (b) Impact of Agitator Failure and Repair Rate on Bleaching and Washing System Availability

Table 4.11 and Figure 4.10 demonstrate the impact of filter repair and failure rates on bleaching and washing system availability. As filter repair rates (Φ_{10}) rises from 0.25 to 0.39, the long run availability of the frame work only improves by 0.333 %. In the same way as failure rate (Ψ_{10}) rises from 0.0025 to 0.0039, the framework long run availability reduces by 0.533 %.

Table 4.12 and Figure 4.11 demonstrate the impact of cleaner repair and failure rates on bleaching and washing system availability. As bleaching and washing repair rates (Φ_{11}) rises from 0.4 to 0.7, the long run availability of the frame work only improves by 0.52 %. In the same way as the bleaching and washing failure rate (Ψ_{11}) rises from 0.005 to 0.008, the framework long run availability reduces by 0.71 %.

Table 4.11 Availability Matrix for Filter Subsystem of Bleaching and Washing system

Φ_{10}	Ψ_{10}					Constant Values
	0.0025	0.00285	0.0032	0.00355	0.0039	
0.25	0.9566	0.9553	0.954	0.9527	0.9515	Ψ_9=0.0034, Φ_9=0.25
0.285	0.9577	0.9566	0.9554	0.9543	0.9532	Ψ_{11}=0.0065,Φ_{11}=0.55
0.32	0.9586	0.9576	0.9566	0.9556	0.9546	Ψ_{12}=0.0025,Φ_{12}=0.25
0.355	0.9593	0.9584	0.9575	0.9566	0.9557	Ψ_{13}=0.0035,Φ_{13}=0.75
0.39	0.9598	0.959	0.9582	0.9574	0.9566	Ψ_{14}=0.0046, Φ_{14}=0.4

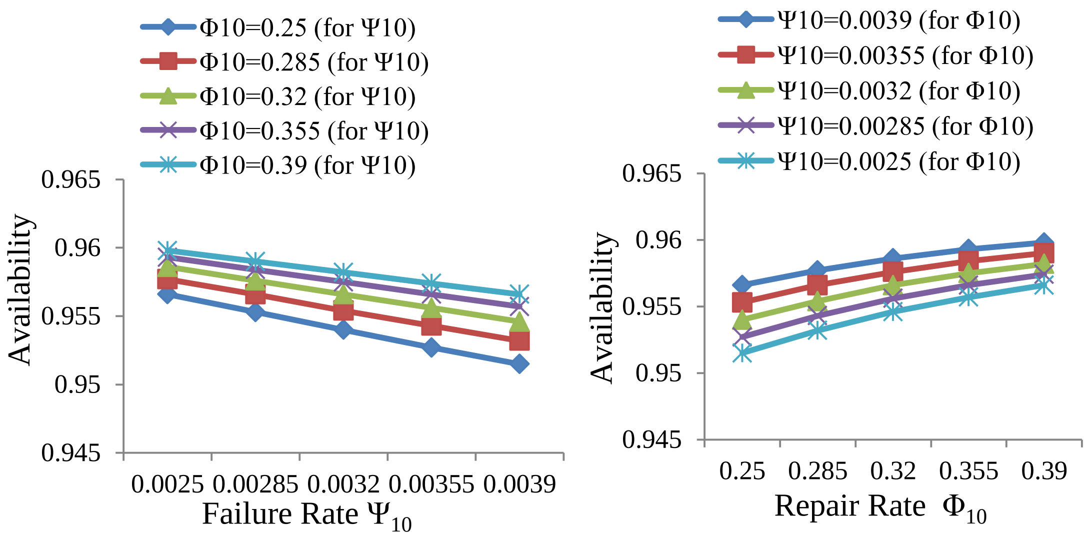


Figure 4.10(a) (b) Impact of Filter Failure and Repair Rate on Bleaching and Washing System Availability

Table 4.12 Availability Matrix for Cleaner Subsystem of Bleaching and Washing System

Φ_{11}	Ψ_{11}					Constant Values
	0.005	0.00575	0.0065	0.00725	0.008	
0.4	0.9559	0.9542	0.9525	0.9508	0.9491	Ψ_9=0.0034, Φ_9=0.25
0.475	0.9577	0.9563	0.9548	0.9534	0.952	Ψ_{10}=0.0032,Φ_{10}=0.32
0.55	0.9591	0.9578	0.9566	0.9553	0.9541	Ψ_{12}=0.0025,Φ_{12}=0.25
0.625	0.9601	0.959	0.9579	0.9568	0.9557	Ψ_{13}=0.0035,Φ_{13}=0.75
0.7	0.9609	0.9599	0.9589	0.9579	0.9569	Ψ_{14}=0.0046, Φ_{14}=0.4

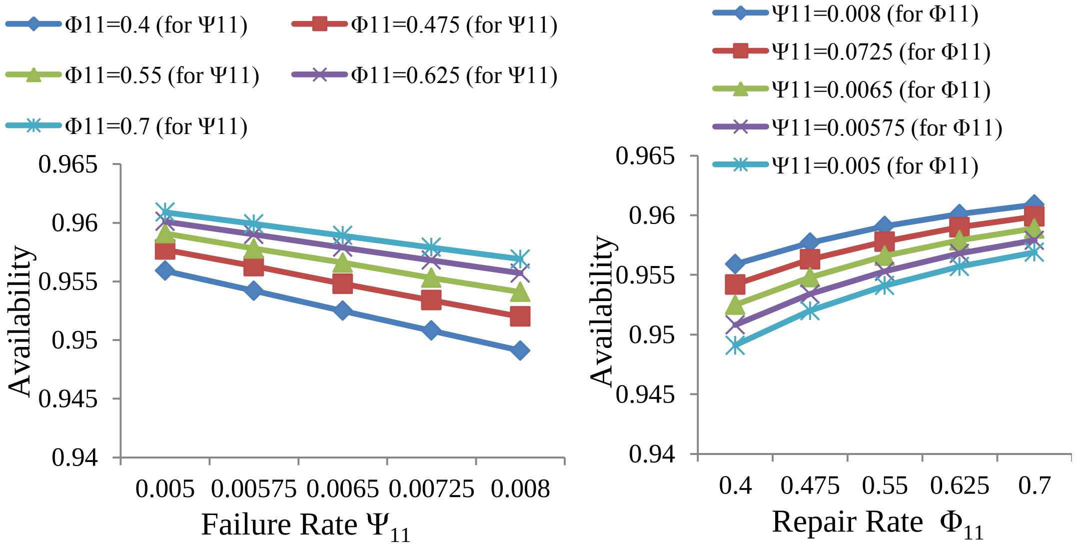


Figure 4.11(a) (b) Impact of Cleaner Failure and Repair Rate on Bleaching and Washing System Availability

Table 4.13 and Figure 4.12 demonstrate the impact of washer repair and failure rates on bleaching and washing system availability. As bleaching and washing repair rates (Φ_{12}) rises from 0.2 to 0.3, the long run availability of the frame work only improves by 0.31 %. In the same way as the bleaching and washing failure rate (Ψ_{12}) rises from 0.002 to 0.003, the framework long run availability reduces by 0.48 %.

Table 4.13 Availability Matrix for Washer Subsystem of Bleaching and Washing System

Φ_{12}	Ψ_{12}					Constant Values
	0.002	0.00225	0.0025	0.00275	0.003	
0.2	0.9566	0.9554	0.9543	0.9531	0.952	Ψ_9=0.0034, Φ_9=0.25
0.225	0.9576	0.9566	0.9555	0.9545	0.9535	Ψ_{10}=0.0032,Φ_{10}=0.32
0.25	0.9584	0.9575	0.9566	0.9556	0.9547	Ψ_{11}=0.0065,Φ_{11}=0.55
0.275	0.9591	0.9582	0.9574	0.9566	0.9557	Ψ_{13}=0.0035,Φ_{13}=0.75
0.3	0.9596	0.9588	0.9581	0.9573	0.9566	Ψ_{14}=0.0046, Φ_{14}=0.4

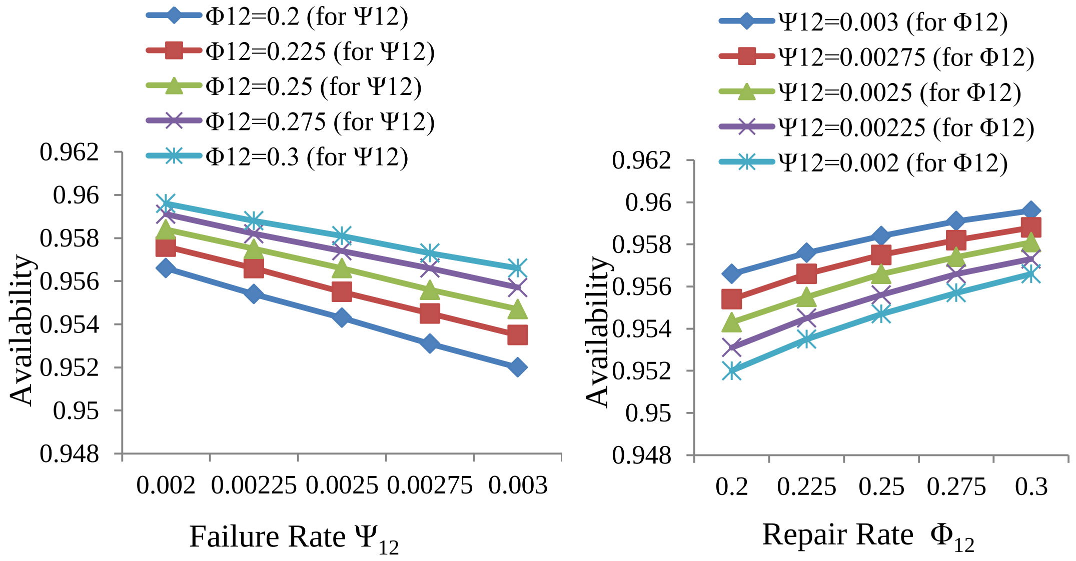


Figure 4.12(a) (b) Impact of Washer Failure and Repair Rate on Bleaching and Washing System Availability

Table 4.14 and Figure 4.13 demonstrate the impact of vacuum pump repair and failure rates on bleaching and washing system availability. As bleaching and washing repair rates (Φ_{13}) rises from 0.6 to 0.9, the long run availability of the frame work improves negligibly. In the same way as the bleaching and washing failure rate

(Ψ_{13}) rises from 0.003 to 0.004, the framework long run availability reduces negligibly.

Table 4.14 Availability Matrix for Vacuum Pump Subsystem of Bleaching and Washing System

Φ_{13}	Ψ_{13}					Constant Values
	0.0037	0.00415	0.0046	0.00505	0.0055	
0.6	0.95655329	0.95655320	0.95655309	0.95655296	0.95655282	Ψ_9=0.0034, Φ_9=0.25
0.675	0.95655344	0.95655338	0.95655332	0.95655325	0.95655316	Ψ_{10}=0.0032,Φ_{10}=0.32
0.75	0.95655351	0.95655347	0.95655343	0.95655339	0.95655333	Ψ_{11}=0.0065,Φ_{11}=0.55
0.825	0.95655355	0.95655352	0.95655350	0.95655347	0.95655343	Ψ_{12}=0.0025,Φ_{12}=0.25
0.9	0.95655357	0.95655356	0.95655354	0.95655351	0.95655349	Ψ_{14}=0.0046, Φ_{14}=0.4

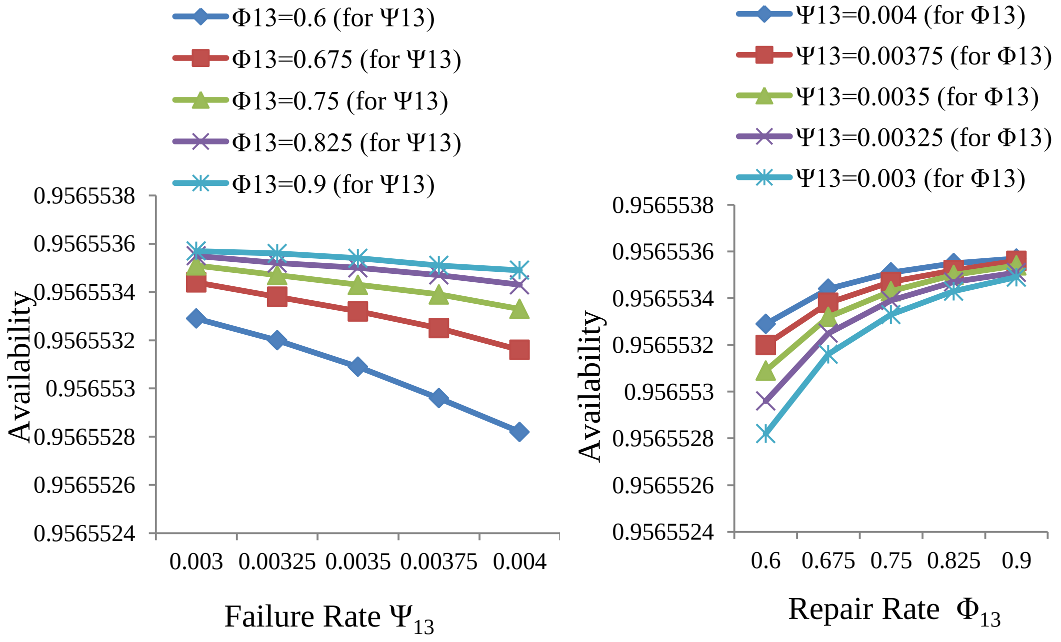


Figure 4.13(a) (b) Impact of Vacuum Pumps Failure and Repair Rate on Bleaching and Washing System Availability

Table 4.15 and Figure 4.14 demonstrate the impact of centrifugal pump repair and failure rates on bleaching and washing system availability. As bleaching and washing repair rates (Φ_1) rises from 0.3 to 0.5, the long run availability of the frame work improves negligibly. In the same way as the bleaching and washing failure rate (Ψ_1) rises from 0.0037 to 0.0055, the framework long run availability reduces negligibly.

Table 4.15 Availability matrix for centrifugal pump subsystem of bleaching and washing system

Φ_{14}	Ψ_{14}					Constant Values
	0.0037	0.00415	0.0046	0.00505	0.0055	
0.3	0.95655316	0.95655246	0.95655160	0.95655056	0.95655031	Ψ_9=0.0034, Φ_9=0.25
0.35	0.95655376	0.95655333	0.95655278	0.95655212	0.95655134	Ψ_{10}=0.0032,Φ_{10}=0.32
0.4	0.95655409	0.95655380	0.95655343	0.95655299	0.95655246	Ψ_{11}=0.0065,Φ_{11}=0.55
0.45	0.95655427	0.95655407	0.95655381	0.95655350	0.95655312	Ψ_{12}=0.0025,Φ_{12}=0.25
0.5	0.95655436	0.95655421	0.95655402	0.95655380	0.95655353	Ψ_{13}=0.0035,Φ_{13}=0.75

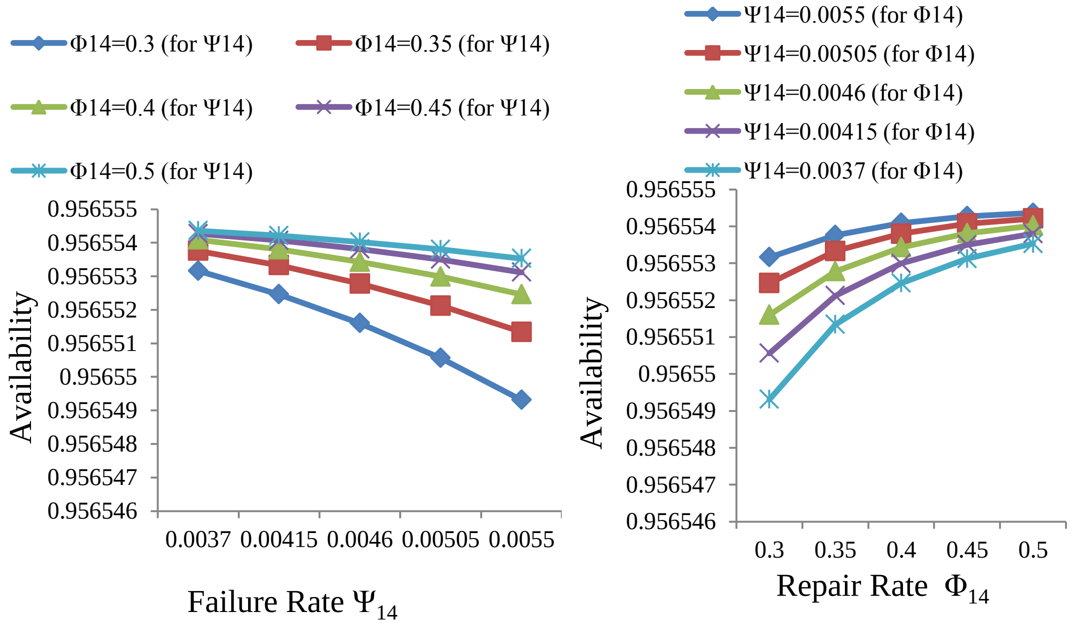


Figure 4.14(a) (b) Impact of centrifugal pumps failure and repair rate on bleaching and washing system availability

4.2.4 Performance Analysis of the Screening system:

Table 4.16 and Figure 4.15 demonstrate the impact of filter repair and failure rates on screening system availability. As filter repair rates (Φ_{15}) rises from 0.25 to 0.45, the long run availability of the frame work only improves by 0.33%.In the same way as the filter failure rate (Ψ_{15}) rises from 0.002 to 0.004, the framework long run availability reduces by 0.75%.

Table 4.17 and Figure 4.16 demonstrate the impact of vibrating screen repair and failure rates on screening system availability. As pump repair rates (Φ_{16}) rises from 0.1 to 0.3, the long run availability of the framework improves by 6.59%.In the same way as the pump failure rate (Ψ_{16}) rises from 0.007 to 0.011, the framework long run availability reduces by 3.56 %.

Table 4.16 Availability matrix for filter subsystem of screening system

Φ_{15}	Ψ_{15}					Constant Values
	0.002	0.0025	0.003	0.0035	0.004	
0.25	0.9444	0.9426	0.9408	0.9390	0.9373	
0.3	0.9456	0.9441	0.9426	0.9411	0.9396	Ψ_{16}=0.008, Φ_{16}=0.2
0.35	0.9464	0.9451	0.9439	0.9426	0.9413	Ψ_{17}=0.006, Φ_{17}=0.55
0.4	0.9471	0.9459	0.9448	0.9437	0.9426	Ψ_{18}=0.004, Φ_{18}=0.7
0.45	0.9475	0.9466	0.9456	0.9446	0.9436	

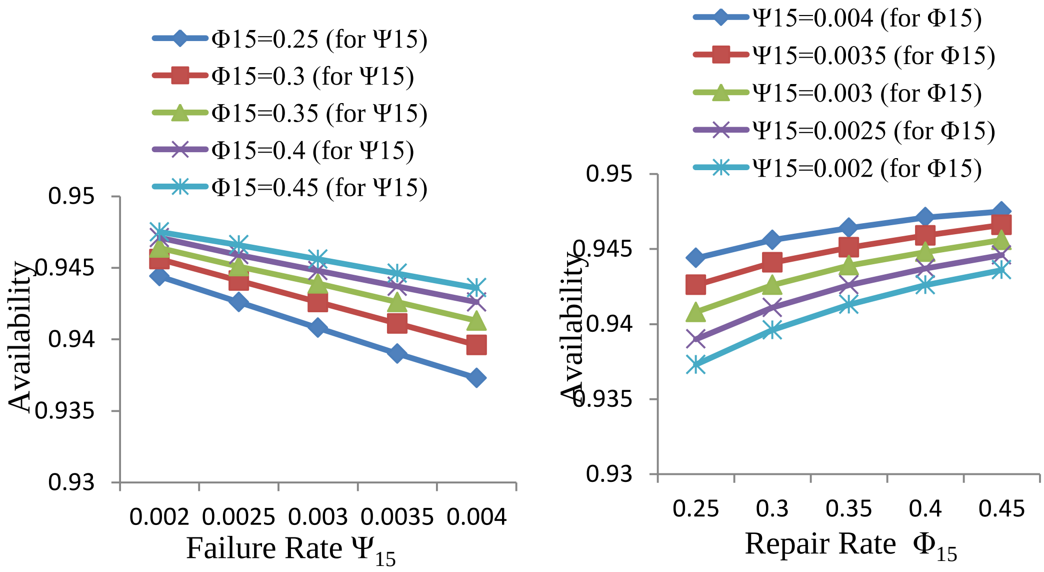


Figure 4.15(a) (b) Impact of filter failure and repair rate on screening system availability

Table 4.17 Availability matrix for vibrating screen subsystem of screening system

Φ_{16}	Ψ_{16}					Constant Values
	0.007	0.008	0.009	0.010	0.011	
0.1	0.8838	0.8757	0.8677	0.8599	0.8522	
0.15	0.9139	0.9081	0.9025	0.8969	0.8913	Ψ_{15}=0.003, Φ_{15}=0.35
0.2	0.9297	0.9252	0.9209	0.9165	0.9122	Ψ_{17}=0.006, Φ_{17}=0.55
0.25	0.9394	0.9358	0.9323	0.9287	0.9252	Ψ_{18}=0.004, Φ_{18}=0.7
0.3	0.9461	0.9430	0.9400	0.9370	0.9340	

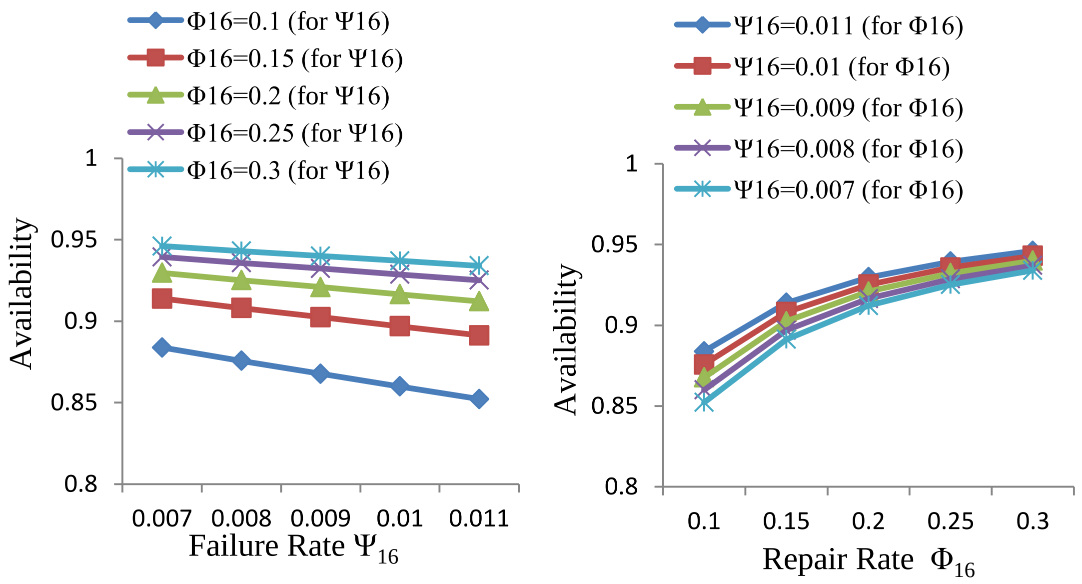


Figure 4.16(a) (b) Impact of vibrating screen failure and repair rate on screening system availability

Table 4.18 Availability matrix for cleaner subsystem of screening system

Φ_{17}	Ψ_{17}					Constant Values
	0.004	0.005	0.006	0.007	0.008	
0.45	0.95351	0.95347	0.95342	0.95336	0.95330	
0.5	0.95352	0.95349	0.95345	0.95341	0.95335	Ψ_{15}=0.003, Φ_{15}=0.35
0.55	0.95353	0.95351	0.95347	0.95343	0.95339	Ψ_{16}=0.008, Φ_{16}=0.2
0.6	0.95354	0.95352	0.95349	0.95346	0.95342	Ψ_{18}=0.004, Φ_{18}=0.7
0.65	0.95355	0.95353	0.95350	0.95348	0.95344	

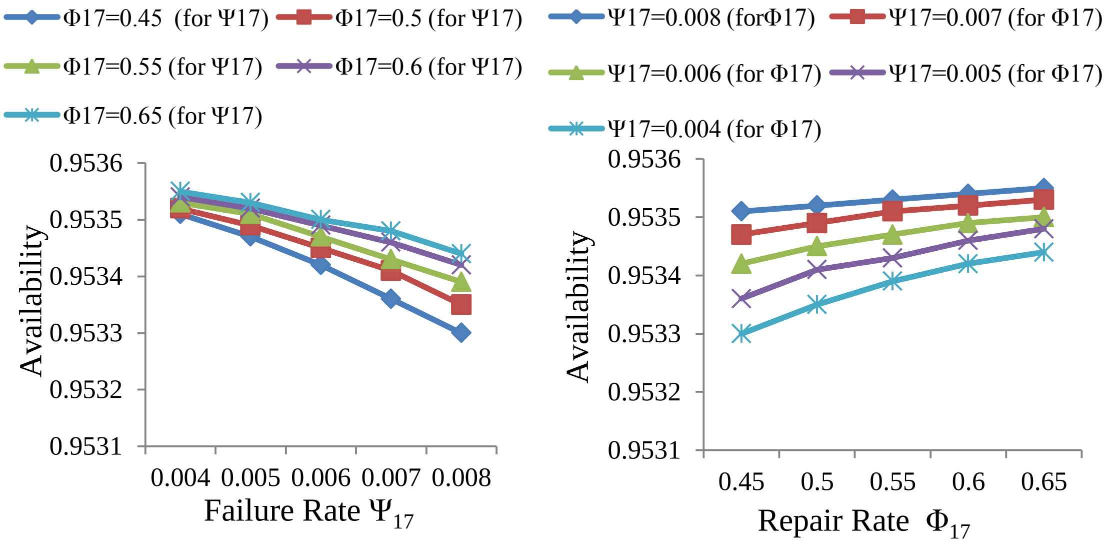


Figure 4.17(a) (b) Impact of cleaner failure and repair rate on screening system availability

Table 4.18 and Figure 4.17 demonstrate the impact of cleaner repair and failure rates on screening system availability. As cleaner repair rates (Φ_{17}) rises from 0.45 to 0.65, the long run availability of the framework only improves by 0.004%.In the same way as the cleaner failure rate (Ψ_{17}) rises from 0.004 to 0.008, the framework long run availability reduces by 0.022%.

Table 4.19 and Figure 4.18 demonstrate the impact of pump repair and failure rates on screening system availability. As pump repair rates (Φ_{18}) rises from 0.6 to 0.8, the long run availability of the framework only improves by 0.0001%.In the same way as the pump failure rate (Ψ_{18}) rises from 0.002 to 0.006, the framework long run availability reduces by 0.025%.

Table 4.19 Availability matrix for pump subsystem of screening system

Φ_{18}	Ψ_{18}					Constant Values
	0.002	0.003	0.004	0.005	0.006	
0.6	0.953542	0.953528	0.953513	0.953498	0.953484	
0.65	0.953544	0.953531	0.953518	0.953504	0.953491	Ψ_{15}=0.003,Φ_{15}=0.35
0.7	0.953546	0.953534	0.953521	0.953509	0.953497	Ψ_{16}=0.008, Φ_{16}=0.2
0.75	0.953548	0.953536	0.953525	0.953513	0.953502	Ψ_{17}=0.006,Φ_{17}=0.55
0.8	0.953550	0.953539	0.953528	0.953517	0.953506	

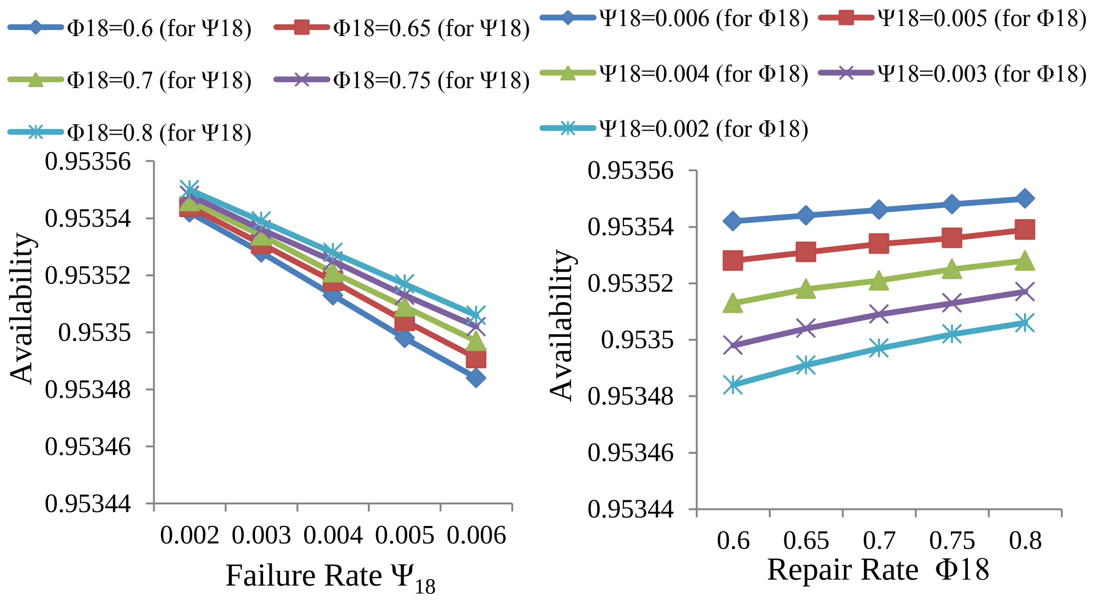


Figure 4.18(a) (b) Impact of pump failure and repair rate on screening system availability

4.2.5 Performance Analysis of the Paper Making system:

Table 4.20 and Figure 4.19 demonstrate the impact of wire mat repair and failure rates on paper making system availability. As wire mat repair rates (Φ_{19}) rises from 0.07 to 0.1, the long run availability of the framework only improves by 0.97%.In the same way as the wire mat failure rate (Ψ_{19}) rises from 0.0026 to 0.0038, the framework long run availability reduces by 1.47%.

Table 4.20 Availability matrix for wire mat subsystem of paper making system

Φ_{19}	Ψ_{19}					Φ_1
	0.0026	0.0029	0.0032	0.0035	0.0038	
0.07	0.8747	0.8715	0.9682	0.865	0.8618	Ψ_{20}=0.0045,Φ_{20}=0.18
0.0775	0.8775	0.8745	0.8716	0.8686	0.8657	Ψ_{21}=0.0011,Φ_{21}=0.55
0.085	0.8798	0.8771	0.8744	0.8717	0.869	Ψ_{22}=0.0011,Φ_{22}=0.25
0.925	0.8817	0.8792	0.8767	0.8742	0.8717	Ψ_{23}=0.0055,Φ_{23}=0.20
0.1	0.8833	0.881	0.8787	0.8764	0.8741	Ψ_{24}=0.0045,Φ_{24}=0.18
						Ψ_{25}=0.0040,Φ_{25}=0.32

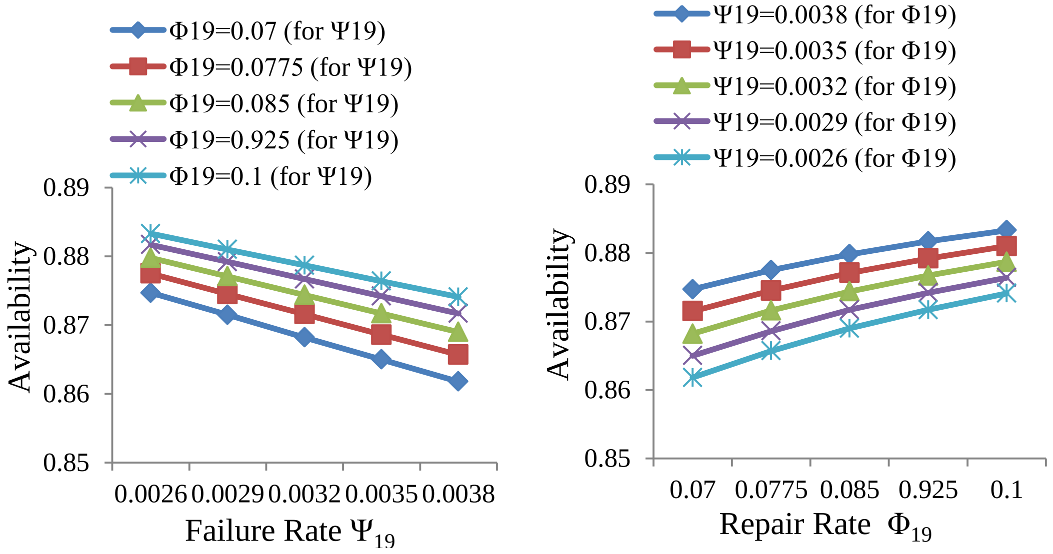


Figure 4.19(a) (b) Impact of wire mat failure and repair rate on paper production system availability

Table 4.21 and Figure 4.20 demonstrate the impact of roller repair and failure rates on screening system availability. As roller repair rates (Φ_{20}) rises from 0.14 to 0.22, the long run availability of the framework only improves by 0.81%.In the same way as the roller failure rate (Ψ_{20}) rises from 0.0036 to 0.0054, the framework long run availability reduces by 0.025%.

Table 4.21 Availability matrix for roller subsystem of paper production system

Φ_{20}	Ψ_{20}					Constant Values
	0.0036	0.0041	0.0045	0.0050	0.0054	
0.14	0.8738	0.8711	0.8689	0.8662	0.8641	Ψ_{19}=0.0032,Φ_{19}=0.085
0.16	0.8763	0.8739	0.872	0.8696	0.8677	Ψ_{21}=0.0011, Φ_{21}=0.55
0.18	0.8782	0.8761	0.8744	0.8722	0.8705	Ψ_{22}=0.0011, Φ_{22}=0.25
0.20	0.8797	0.8778	0.8763	0.8744	0.8728	Ψ_{23}=0.0055, Φ_{23}=0.20
0.22	0.881	0.8792	0.8778	0.8761	0.8747	Ψ_{24}=0.0045, Φ_{24}=0.18
						Ψ_{25}=0.0040, Φ_{25}=0.32

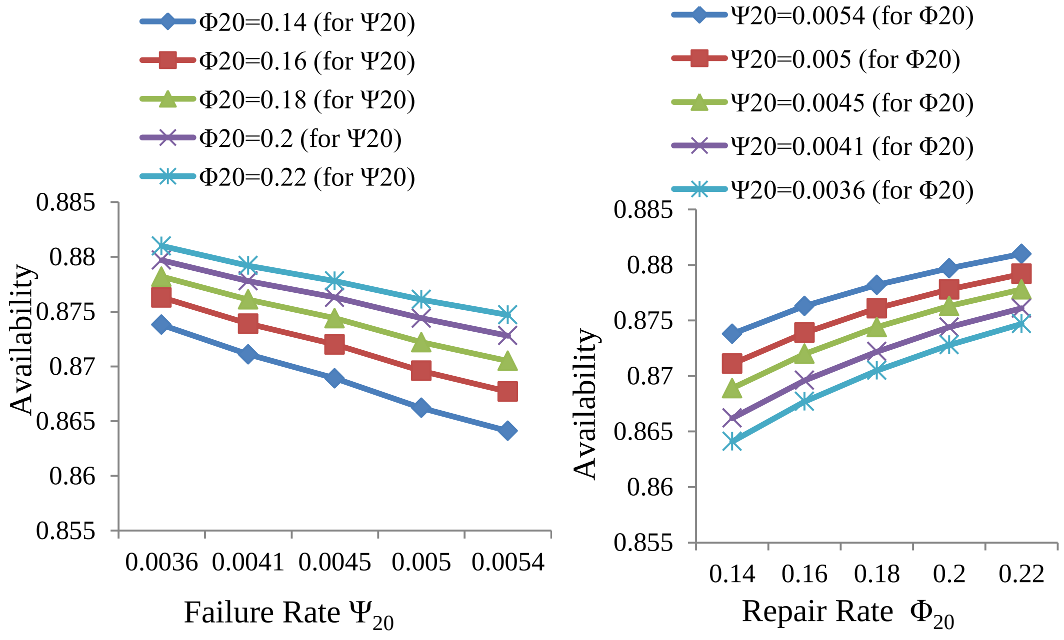


Figure 4.20(a) (b) Impact of roller failure and repair rate on paper production system availability.

Table 4.22 and Figure 4.21 demonstrate the impact of suction pump repair and failure rates on paper production system availability. As suction pump repair rates (Φ_{21}) rises from 0.35 to 0.55, the long run availability of the framework improves negligibly. In the same way as the suction pump failure rate (Ψ_{21}) rises from 0.0009 to 0.0013, the framework long run availability reduces negligibly.

Table 4.22 Availability matrix for suction pump subsystem of paper production system

Φ_{21}	Ψ_{21}					Constant Values
	0.0009	0.0010	0.0011	0.0012	0.0013	
0.35	0.874350981	0.874350971	0.874350971	0.874350964	0.874350955	Ψ_{19}=0.0032,Φ_{19}=0.085
0.40	0.874350986	0.874350982	0.874350978	0.874350974	0.874350968	Ψ_{20}=0.0045, Φ_{20}=0.18
0.45	0.874350988	0.874350986	0.874350983	0.874350980	0.874350976	Ψ_{22}=0.0011, Φ_{22}=0.25
0.50	0.874350990	0.874350988	0.874350986	0.874350984	0.874350981	Ψ_{23}=0.0055, Φ_{23}=0.20
0.55	0.874350991	0.874350990	0.874350988	0.874350986	0.874350984	Ψ_{24}=0.0045, Φ_{24}=0.18
						Ψ_{25}=0.0040, Φ_{25}=0.32

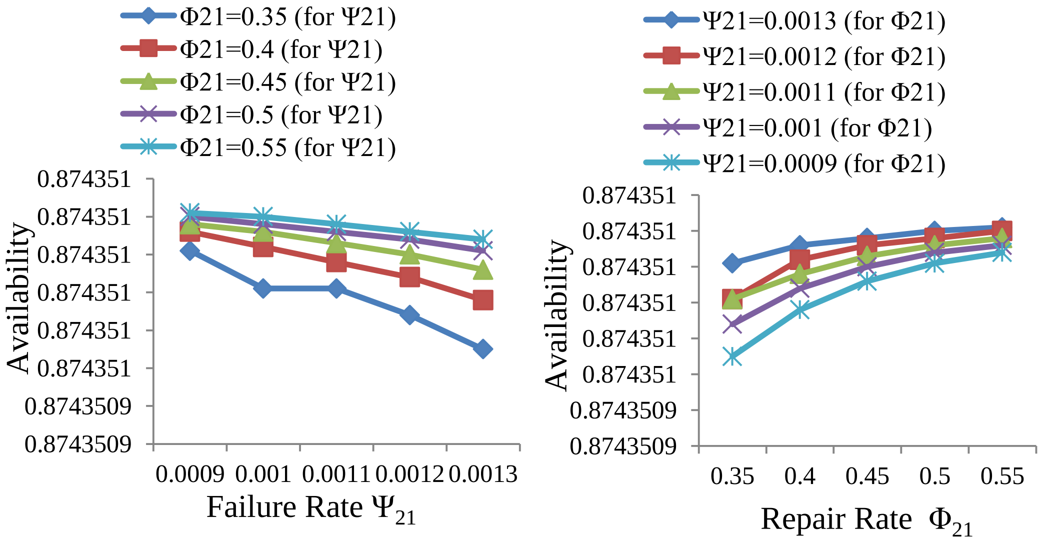


Figure 4.21(a) (b) Impact of suction pumps failure and repair rate on paper production system availability.

Table 4.23 and Figure 4.22 demonstrate the impact of synthetic belt repair and failure rates on screening system availability. As synthetic belt repair rates (Φ_{22}) rises from 0.054 to 0.083, the long run availability of the framework only improves by 0.51%.In the same way as the pump failure rate (Ψ_{22}) rises from 0.0009 to 0.0013, the framework long run availability reduces by 0.64%.

Table 4.24 and Figure 4.23 demonstrate the impact of press roll repair and failure rates on paper production system availability. As press roll repair rates (Φ_{23}) rises from 0.16 to 0.24, the long run availability of the framework only improves by 0.817%.In the same way as the press roll failure rate (Ψ_{23}) rises from 0.0045 to 0.0065, the framework long run availability reduces by 1.087 %.

Table 4.23 Availability matrix for synthetic belt subsystem of paper production system

Φ_{22}	Ψ_{22}					Constant Values
	0.0009	0.0010	0.0011	0.0012	0.0013	
0.054	0.8739	0.8725	0.8711	0.8697	0.8683	Ψ_{19}=0.0032,Φ_{19}=0.085
0.0613	0.8754	0.8742	0.8729	0.8717	0.8704	Ψ_{20}=0.0045, Φ_{20}=0.18
0.0685	0.8760	0.8755	0.8744	0.8732	0.8721	Ψ_{21}=0.0011, Φ_{21}=0.55
0.0758	0.8776	0.8765	0.8755	0.8745	0.8735	Ψ_{23}=0.0055, Φ_{23}=0.20
0.083	0.8784	0.8774	0.8765	0.8756	0.8747	Ψ_{24}=0.0045, Φ_{24}=0.18
						Ψ_{25}=0.0040, Φ_{25}=0.32

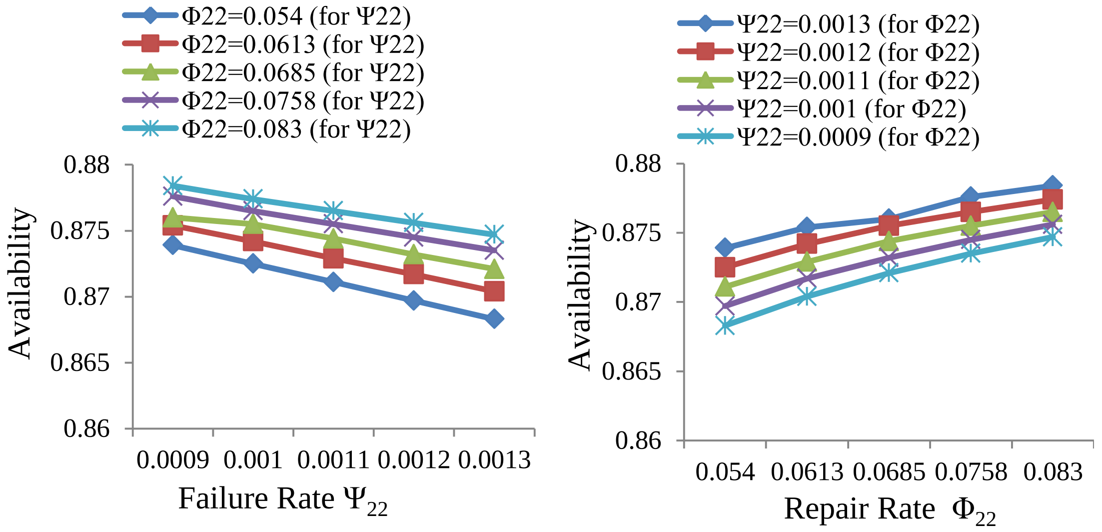


Figure 4.22(a) (b) Impact of synthetic belt repair and failure rates on paper production system availability.

Table 4.24 Availability matrix for press roll subsystem of paper production system

Φ_{23}	Ψ_{23}					Constant Values
	0.0045	0.0050	0.0055	0.0060	0.0065	
0.16	0.8739	0.8715	0.8691	0.8668	0.8644	Ψ_{19}=0.0032,Φ_{19}=0.085
0.18	0.8763	0.8741	0.872	0.8699	0.8678	Ψ_{20}=0.0045, Φ_{20}=0.18
0.20	0.8782	0.8763	0.8744	0.8724	0.8705	Ψ_{21}=0.0011, Φ_{21}=0.55
0.22	0.8798	0.878	0.8763	0.8745	0.8728	Ψ_{22}=0.0011, Φ_{22}=0.25
0.24	0.8811	0.8795	0.8779	0.8763	0.8747	Ψ_{24}=0.0045, Φ_{24}=0.18
						Ψ_{25}=0.0040, Φ_{25}=0.32

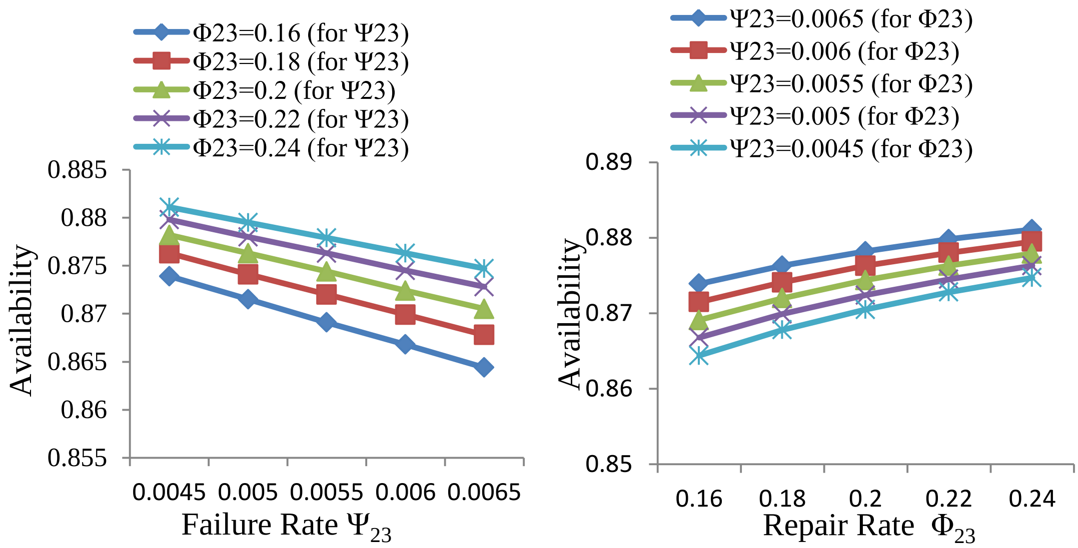


Figure 4.23(a) (b) Impact of press roll failure and repair rate on paper production system availability.

Table 4.25 and Figure 4.24 demonstrate the impact of drier roll repair and failure rates on paper production system availability. As drier roll repair rates (Φ_{24}) rises from 0.14 to 0.22, the long run availability of the framework only improves by 0.81%.In the same way as the drier roll failure rate (Ψ_{24}) rises from 0.0036 to 0.0054, the framework long run availability reduces by 1.11%.

Table 4.26 and Figure 4.25 demonstrate the impact of steam handling unit repair and failure rates on paper production system availability. As steam handling unit repair rates (Φ_{25}) rises from 0.24 to 0.4, the long run availability of the framework only improves by 0.432%.In the same way as the steam handling unit failure rate (Ψ_{25}) rises from 0.003 to 0.005, the framework long run availability reduces by 0.73%.

Table 4.25 Availability matrix for drier roll subsystem of paper production system

Φ_{24}	Ψ_{24}					Constant Values
	0.0036	0.0041	0.0045	0.0050	0.0054	
0.14	0.8738	0.8711	0.8689	0.8662	0.8641	Ψ_{19}=0.0032,Φ_{19}=0.085
0.16	0.8763	0.8739	0.872	0.8696	0.8677	Ψ_{20}=0.0045, Φ_{20}=0.18
0.18	0.8782	0.8761	0.8744	0.8722	0.8705	Ψ_{21}=0.0011, Φ_{21}=0.55
0.20	0.8797	0.8778	0.8763	0.8744	0.8728	Ψ_{22}=0.0011, Φ_{22}=0.25
0.22	0.881	0.8792	0.8778	0.8761	0.8747	Ψ_{23}=0.0055, Φ_{23}=0.20
						Ψ_{25}=0.0040, Φ_{25}=0.32

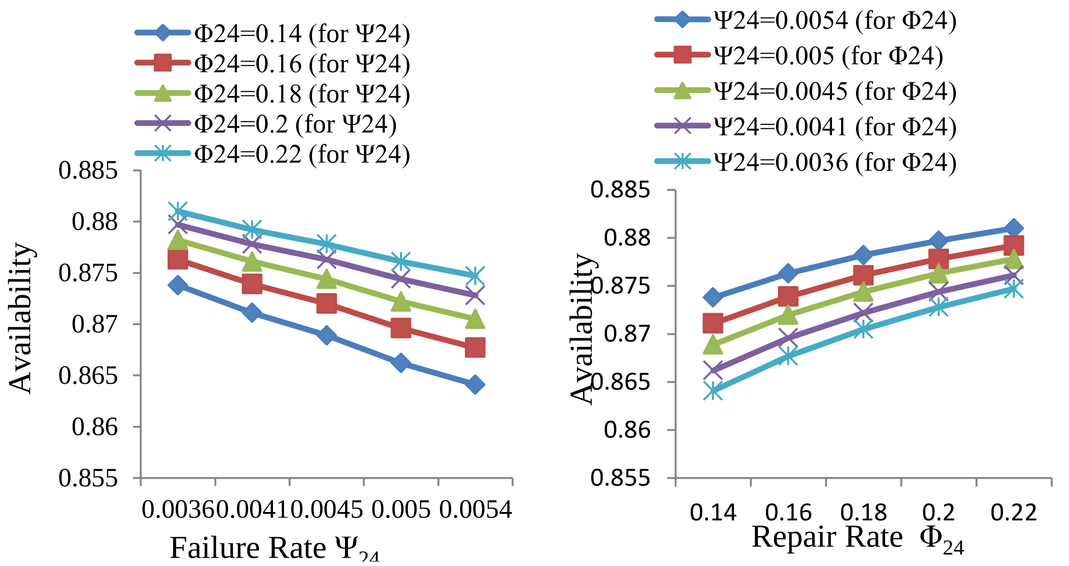


Figure 4.24(a) (b) Impact of drier roll failure and repair rate on paper production system availability.

Table 4.26 Availability matrix for steam handling subsystem of paper production system

Φ_{25}	Ψ_{25}					Constant Values
	0.003	0.0035	0.004	0.0045	0.005	
0.24	0.8744	0.8728	0.8712	0.8696	0.868	Ψ_{19}=0.0032, Φ_{19}=0.085
0.28	0.8757	0.8744	0.873	0.8716	0.8703	Ψ_{20}=0.0045, Φ_{20}=0.18
0.32	0.8767	0.8755	0.8744	0.8732	0.872	Ψ_{21}=0.0011, Φ_{21}=0.55
0.36	0.8775	0.8765	0.8754	0.8744	0.8733	Ψ_{22}=0.0011, Φ_{22}=0.25
0.4	0.8782	0.8772	0.8763	0.8753	0.8744	Ψ_{23}=0.0055, Φ_{23}=0.20
						Ψ_{24}=0.0045, Φ_{24}=0.18

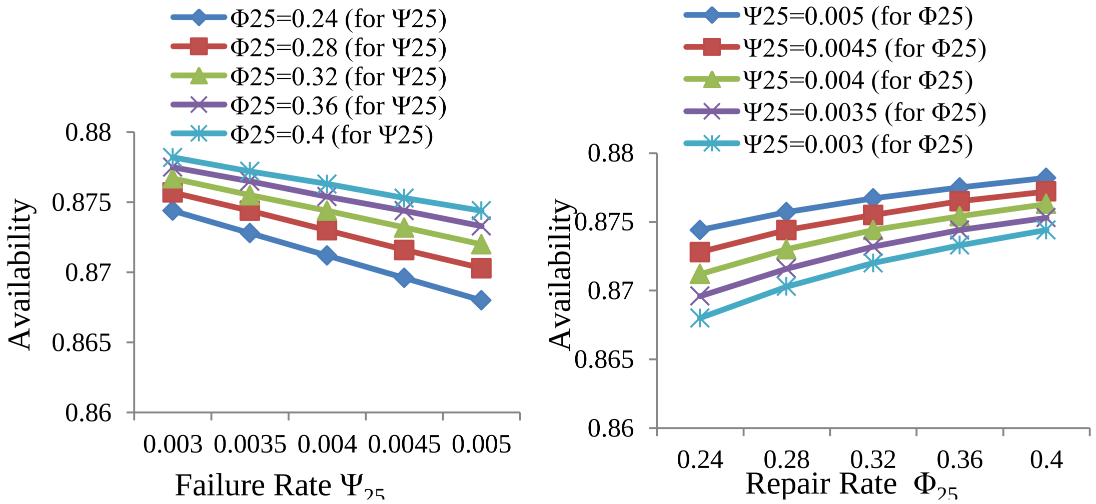


Figure 4.25(a) (b) Impact of steam handling failure and repair rate on paper production system availability.

4.3 FEASIBLE COMBINATIONS OF FAILURE AND REPAIR RATES

With the help of availability matrices (Table 4.2 to Table 4.26) the feasible values of failure rates and repair rates are found for the desired availability level of each system of paper plant. These values are illustrated in Table 4.27.

Table 4.27 Feasible values of failure rates and repair rates

System with desired availability level	**Table No.**	**Variable values of failure rates and repair rates**	**Constant values of failure rates and repair rates**
Feeding System (Desired Availability level 93%)	4.2	Ψ_1=0.009 Φ_1=0.12	Ψ_2=0.040, Φ_2=0.45 Ψ_3=0.013, Φ_3=0.187
	4.3	Ψ_2=0.05 Φ_2=0.3	Ψ_1=0.007, Φ_1=0.1 Ψ_3=0.013, Φ_3=0.187
	4.4	Ψ_3=0.015 Φ_3=0.125	Ψ_1=0.007, Φ_1=0.1 Ψ_2=0.040, Φ_2=0.45
Pulping System (Desired Availability level 94%)	4.5	Ψ_4=0.003 Φ_4=0.07	Ψ_5=0.003,Φ_5=0.4;Ψ_6=0.009,Φ_6=0.17 Ψ_7=0.004,Φ_7=0.3; Ψ_8=0.125, Φ_8=0.2
	4.6	Ψ_5=0.006 Φ_5=0.3	Ψ_4=0.002,Φ_4=0.05;Ψ_6=0.009,Φ_6=0.17 Ψ_7=0.004, Φ_7=0.3; Ψ_8=0.125, Φ_8=0.2
	4.7	Ψ_6=0.01 Φ_6=0.12	Ψ_4=0.002,Φ_4=0.05; Ψ_5=0.003, Φ_5=0.4 Ψ_7=0.004, Φ_7=0.3; Ψ_8=0.125, Φ_8=0.2
	4.8	Ψ_7=0.004,0.006 Φ_7=0.2, 0.3	Ψ_4=0.002,Φ_4=0.05; Ψ_5=0.003, Φ_5=0.4 Ψ_6=0.009,Φ_6=0.17; Ψ_8=0.125, Φ_8=0.2
	4.9	Ψ_8=0.0175 Φ_8=0.1	Ψ_4=0.002,Φ_4=0.05; Ψ_5=0.003, Φ_5=0.4 Ψ_6=0.009,Φ_6=0.17; Ψ_7=0.004, Φ_7=0.3
Bleaching and washing System	4.10	Ψ_9=0.004 Φ_9=0.2	Ψ_{10}=0.0032,Φ_{10}=0.32;Ψ_{11}=0.0065, Φ_{11}=0.55 Ψ_{12}=0.0025, Φ_{12}=0.25; Ψ_{13}=0.0035, Φ_{13}=0.75 Ψ_{14}=0.0046, Φ_{14}=0.4

(Desired Availability level 95%)	4.11	$\Psi_{10}=0.0039$ $\Phi_{10}=0.25$	$\Psi_{9}=0.0034$, $\Phi_{9}=0.25$; $\Psi_{11}=0.0065$, $\Phi_{11}=0.55$ $\Psi_{12}=0.0025$, $\Phi_{12}=0.25$; $\Psi_{13}=0.0035$, $\Phi_{13}=0.75$ $\Psi_{14}=0.0046$, $\Phi_{14}=0.4$
	4.12	$\Psi_{11}=0.00725$ $\Phi_{11}=0.4$	$\Psi_{9}=0.0034$, $\Phi_{9}=0.25$; $\Psi_{10}=0.0032$, $\Phi_{10}=0.32$ $\Psi_{12}=0.0025$, $\Phi_{12}=0.25$; $\Psi_{13}=0.0035$, $\Phi_{13}=0.75$ $\Psi_{14}=0.0046$, $\Phi_{14}=0.4$
	4.13	$\Psi_{12}=0.003$ $\Phi_{12}=0.2$	$\Psi_{9}=0.0034$, $\Phi_{9}=0.25$; $\Psi_{10}=0.0032$, $\Phi_{10}=0.32$ $\Psi_{11}=0.0065$, $\Phi_{11}=0.55$; $\Psi_{13}=0.0035$, $\Phi_{13}=0.75$ $\Psi_{14}=0.0046$, $\Phi_{14}=0.4$
	4.14	$\Psi_{13}=0.0055$ $\Phi_{13}=0.6$	$\Psi_{9}=0.0034$, $\Phi_{9}=0.25$; $\Psi_{10}=0.0032$, $\Phi_{10}=0.32$ $\Psi_{11}=0.0065$, $\Phi_{11}=0.55$; $\Psi_{12}=0.0025$, $\Phi_{12}=0.25$ $\Psi_{14}=0.0046$, $\Phi_{14}=0.4$
	4.15	$\Psi_{14}=0.0055$ $\Phi_{14}=0.3$	$\Psi_{9}=0.0034$, $\Phi_{9}=0.25$; $\Psi_{10}=0.0032$, $\Phi_{10}=0.32$ $\Psi_{11}=0.0065$, $\Phi_{11}=0.55$; $\Psi_{12}=0.0025$, $\Phi_{12}=0.25$ $\Psi_{13}=0.0035$, $\Phi_{13}=0.75$
Screening System (Desired Availability level 92%)	4.16	$\Psi_{15}=0.004$ $\Phi_{15}=0.25$	$\Psi_{16}=0.008$, $\Phi_{16}=0.2$; $\Psi_{17}=0.006$, $\Phi_{17}=0.55$ $\Psi_{18}=0.004$, $\Phi_{18}=0.7$
	4.17	$\Psi_{16}=0.009$ $\Phi_{16}=0.2$	$\Psi_{15}=0.003$, $\Phi_{15}=0.35$; $\Psi_{17}=0.006$, $\Phi_{17}=0.55$ $\Psi_{18}=0.004$, $\Phi_{18}=0.7$
	4.18	$\Psi_{17}=0.008$ $\Phi_{17}= 0.45$	$\Psi_{15}=0.003$, $\Phi_{15}=0.35$; $\Psi_{16}=0.008$, $\Phi_{16}=0.2$ $\Psi_{18}=0.004$, $\Phi_{18}=0.7$
	4.19	$\Psi_{18}=0.006$ $\Phi_{18}=0.6$	$\Psi_{15}=0.003$, $\Phi_{15}=0.35$; $\Psi_{16}=0.008$, $\Phi_{16}=0.2$ $\Psi_{17}=0.006$, $\Phi_{17}=0.55$
Paper Production	4.20	$\Psi_{19}=0.0038$ $\Phi_{19}=0.085$	$\Psi_{20}=0.0045$, $\Phi_{20}=0.18$; $\Psi_{21}=0.0011$, $\Phi_{21}=0.55$ $\Psi_{22}=0.0011$, $\Phi_{22}=0.25$; $\Psi_{23}=0.0055$, $\Phi_{23}=0.20$

System (Desired Availability level 87 %)			Ψ_{24}=0.0045, Φ_{24}=0.18; Ψ_{25}=0.0040, Φ_{25}=0.32
	4.21	Ψ_{20}=0.0050 Φ_{20}=0.16	Ψ_{19}=0.0032,Φ_{19}=0.085;Ψ_{21}=0.0011, Φ_{21}=0.55 Ψ_{22}=0.0011, Φ_{22}=0.25; Ψ_{23}=0.0055, Φ_{23}=0.20 Ψ_{24}=0.0045, Φ_{24}=0.18; Ψ_{25}=0.0040, Φ_{25}=0.32
	4.22	Ψ_{21}=0.0013 Φ_{21}=0.35	Ψ_{19}=0.0032,Φ_{19}=0.085;Ψ_{20}=0.0045, Φ_{20}=0.18 Ψ_{22}=0.0011, Φ_{22}=0.25; Ψ_{23}=0.0055, Φ_{23}=0.20 Ψ_{24}=0.0045, Φ_{24}=0.18; Ψ_{25}=0.0040, Φ_{25}=0.32
	4.23	Ψ_{22}=0.0012 Φ_{22}=0.054	Ψ_{19}=0.0032,Φ_{19}=0.085;Ψ_{20}=0.0045, Φ_{20}=0.18 Ψ_{21}=0.0011, Φ_{21}=0.55; Ψ_{23}=0.0055, Φ_{23}=0.20 Ψ_{24}=0.0045, Φ_{24}=0.18; Ψ_{25}=0.0040, Φ_{25}=0.32
	4.24	Ψ_{23}=0.006 Φ_{23}=0.18	Ψ_{19}=0.0032,Φ_{19}=0.085;Ψ_{20}=0.0045, Φ_{20}=0.18 Ψ_{21}=0.0011, Φ_{21}=0.55; Ψ_{22}=0.0011, Φ_{22}=0.25 Ψ_{24}=0.0045, Φ_{24}=0.18; Ψ_{25}=0.0040, Φ_{25}=0.32
	4.25	Ψ_{24}=0.005 Φ_{24}=0.16	Ψ_{19}=0.0032,Φ_{19}=0.085;Ψ_{20}=0.0045, Φ_{20}=0.18 Ψ_{21}=0.0011, Φ_{21}=0.55; Ψ_{22}=0.0011, Φ_{22}=0.25 Ψ_{23}=0.0055, Φ_{23}=0.20; Ψ_{25}=0.0040, Φ_{25}=0.32
	4.26	Ψ_{25}=0.0045 Φ_{25}=0.24	Ψ_{19}=0.0032,Φ_{19}=0.085;Ψ_{20}=0.0045, Φ_{20}=0.18 Ψ_{21}=0.0011, Φ_{21}=0.55; Ψ_{22}=0.0011, Φ_{22}=0.25 Ψ_{23}=0.0055, Φ_{23}=0.20; Ψ_{24}=0.0045, Φ_{24}=0.18

4.4 PERFORMANCE ANALYSIS OF SYSTEMS

The availability values indicated in the availability matrices (Table 4.2 to 4.26) are further analysed for selection of maintenance strategy/decisions. The analysis made helps in following: for making various alternative maintenance decisions, for finding the most critical subsystem of concerned system for maintenance point of view, for finding the system which is having maximum or minimum availability and for making useful decisions that how availability can be increased. The Table 4.28 to 4.32

illustrates the analysis of the availability values shown in availability matrices (Tables 4.2 to 4.26).

Table 4.28 Decision Criteria for the Repair Priority of the Feeding System

Subsystem	Increase in failure rate	Decrease in Availability	Increase in repair rate	Increase in Availability	Repair Priority
Blower	0.005-0.009	4.55%	0.08-0.12	1.98%	I
Conveyor	0.03-0.05	0.052%	0.3-0.6	0.217%	III
Feeder	0.011-0.015	0.087%	0.125-0.25	0.023%	II

Table 4.29 Decision Criteria for the Repair Priority of the Pulping System

Subsystem	Increase in failure rate	Decrease in Availability	Increase in repair rate	Increase in Availability	Repair Priority
Digester	0.001-0.004	6.7%	0.04-0.07	1%	I
Pump	0.002-0.005	0.02%	0.3-0.6	0.03%	V
Knotter	0.008-0.011	0.4%	0.12-0.27%	0.3%	IV
Decker	0.003-0.006	1.4%	0.2-0.5%	0.8%	II
Opener	0.01-0.0175	0.5%	0.1-0.4	0.2%	III

Table 4.30 Decision Criteria for the Repair Priority of the Bleaching and Washing System

Subsystem	**Increase in failure rate**	**Decrease in Availability**	**Increase in repair rate**	**Increase in Availability**	**Repair Priority**
Agitator	0.0028-0.004	0.575%	0.2-0.3	0.447%	II
Filter	0.0025-0.0039	0.533%	0.25-0.39	0.333%	III
Cleaner	0.005-0.008	0.71%	0.4-0.7	0.52%	I

Washer	0.002-0.003	0.48%	0.2-0.3	0.31%	IV
Vacuum pump	0.003-0.004	Negligible	0.6-0.9	Negligible	V
Centrifugal pump	0.0037-0.0055	Negligible	0.3-0.5	Negligible	V

Table 4.31 Decision Criteria for the Repair Priority of the Screening System

Subsystem	**Increase in failure rate**	**Decrease in Availability**	**Increase in repair rate**	**Increase in Availability**	**Repair Priority**
Filter	0.002-0.004	0.75%	0.25-0.45	0.33%	II
Vibrating Screen	0.007-0.011	3.56%	0.1-0.3	6.59%	I
Cleaner	0.004-0.008	0.022%	0.45-0.65	0.004%	IV
Pump	0.002-0.006	0.025%	0.6-0.08	0.0001%	III

Table 4.32 Decision Criteria for the Repair Priority of the Paper making System

Subsystem	Increase in failure rate	Decrease in Availability	Increase in repair rate	Increase in Availability	Repair Priority
Wire mat	0.0026-0.0038	1.47	0.07-0.1	0.97%	II
Roller	0.0036-0.0054	1.11%	0.14-0.22	0.81%	III
Suction Pump	0.0009-0.0013	Negligible	0.35-0.55	Negligible	VII
Synthetic belt	0.0009-0.0013	0.64%	0.054-0.083	0.51%	VI
Press Roll	0.0045-0.0065	1.087%	0.16-0.24	0.817%	V
Drier roll	0.0036-0.0054	1.11%	0.14-0.22	0.81%	III
Steam Handling Unit	0.003-0.005	1.73%	0.24-0.4	1.132%	I

CHAPTER V

MAINTENANCE PLANNING

5.1 INTRODUCTION

One of the major tasks in implementing RCM program in any organization is to categorize the equipments or the parts depending upon their respective criticality, in order to identify appropriate maintenance policy such as preventive maintenance, repair, condition monitoring and replacement. The decision for the best maintenance policy is not an easy task for maintenance managers. A good maintenance program must define maintenance strategies for different facilities, i.e., it must combine technical requirements with the management strategy. The failure mode of every component must be studied in order to assess the best maintenance solution, in accordance with its failure pattern, impact and cost on the whole system. This information helps the maintenance personnel to decide the best maintenance action and to assign the different priorities to various components and machines in a plant. The management of large number of tangible and intangible attributes that must be taken into account represents the complexity of the problem.

In the literature, the most commonly used technique to evaluate the maintenance significance of the items/failure causes and categorize these in several groups of risk, is based on using failure mode effect and criticality analysis (FMECA). This methodology has been proposed in different possible variants, in terms of relevant criteria considered and/or risk priority number formulation. Using this approach, the suitable maintenance policy is selected through the analysis of obtained risk priority number (RPN). RPN evaluation with FMEA is observed as the most popular reliability and failure analysis technique for products and processes. One of the major reasons for its wide acceptability may be attributed to its visibility and easiness. However, at the same time several problems associated with its practical implementation in real industrial situations are also discussed in the literature. Some of the major problems to mention are: it does not consider the interdependence among the various failure modes and effects; it considers only three kinds of attributes: chance of failure, chance of non-detection and severity (mainly in terms of safety). Whereas other important aspects like spare parts, maintenance criticality and economic aspects are neglected. Also it is assumed that the three indices are equally important. As the direct scores are assigned for the three attributes, but in real practical situations it is very difficult even for the most expert maintenance staff to give a direct and exact evaluations of the three intangible quantities.

Taking note of limitations of traditional FMECA approach a new methodology based on integrated cloud model and PROMETHEE II is proposed in this chapter for evaluating the maintenance criticality of failure causes. Additional number of criteria viz. chance of failure, chance of non-detection, downtime length, spare parts criticality and safety factor are considered to make the index more consistent and realistic.

5.2 AHP METHODOLOGY

The AHP (Saaty, 1980) is considered as one of the most popular tool for complex multicriteria decision making problem by reducing complex decisions to a progression of basic comparisons and rankings, then blending the results to assist the decision maker to arrive at the best decision. AHP has been widely used in process industries (Sachdeva et al., 2008), strategic planning (Chen and Wang, 2010), supplier selection (Labib, 2011), performance evaluation (Wu et al., 2012) and undergraduate program selection (Dominguez-Paz , 2018); modular product selection (Mittal et al., 2018), portfolio selection (Roodposhti et al., 2018) and many other applications.

To find the criteria weights w_j of relative importance of considered criteria first of all pair wise comparison matrix need to be constructed using a scale of relative importance and after that consistency indexes (CI) is calculated using equation (5.2.1). The criteria weights derived above are considered acceptable if consistency ratio (CR) is less than 0.1 and if the ratio is 0.1 or more the assessment process is repeated again.

$$CI = \frac{\psi_{\max} - n}{n-1} \qquad (5.2.1)$$

$$CR = \frac{CI}{RCI} \qquad (5.2.2)$$

Where RCI is the random consistency index for n x n matrix whose values are shown (Saaty, 1980) in Table 1, $\psi_{\max}$ is the maximum eigen value of the matrix.

Table 5.1 RCI values for different orders

n	1	2	3	4	5	6	7
RCI	0	0	0.52	0.89	1.11	1.25	1.35

To find the priority weightage, a pairwise comparison is made among the evaluation criteria through the brainstorming sessions and efforts were made to consider the idea of each people which are directly or indirectly concerned with the maintenance problem. Priority weightage computed for each evaluation criteria is shown in Table 5.2.

Table 5.2 Criteria for priorities evaluation

	F_o	N_d	D_l	S_{pc}	S_r	**Priority**
F_o	1	3	3	4	4	0.427
N_d	1/3	1	2	2	3	0.208
D_l	1/3	1/2	1	3	4	0.191
S_{pc}	1/4	1/2	1/3	1	3	0.111
S_r	1/4	1/3	1/4	1/3	1	0.063
	2.16	5.33	6.58	10.33	15	
CR=0.07204						

5.3 CLOUD MODEL METHODOLOGY

According to Li et al. (2009) cloud model is a modern cognition demonstrates of vulnerability proposed based on likelihood hypothesis and fuzzy set hypothesis, which permits a stochastic unsettling influence of the membership degree encompassing a decided central esteem.

Definition 1: Li et al. (2009) and Wang et al. (2015). Given a subjective concept N characterized on a universe of talk$V, P \subseteq V$, let $p\left(p \in P\right)$ be an arbitrary instantiation of the concept N and $F_N\left(P\right) \in \left[0,1\right]$ be the membership degree of p belonging to F, which corresponds to an arbitrary number with steady inclination. Then the dispersion of the membership over the space is called a membership cloud, or basically, a cloud.

Definition 2: Li et al. (2009) and Wang et al. (2015). The characteristics of a cloud z are delineated by three numerical parameters, specially expectation E_p, entropy S_n and hyper entropy S_e. Here, E_p is the middle value of the subjective concept space, S_n measures the uncertainty of the subjective concept, and S_e reflects the scattering degree of a cloud's beads and the irregular changes of the membership. The cloud can be written as $\tilde{z} = \left(E_p, S_n, S_e\right)$.

Note that the cloud $\tilde{z} = \left(\left[\underline{Ep}, \overline{Ep}\right], Sn, Se\right)$ is called an interval integrated cloud when the anticipated value is an interval range $\left[\underline{E_p}, \overline{E_p}\right]$.

Definition 3: Consider any two interval integrated clouds $\tilde{z}_1 = \left(\left[\underline{Ep_1}, \overline{Ep_1}\right], Sn_1, Se_1\right)$ and $\tilde{z}_2 = \left(\left[\underline{Ep_2}, \overline{Ep_2}\right], Sn_2, Se_2\right)$, then

$$\tilde{z}_1 \times \tilde{z}_2 = \left(\left[\underline{Ep_1 Ep_2}, \overline{Ep_1 Ep_2}\right], \sqrt{\left(Sn_1 Ep_2\right)^2 + \left(Sn_2 Ep_1\right)^2}, \sqrt{\left(Se_1 Ep_2\right)^2 + \left(Se_2 Ep_1\right)^2}\right) \tag{5.3.1}$$

$$\lambda \tilde{z}_1 = \left(\left[\lambda \underline{Ep_1}, \lambda \overline{Ep_2}\right], \sqrt{\lambda} Sn_1, \sqrt{\lambda} Se_1\right), \lambda > 0 \tag{5.3.2}$$

$$\tilde{z}_1^{\lambda} = \left(\left[\underline{Ep_1^{\lambda}}, \overline{Ep_1^{\lambda}}\right], \sqrt{\lambda}\left(Ep_1\right)^{\lambda-1} Sn_{1,} \sqrt{\lambda}\left(Ep_1\right)^{\lambda-1} Se_1\right), \lambda > 0 \tag{5.3.3}$$

Where $Ep_1 = \dfrac{\underline{Ep_1} + \overline{Ep_1}}{2}$ and $Ep_2 = \dfrac{\underline{Ep_2} + \overline{Ep_2}}{2}$.

Using equation (5.3.1) we can find multiplication of two interval clouds and with equation (5.3.2) we can find out weighted interval cloud.

Definition 4: Let $\tilde{z}_i = \left(\left[\underline{Ep_i}, \overline{Ep_i}\right], Sn_i, Se_i\right)$ $\left(i = 1, 2, ...n\right)$ be n interval integrated clouds in the space V, and $w = \left(w_1, w_2, ..., w_n\right)^N$ be their associated weights with $w_i \in \left[0,1\right]$ and $\sum_{i=1}^{n} w_i = 1$, then the floating interval cloud $\tilde{z} = \left(\left[\underline{Ep}, \overline{Ep}\right], Sn, Se\right)$ is generated as follows

$$\tilde{z} = \sum_{i=1}^{n} w_i \tilde{z}_i = \sum_{i=1}^{n} w_i \left(\left[\underline{Ep_i}, \overline{Ep_i}\right], Sn_i, Se_i\right) \tag{5.3.4}$$

$$\tilde{z} = \left(\sum_{i=1}^{n} w_i \left[\underline{Ep_i}, \overline{Ep_i}\right], \sqrt{\sum_{i=1}^{n} w_i Sn_i^2}, \sqrt{\sum_{i=1}^{n} w_i Se_i^2}\right..$$

Definition 5: According to Wang et al. (2015) Let $\tilde{z}_1 = \left(\left[\underline{Ep_1}, \overline{Ep_1}\right], Sn_1, Se_1\right)$ and $\tilde{z}_2 = \left(\left[\underline{Ep_2}, \overline{Ep_2}\right], Sn_2, Se_2\right)$ be two self-assertive interval integrated clouds, then the distance between the two is characterized as

$$d\left(\tilde{z}_1, \tilde{z}_2\right) = \frac{1}{2}\left(\left|\left(1 - \frac{Sn_1 + Se_1}{Sn_1}\right)\underline{Ep_1} - \left(1 - \frac{Sn_2 + Se_2}{Sn_2}\right)\underline{Ep_2}\right| + \left|\left(1 - \frac{Sn_1 + Se_1}{Sn_1}\right)\overline{Ep_1} - \left(1 - \frac{Sn_1 + Se_2}{Sn_2}\right)\overline{Ep_2}\right|\right). \tag{5.3.5}$$

If $Sn_1 = Se_1 = Sn_2 = Se_2 = 0,$ then the interval integrated clouds changes to interval numbers and $d(\tilde{z}_1, \tilde{z}_2) = \frac{1}{2}\left(\left|\underline{Ep_1} - \underline{Ep_2}\right| + \left|\overline{Ep_1} - \overline{Ep_2}\right|\right).$

Definition 6: $L = \{l_0, l_1 .... l_m\}$ be linguistic term set, then m +1 essential clouds corresponding to the expression of linguistic values can be produced and denoted as $z_0 = \left(Ep_0, Sn_0, Se_0\right),\ z_1 = \left(Ep_1, Sn_1, Se_1\right), ..., z_m = \left(Ep_g, Sn_g, Se_g\right)$

By golden section method Wang et al. (2015), Shi et al. (2017) based on a seven label linguistic term set.

$$L = \begin{Bmatrix} l_0 = verylow\left(V_L\right), l_1 = Low\left(L\right), l_2 = MediumLow\left(M_L\right), l_3 = Medium\left(M\right), l_4 = MediumHigh\left(M_H\right), \\ l_5 = High\left(H\right), l_6 = VeryHigh\left(V_H\right) \end{Bmatrix},$$

and the corresponding expressions are shown below:

$$\begin{aligned} & Ep_i = \frac{i}{m}, i = 0, 2, ..., g, \\ & Sn_2 = Sn_4 = 0.382(Y_{\max} - Y_{\min}) / 6, Sn_3 = 0.618 Sn_2, \\ & Sn_1 = Sn_5 = Sn_2 / 0.618, Sn_0 = Sn_6 = Sn_1 / 0.618, \\ & Se_2 = Se_4 = Se_3 / 0.618, Se_1 = Se_5 = Se_2 / 0.618, \\ & Se_0 = Se_6 = Se_1 / 0.618 \end{aligned}$$

The effective domain $V = \left[Y_{\min}, Y_{\max}\right] = \left[0,1\right]$ and Se_3 is defined in advance. In golden section method Sn and Se of the cloud would be smaller if it is closer to the centre of the valid universe, and S_n and S_e of the cloud would be larger if it is far from the centre of the valid universe. The larger one of the Sn and Se of the adjacent cloud is 1/0.618 times the smaller one.

Example 1: Assuming Se=0.1, Seven basic clouds can be generated as

z_0= (0, 0.167, 0.424), z_1= (0.167, 0.103, 0.267), z_2= (0.333, 0.064, 0.162), z_3= (0.5, 0.039, 0.1), z_4= (0.667, 0.064, 0.162), z_5= (0.833, 0.103, 0.262), z_6= (1, 0.167, 0.424)

Definition 7: Let $L=\{l_0, l_1 ......l_m\}$ be a linguistic term set and $\left[l_i, l_j\right]$ be an interval linguistic value, and then its equivalent interval cloud $\tilde{z}=\left(\left[\underline{Ep}, \overline{Ep}\right], Sn, Se\right)$ is acquired by

$$\begin{aligned} &\underline{Ep}=\min\left\{Ep_i, Ep_j\right\}, \overline{Ep}=\max\left\{Ep_i, Ep_j\right\} \\ &Sn=\sqrt{\frac{Sn_i^2+Sn_j^2}{2}}, Se=\sqrt{\frac{Se_i^2+Se_j^2}{2}} \end{aligned} \tag{5.3.6}$$

Where $z_i=(Ep_i, Sn_i, Se_i)$ and $z_j=(Ep_j, Sn_j, Se_j)$ are the clouds formed from the linguistic term set S.

Example 2: Let the domain V be [0, 1] and [s_1 and s_2] be the interval linguistic value. First convert linguistic term s_1 and s_2 into two clouds z_1= (0.167, 0.103, 0.267) and z_2= (0.333, 0.064, 0.162) respectively, and then

$\underline{Ep}$ = min {0.167, 0.333} = 0.167, $\overline{Ep}$= max {0.167, 0.333}=0.333

$Sn=\sqrt{\frac{0.103^2+0.064^2}{2}}$=0.086, $Se=\sqrt{\frac{0.267^2+0.162^2}{2}}$= 0.218

5.4 PROPOSED CLOUD MODEL AND EXTENDED PROMETHEE

In the succeeding section, a new risk assessment ranking model using cloud and extended PROMETHEE method is proposed. The proposed methodology consists of three phases:

1) Risk assessment of failure causes through cloud model.

2) Determining the weights of decision makers through cloud model, and

3) Using PROMETHEE II method to obtain the ranking of failure causes.

Figure 5.1 shows the schematic representation of the proposed methodology.

Phase 1. Failure causes risk assessment

Suppose there are p failure causes D_i $(i=1,2,......p)$, and q risk factors $C_j\left(j=1,2,.....q\right)$ with the weight vector $w=\left(w_1, w_2, ...w_q\right)$, where $w_j\in\left[0,1\right]$ and $\sum_{j=1}^{q} w_j=1$. Assume that h decision makers $DM_k\left(k=1,2,....h\right)$ are included in the risk assessment process whose relative weights are obscure. Let $T^k=\left(t_{ij}^k\right)_{p\times q}$ be the linguistic assessment matrix of the k^{th} decision maker, where d_{ij}^k is the linguistic rating of D_i on CF_j inferred from the linguistic term set $L^k=\left\{l_0^k, l_1^k, ...l_m^k\right\}$.

Step 1: Construct risk assessment normalized linguistic evaluation matrix using definition 6.

Step 2: Convert the linguistic evaluation matrix into interval cloud matrix using definition 7.

Phase 2 Computing weights of FMEA decision makers

Step 3: Determine the weights of FMEA decision makers based on uncertainty degree

For finding weightage of decision makers, the uncertainty degree has been used by Wang et al. (2015) and Shi et al. (2017) in MCDM by the expression

$$H\left(\tilde{R}^k\right)=\sum_{i=1}^{p}\sum_{j=1}^{q}\frac{\overline{Ep_{ij}^k}-\underline{\underline{Ep_{ij}^k}}}{m+1} \qquad (5.3.7)$$

Where $H(\tilde{R}^k)$is Uncertainty degree of the risk assessment matrix $(\tilde{R}^k)$

Lower the uncertainty degree, the more exact the assessment information will be, which recommends that higher weight should be given to the decision maker. Hence, the primary weight vector of decision maker $\lambda^{(1)}=\left(\lambda_1^{(1)},\lambda_2^{(1)},...,\lambda_h^{(1)}\right)$is derived by

$$\lambda_k^{(1)}=\frac{1/\,H(\tilde{R}^k)}{\sum_{k=1}^{l}1/\,H(\tilde{R}^k)} \qquad (5.3.8)$$

Step 4: Determine the weights of FMEA decision makers based on divergence degree

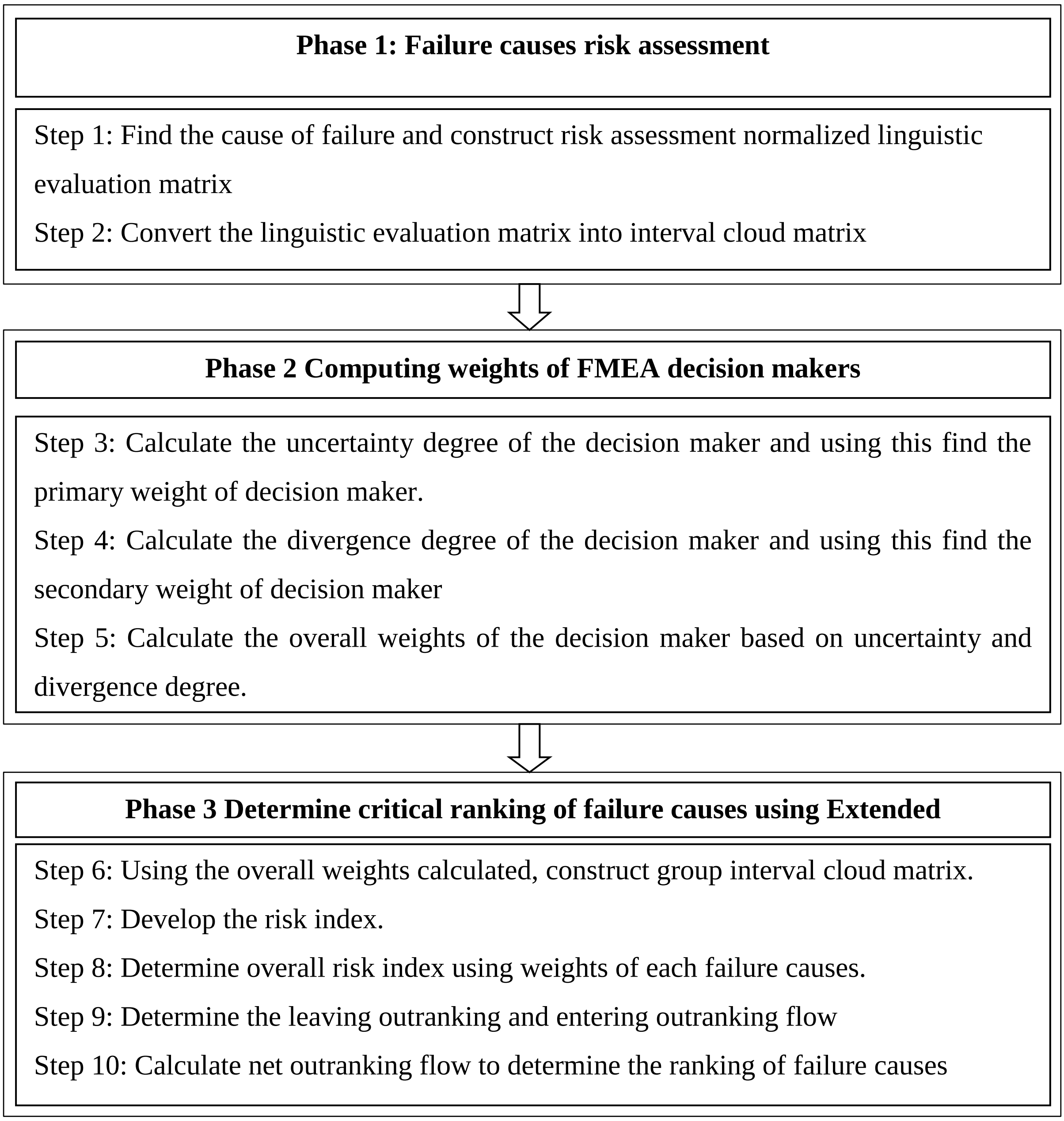
While making a group decision, the risk rating of the individual team member should be consistent with the others to the maximum extent. Therefore according to Shi et al. (2017) the divergence degree between the risk assessment matrix $\tilde{R}^k$ and the risk assessment matrices of other FMEA decision makers is derived by

$$G\left(\tilde{R}^k\right)=\frac{1}{\sum_{u=1,u\neq\kappa}^{l}\sum_{i=1}^{p}\sum_{j=1}^{q}d\left(\tilde{z}_{ij}^k,\tilde{z}_{ij}^u\right)} \qquad (5.3.9)$$

Where $G(\tilde{R}^k)$ is divergence degree of the risk assessment matrix $(\tilde{R}^k)$ and $d\left(\tilde{z}_{ij}^k,\tilde{z}_{ij}^u\right)$ is the distance between two interval clouds and can be calculated by (5.3.5)

If the risk evaluation given by the k^{th} decision maker DM_k is consistent with other decision makers, then it can be seen that DM_k plays a moderately greater part and ought to be given a greater weight. Thus, the secondary weight vector of decision maker $\lambda^{(2)} = \left(\lambda_1^{(2)}, \lambda_2^{(2)}, \ldots, \lambda_h^{(2)}\right)$ is calculated by

$$\lambda_k^2 = \frac{G(\tilde{R}^k)}{\sum_{k=1}^{l} G(\tilde{R}^k)} \tag{5.3.10}$$



Phase 1: Failure causes risk assessment

Step 1: Find the cause of failure and construct risk assessment normalized linguistic evaluation matrix

Step 2: Convert the linguistic evaluation matrix into interval cloud matrix

Phase 2 Computing weights of FMEA decision makers

Step 3: Calculate the uncertainty degree of the decision maker and using this find the primary weight of decision maker.

Step 4: Calculate the divergence degree of the decision maker and using this find the secondary weight of decision maker

Step 5: Calculate the overall weights of the decision maker based on uncertainty and divergence degree.

Phase 3 Determine critical ranking of failure causes using Extended

Step 6: Using the overall weights calculated, construct group interval cloud matrix.

Step 7: Develop the risk index.

Step 8: Determine overall risk index using weights of each failure causes.

Step 9: Determine the leaving outranking and entering outranking flow

Step 10: Calculate net outranking flow to determine the ranking of failure causes

Figure 5.1 Framework of ranking failure causes.

Step 5 Determine the overall weights of decision makers

In order to calculate overall weight of the decision maker the primary and secondary weight are combined using the following equation:

$$\lambda^{k} = \sigma\lambda_{k}^{(1)} + (1-\sigma)\lambda_{k}^{2} \tag{5.3.11}$$

where σ shows characteristics of risk examiners and satisfies $0 \le \sigma \le 1$.

Phase 3. Determine the Ranking of Failure causes

In PROMETHEE first normalisation of decision matrix is performed, then alternative pair wise comparison to calculate the preference function, and then computes leaving and entering outranking flows to find out the overall outranking flow to rank the alternatives. In the proposed methodology, PROMETHEE II approach is suggested to rank the failure causes taken under consideration, whose description is shown as below.

Step 6: Using the overall weights calculated, construct group interval cloud matrix. The individual interval cloud matrices $\tilde{Z}^{k}\left(k = 1, 2, ..., h\right)$ are aggregated using the overall weights derived for decision maker $\lambda = \left(\lambda_{1}, \lambda_{2}, ..., \lambda_{h}\right)$, from uncertainty $H\left(\tilde{R}^{k}\right)$ and divergence $G\left(\tilde{R}^{k}\right)$ degree to develop a group interval cloud matrix $\tilde{Z} = \left(\tilde{z}_{ij}\right)_{p\times q}$ by using the Interval cloud weighted averaging (ICWA) operator Wang et al. (20015). $\tilde{z}_{ij} = \left(\left[\underline{Ep_{ij}}, \overline{Ep_{ij}}\right], Sn_{ij}, Se_{ij}\right)$ of failure cause D_{i} against risk factor C_{j} is computed by

$$\tilde{z}_{ij} = ICWA_{\lambda}(\tilde{z}_{ij}^{1}, \tilde{z}_{ij}^{2}, ...\tilde{z}_{ij}^{h}) = \sum_{k=1}^{h}\lambda_{k}\tilde{z}_{ij}^{1} = \left(\sum_{k=1}^{h}\lambda_{k}\left[\underline{Ep_{ij}}^{k}, \overline{Ep_{ij}}^{k}\right], \sqrt{\sum_{k=1}^{h}\lambda_{k}\left(Sn_{ij}^{k}\right)^{2}}, \sqrt{\sum_{k=1}^{h}\lambda_{k}\left(Se_{ij}^{k}\right)^{2}}\right) \tag{5.3.12}$$

The ICWA operator accomplishes the usual properties of weighted average operators.

Step 7: Develop the risk index $C_{j}(D_{r}, D_{s})$

According to Sen et al. (2015), the risk index for each pair of failure cause (D_{r}, D_{s}) $\left(r, s = 1, 2, ..., p, r \ne s\right)$ is designed as

$C_j(D_r, D_s) = 0 \qquad \text{if } \tilde{z}_{rj} \le \tilde{z}_{sj}$

$$C_j(D_r, D_s) = d(\tilde{z}_{rj}, \tilde{z}_{sj}) \qquad \text{if } \tilde{z}_{rj} > \tilde{z}_{sj} \tag{5.3.13}$$

Where j=1,2,…………..n and $d\left(\tilde{z}_{rj}, \tilde{z}_{sj}\right)$ is the distance between two interval clouds $\tilde{z}_{rj}$ and $\tilde{z}_{sj}$. The risk index $C_j(D_r, D_s)$ is the measure to back the theory that D_r has a higher risk than D_s concerning the risk factor C_j.

Step 8: Determine overall risk index $C(D_r, D_s)$ using weights of each failure causes

Considering risk factor weights, the overall risk index of D_r over D_s across q risk factors can be determined by

$$C(D_r, D_s) = \sum_{j=1}^{q} w_j C_j\left(D_r, D_s\right), \tag{5.3.14}$$

$$r, s = 1, 2, \ldots\ldots\ldots. p, r \ne s$$

where w_j shows the priority weight of the j^{th} risk factor.

Step 9: Determine the leaving and the entering outranking flows

The leaving outranking flow of failure cause D_r, a measure of the risk of failure cause D_r over the other failure causes, is denoted by

$$\beta^{+}\left(D_r\right) = \frac{1}{p-1} \sum_{r=1, r \ne s}^{p} C(D_r, D_s), \tag{5.3.15}$$

In the same way, the entering outranking flow of failure cause D_r, a measure of the risk of failure cause D_r over the other failure causes, is denoted by

$$\beta^{-}\left(D_r\right) = \frac{1}{p-1} \sum_{r=1, r \ne s}^{p} C(D_s, D_r), \tag{5.3.16}$$

Step 10: Obtain the net outranking flow for each failure cause

The net outranking flows can be obtained by

$$\beta\left(D_r\right) = \beta^{+}\left(D_r\right) - \beta^{-}\left(D_r\right), \quad \text{r=1,2,……p} \tag{5.3.17}$$

To illustrate the proposed methodology risk analysis of steam handling subsystem in a paper production system of a paper plant is performed. The objective of the steam handling subunit is to heat the dryer's rolls with the superheated steam to remove the moisture content of the paper rolled over the dryer rolls. To find the failure cause of steam handling subsystem, a team is constructed which consist of graduate engineer trainee, maintenance assistant engineer and maintenance head denoted as $DM_k\left(k=1,2,3\right)$. After that root cause failures of steam handling subsystem is identified and root cause analysis diagram is drawn (Figure 5.2), which shows that there are 8 causes of failure. The entire three decision maker DM_1, DM_2, DM_3 assesses the failure causes risks using definition 6 in terms of seven label linguistic term.

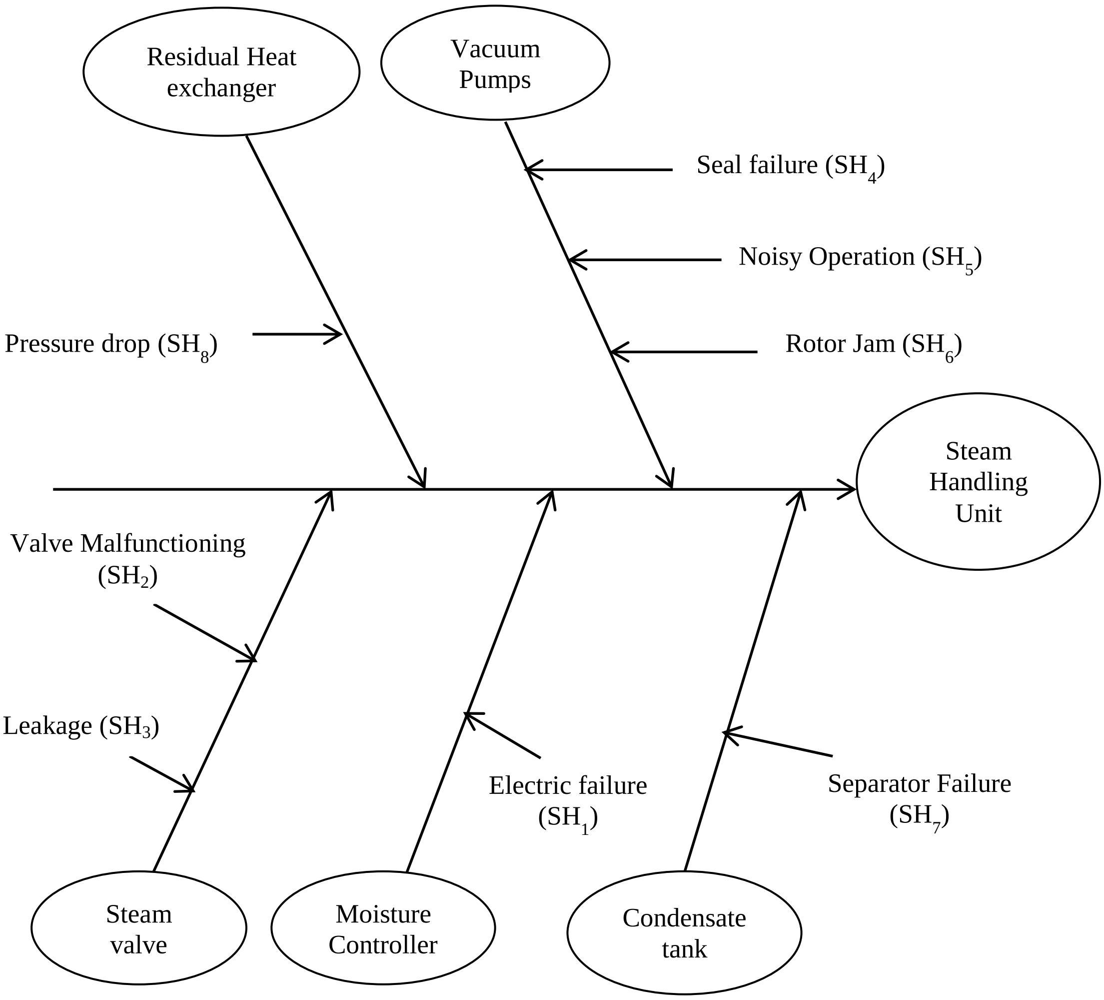


Figure 5.2 Root cause analysis of Steam handling subsystem.

5.3.1 Illustration of proposed Model

As discussed in the preceding sections an integrated cloud model and extended PROMETHEE approach is used to find out the risk ranking of eight failure causes of steam handling subunit. To begin with in phase 1st, the different sorts of linguistic evaluations given in Table 5.3 are represented as linguistic intervals to develop the interval linguistic assessment evaluation matrices $\tilde{C}^k=\left(\tilde{c}_{ij}^k\right)_{8\times 5}\left(k=1,2,3\right)$. Then, the interval cloud matrices $\tilde{Z}^k = \left(\tilde{z}_{ij}^k\right)_{8\times5} \left(k = 1, 2, 3\right)$ are determined in line with the conversion method between linguistic ratings and interval clouds. The interval linguistic evaluation matrix and the interval cloud matrix are obtained for 1st decision maker DM_1 as shown in Tables 5.4 and 5.5, 2nd decision maker DM_2 as shown in Table 5.6 and 5.7 and 3rd decision maker DM_3 as shown in Table 5.8 and 5.9 respectively.

Table 5.3 Linguistic evaluation on the eight failure causes by the three FMEA decision makers

Decision Maker	Risk Factors	SH_1	SH_2	SH_3	SH_4	SH_5	SH_6	SH_7	SH_8
DM_1	F_o	M_L	H-V_H	M-H	M_L	M_L	M-H	M_L	L-M
	N_d	M-H	V_H	H	M_H-H	V_L	L	H-V_H	M
	D_l	V_H	M	L-M	M_L	M_L-M_H	M_L-M_H	H	V_H
	S_{pc}	M-H	L-M_L	M_L	M_L	V_L	M_L	M_H-V_H	M_H-V_H
	S_r	M_L	V_H	H-V_H	L-M_L	L-M_L	M_L	M	M
DM_2	F_o	L-M	H	M_H-H	L-M_L	M_L	M_H	M_L	M_L-M_H
	N_d	M_H	H-V_H	H	M-H	V_L-L	V_L-M_L	H	L-M
	D_l	M_H-V_H	M_L-M_H	M_L-M	M_L	M_L	M	H-V_H	H-V_H
	S_{pc}	M	M_L	V_L-M_L	M_L	V_L	M_L-M_H	H	H
	S_r	V_L-M	V_H	V_H	M_L	V_L-M_L	M_L	L-M	M_L-M_H
DM_3	F_o	M_L-M	M_H-V_H	H	M_L	V_L-M_L	M_H	L-M	M
	N_d	M-V_H	V_H	M_L-H	M_H	L	L-M	M_H-H	M_L-M
	D_l	V_H	M	M	V_L-M_L	M_L	M_L-M_H	H	H-V_H
	S_{pc}	M_L-M_H	M_L-M	M_L	L-M_L	V_L-L	M_L	M-V_H	H
	S_r	V_L-M_L	H-V_H	M_H-V_H	M_L	L	L-M	M_L-M_H	M

Table 5.4 Interval linguistic evaluation matrix for 1st FMEA decision maker

Failure causes	F_o	N_d	D_l	S_{pc}	S_r
SH_{11}	$\left[l_2^1,l_2^1\right]$	$\left[l_3^1,l_5^1\right]$	$\left[l_6^1,l_6^1\right]$	$\left[l_3^1,l_5^1\right]$	$\left[l_2^1,l_2^1\right]$
SH_{12}	$\left[l_5^1,l_6^1\right]$	$\left[l_6^1,l_6^1\right]$	$\left[l_3^1,l_3^1\right]$	$\left[l_1^1,l_2^1\right]$	$\left[l_6^1,l_6^1\right]$
SH_{13}	$\left[l_3^1,l_5^1\right]$	$\left[l_5^1,l_5^1\right]$	$\left[l_1^1,l_3^1\right]$	$\left[l_2^1,l_2^1\right]$	$\left[l_5^1,l_6^1\right]$
SH_{14}	$\left[l_2^1,l_2^1\right]$	$\left[l_4^1,l_5^1\right]$	$\left[l_2^1,l_2^1\right]$	$\left[l_2^1,l_2^1\right]$	$\left[l_1^1,l_2^1\right]$
SH_{15}	$\left[l_2^1,l_2^1\right]$	$\left[l_0^1,l_0^1\right]$	$\left[l_2^1,l_4^1\right]$	$\left[l_0^1,l_0^1\right]$	$\left[l_1^1,l_2^1\right]$
SH_{16}	$\left[l_3^1,l_5^1\right]$	$\left[l_1^1,l_1^1\right]$	$\left[l_2^1,l_4^1\right]$	$\left[l_2^1,l_2^1\right]$	$\left[l_2^1,l_2^1\right]$
SH_{17}	$\left[l_2^1,l_2^1\right]$	$\left[l_5^1,l_6^1\right]$	$\left[l_5^1,l_5^1\right]$	$\left[l_4^1,l_6^1\right]$	$\left[l_3^1,l_3^1\right]$
SH_{18}	$\left[l_1^1,l_3^1\right]$	$\left[l_3^1,l_3^1\right]$	$\left[l_6^1,l_6^1\right]$	$\left[l_4^1,l_6^1\right]$	$\left[l_3^1,l_3^1\right]$

Table 5.5 Interval cloud matrix for 1st FMEA decision maker

Failure causes	F_o	N_d	D_l	S_{pc}	S_r
SH_{11}	([0.333,0.333],0.064,0.162)	([0.5,0.833],0.078,0.198)	([1,1],0.167,0.424)	([0.5,0.833],0.078,0.198)	([0.333,0.333],0.086,0.218)
SH_{12}	([0.833,1],0.139,0.352)	([1,1],0.167,0.424)	([0.5,0.5],0.039,0.1)	([0.167,0.333],0.086,0.218)	([1,1],0.167,0.424)
SH_{13}	([0.5,0.833],0.0780.198)	([0.833,0.833],0.103,0.262)	([0.167,0.5],0.078,0.198)	([0.333,0.333],0.064,0.162)	([0.833,1],0.139,0.352)
SH_{14}	([0.333,0.333],0.064,0.162)	([0.667,0.833],0.086,0.218)	([0.333,0.333],0.064,0.162)	([0.333,0.333],0.064,0.162)	([0.167,0.333],0.086,0.218)
SH_{15}	([0.333,0.333],0.064,0.162)	([0,0],0.167,0.424)	([0.333,0.667],0.064,0.162)	([0,0],0.167,0.424)	([0.167,0.333],0.086,0.218)
SH_{16}	([0.5,0.833],0.0780.198)	([0.167,0.167],0.103,0.262)	([0.333,0.667],0.064,0.162)	([0.333,0.333],0.064,0.162)	([0.333,0.333],0.064,0.162)
SH_{17}	([0.333,0.333],0.064,0.162)	([0.833,1],0.139,0.352)	([0.833,0.833],0.103,0.262)	([0.667,1],0.126,0.321)	([0.5,0.5],0.039,0.1)
SH_{18}	([0.167,0.5],0.078,0.198)	([0.5,0.5],0.039,0.1)	([1,1],0.167,0.424)	([0.667,1],0.126,0.321)	([0.5,0.5],0.039,0.1)

Table 5.6 Interval linguistic evaluation matrix for 2nd FMEA decision maker

Failure causes	F_o	N_d	D_l	S_{pc}	S_r
SH_{21}	$\left[l_1^2, l_3^2\right]$	$\left[l_4^2, l_4^2\right]$	$\left[l_4^2, l_6^2\right]$	$\left[l_3^2, l_3^2\right]$	$\left[l_0^2, l_3^2\right]$
SH_{22}	$\left[l_5^2, l_5^2\right]$	$\left[l_5^2, l_6^2\right]$	$\left[l_2^2, l_4^2\right]$	$\left[l_2^2, l_2^2\right]$	$\left[l_6^2, l_6^2\right]$
SH_{23}	$\left[l_4^2, l_5^2\right]$	$\left[l_5^2, l_5^2\right]$	$\left[l_2^2, l_3^2\right]$	$\left[l_0^2, l_2^2\right]$	$\left[l_6^2, l_6^2\right]$
SH_{24}	$\left[l_1^2, l_2^2\right]$	$\left[l_3^2, l_5^2\right]$	$\left[l_2^2, l_2^2\right]$	$\left[l_2^2, l_2^2\right]$	$\left[l_2^2, l_2^2\right]$
SH_{25}	$\left[l_2^2, l_2^2\right]$	$\left[l_0^2, l_1^2\right]$	$\left[l_2^2, l_2^2\right]$	$\left[l_0^2, l_0^2\right]$	$\left[l_0^2, l_2^2\right]$
SH_{26}	$\left[l_4^2, l_4^2\right]$	$\left[l_0^2, l_2^2\right]$	$\left[l_3^2, l_3^2\right]$	$\left[l_2^2, l_4^2\right]$	$\left[l_2^2, l_2^2\right]$
SH_{27}	$\left[l_2^2, l_2^2\right]$	$\left[l_5^2, l_5^2\right]$	$\left[l_4^2, l_6^2\right]$	$\left[l_5^2, l_5^2\right]$	$\left[l_1^2, l_3^2\right]$
SH_{28}	$\left[l_2^2, l_4^2\right]$	$\left[l_1^2, l_3^2\right]$	$\left[l_5^2, l_6^2\right]$	$\left[l_5^2, l_5^2\right]$	$\left[l_2^2, l_4^2\right]$

Table 5.7 Interval cloud matrix for 2nd FMEA decision maker

Failure causes	F_o	N_d	D_l	S_{pc}	S_r
SH_{21}	([0.167,0.5],0.078,0.198)	([0.667,0.667],0.064,0.162)	([0.667,1],0.126,0.321)	([0.5,0.5],0.039,0.1)	([0,0.5],0.121,0.308)
SH_{22}	([0.833,0.833],0.103,0.262)	([0.833,1],0.139,0.352)	([0.333,0.667],0.064,0.162)	([0.333,0.333],0.064,0.162)	([1,1],0.167,0.424)
SH_{23}	([0.667,0.833],0.086,0.218)	([0.833,0.833],0.103,0.262)	([0.333,0.5],0.053,0.135)	([0,0.333],0.126,0.32)	([1,1],0.167,0.424)
SH_{24}	([0.167,0.333],0.086,0.218)	([0.5,0.833],0.0780.198)	([0.333,0.333],0.064,0.162)	([0.333,0.333],0.064,0.162)	([0.333,0.333],0.064,0.162)
SH_{25}	([0.333,0.333],0.064,0.162)	([0,0.167],0.139,0.352)	([0.333,0.333],0.064,0.162)	([0,0],0.167,0.424)	([0,0.5],0.121,0.308)
SH_{26}	([0.667,0.667],0.064,0.162)	([0,0.333],0.126,0.32)	([0.5,0.5],0.039,0.1)	([0.333,0.667],0.064,0.162)	([0.333,0.333],0.064,0.162)
SH_{27}	([0.333,0.333],0.064,0.162)	([0.833,0.833],0.103,0.262)	([0.667,1],0.126,0.321)	([0.833,0.833],0.103,0.262)	([0.167,0.5],0.078,0.198)
SH_{28}	([0.333,0.667],0.064,0.162)	([0.167,0.5],0.078,0.198)	([0.833,1],0.139,0.352)	([0.833,0.833],0.103,0.262)	([0.333,0.667],0.064,0.162)

Table 5.8 Interval linguistic evaluation matrix for 3rd FMEA decision maker

Failure causes	F_o	N_d	D_l	S_{pc}	S_r
SH_{31}	$\left[l_2^3,l_3^3\right]$	$\left[l_3^3,l_6^3\right]$	$\left[l_6^3,l_6^3\right]$	$\left[l_2^3,l_4^3\right]$	$\left[l_0^3,l_2^3\right]$
SH_{32}	$\left[l_4^3,l_6^3\right]$	$\left[l_6^3,l_6^3\right]$	$\left[l_3^3,l_3^3\right]$	$\left[l_2^3,l_3^3\right]$	$\left[l_5^3,l_6^3\right]$
SH_{33}	$\left[l_5^3,l_5^3\right]$	$\left[l_2^3,l_5^3\right]$	$\left[l_3^3,l_3^3\right]$	$\left[l_2^3,l_2^3\right]$	$\left[l_4^3,l_6^3\right]$
SH_{34}	$\left[l_2^3,l_2^3\right]$	$\left[l_4^3,l_4^3\right]$	$\left[l_0^3,l_2^3\right]$	$\left[l_1^3,l_2^3\right]$	$\left[l_2^3,l_2^3\right]$
SH_{35}	$\left[l_0^3,l_2^3\right]$	$\left[l_1^3,l_1^3\right]$	$\left[l_2^3,l_2^3\right]$	$\left[l_0^3,l_1^3\right]$	$\left[l_1^3,l_1^3\right]$
SH_{36}	$\left[l_4^3,l_4^3\right]$	$\left[l_1^3,l_3^3\right]$	$\left[l_2^3,l_4^3\right]$	$\left[l_2^3,l_2^3\right]$	$\left[l_1^3,l_3^3\right]$
SH_{37}	$\left[l_1^3,l_3^3\right]$	$\left[l_4^3,l_5^3\right]$	$\left[l_5^3,l_5^3\right]$	$\left[l_3^3,l_6^3\right]$	$\left[l_2^3,l_4^3\right]$
SH_{38}	$\left[l_3^3,l_3^3\right]$	$\left[l_2^3,l_3^3\right]$	$\left[l_5^3,l_6^3\right]$	$\left[l_5^3,l_5^3\right]$	$\left[l_3^3,l_3^3\right]$

Table 5.9 Interval cloud matrix for 3rd FMEA decision maker

Failure causes	F_o	N_d	D_l	S_{pc}	S_r
SH_{31}	([0.333,0.5],0.053,0.135)	([0.5,1],0.121,0.308)	([1,1],0.167,0.424)	([0.333,0.667],0.064,0.162)	([0,0.333],0.126,0.32)
SH_{32}	([0.667,1],0.126,0.321)	([1,1],0.167,0.424)	([0.5,0.5],0.039,0.1)	([0.333,0.5],0.053,0.135)	([0.833,1],0.139,0.352)
SH_{33}	([0.5,0.833],0.0780.198)	([0.333,0.833],0.086,0.218)	([0.5,0.5],0.039,0.1)	([0.333,0.333],0.064,0.162)	([0.667,1],0.126,0.321)
SH_{34}	([0.333,0.333],0.064,0.162)	([0.667,0.667],0.064,0.162)	([0,0.333],0.126,0.32)	([0.167,0.333],0.086,0.218)	([0.333,0.333],0.064,0.162)
SH_{35}	([0,0.333],0.126,0.32)	([0.167,0.167],0.103,0.262)	([0.333,0.333],0.064,0.162)	([0,0.167],0.139,0.352)	([0.167,0.167],0.103,0.262)
SH_{36}	([0.667,0.667],0.064,0.162)	([0.167,0.5],0.078,0.198)	([0.333,0.667],0.064,0.162)	([0.333,0.333],0.064,0.162)	([0.167,0.5],0.078,0.198)
SH_{37}	([0.167,0.5],0.078,0.198)	([0.667,0.833],0.086,0.218)	([0.833,0.833],0.103,0.262)	([0.5,1],0.121,0.308)	([0.333,0.667],0.064,0.162)
SH_{38}	([0.5,0.5],0.039,0.1)	([0.333,0.5],0.053,0.135)	([0.833,1],0.139,0.352)	([0.833,0.833],0.103,0.262)	([0.5,0.5],0.039,0.1)

In the 2nd phase, with the interval cloud matrices $\tilde{Z}^k\left(k=1,2,3\right)$, as shown in Table 5.5, 5.7, 5.9 the uncertainty degree of each FMEA decision maker are determined by using equation 5.3.7, and the primary weights $\lambda_k^{(1)}\left(k=1,2,3\right)$ are determined based on equation 5.3.8. Similarly, the divergence degree of each decision maker is found out using equation 5.3.9, the secondary weights $\lambda_k^{(2)}\left(k=1,2,3\right)$ are obtained using equation 5.3.10. Lastly, the overall weight related with the three decision makers $\lambda=\left(\lambda_1,\lambda_2,\lambda_3\right)$ can be obtained with equation 5.3.11. The results obtained are shown in Table 5.10.

Table 5.10 Objective weights of the FMEA decision makers

x	DM$_1$	DM$_2$	DM$_3$
$H\left(\tilde{R}^k\right)$	0.857	0.595	0.952
$\lambda_k^{(1)}$	0.299	0.432	0.269
$G\left(\tilde{R}^k\right)$	0.0082	0.0056	0.0057
$\lambda_k^{(2)}$	0.421	0.287	0.292
λ_k	0.36	0.359	0.281

In the third phase of our approach risk ranking of failure causes of steam handling subsystem is determined. To begin with individual interval cloud matrix of three decision makers considered are aggregated using ICWA operator to set up the group interval cloud matrix $\tilde{Z}=\left(\tilde{z}_{ij}\right)_{8\times5}$ as shown in Table 5.11. Then using equation 5.3.13 and 5.3.14, the risk indices $C_j\left(D_r,D_s\right)\left(r,s=1,2,......8,r\neq s\right)$ related to the risk factors F$_o$, N$_d$, D$_l$, S$_{pc}$, S$_r$ and the overall risk indices $C\left(D_r,D_s\right)\left(r,s=1,2,......8,r\neq s\right)$ are calculated. Table 5.12 shows the overall risk indices for each eight pair of failure causes. The weights of the considered five risk factors are taken from the Table 5.2 as 0.427, 0.208, 0.191, 0.111 and 0.2, respectively using AHP. Subsequently, using equation 5.3.15 and 5.3.16, the leaving outranking flows $\beta^+\left(D_r\right)\left(r=1,2,...,8\right)$ and the entering outranking flows $\beta^-\left(D_r\right)\left(r=1,2,...,8\right)$ of the eight failure causes are determined and shown in Table 5.13. At last, the net outranking flow for each failure causes $\beta\left(D_r\right)\left(r=1,2,...,8\right)$ is derived using equation 5.3.17, as shown in Table 5.13. From the Table 5.13 it can be concluded that the order of eight failure causes are $SH_1 \succ SH_6 \succ SH_5 \succ SH_3 \succ SH_4 \succ SH_7 \succ SH_8 \succ SH_2$, in short failure cause electric failure in moisture controller is most critical and steam valve malfunctioning is least critical.

Table 5.11 Group Interval Cloud Matrix

Failure causes	F_o	N_d	D_l	S_{pc}	S_r
SH_1	([0.273,0.44],0.067,0.169)	([0.56,0.7],0.088,0.224)	([0.88,1],0.153,0.39)	([0.453,0.667],0.062,0.158)	([0.12,0.393],0.111,0.283)
SH_2	([0.786,0.94],0.123,0.313)	([0.76,0.82],0.157,0.25)	([0.44,0.56],0.049,0.126)	([0.273,0.38],0.07,0.178)	([0.953,1],0.16,0.405)
SH_3	([0.56,0.833],0.081,0.205)	([0.753,0.893],0.098,0.25)	([0.32,0.5],0.06,0.153)	([0.213,0.333],0.091,0.232)	([0.846,1],0.146,0.372)
SH_4	([0.273,0.333],0.073,0.184)	([0.607,0.727],0.077,0.196)	([0.239,0.333],0.086,0.219)	([0.286,0.333],0.071,0.179)	([0.273,0.333],0.073,0.184)
SH_5	([0.239,0.333],0.086,0.219)	([0.227,0.287],0.141,0.358)	([0.333,0.453],0.064,0.162)	([0,0.047],0.16,0.405)	([0.107,0.346],0.104,0.265)
SH_6	([0.607,0.727],0.069,0.176)	([0.347,0.62],0.106,0.27)	([0.393,0.607],0.056,0.143)	([0.333,0.453],0.064,0.162)	([0.286,0.38],0.068,0.173)
SH_7	([0.286,0.38],0.068,0.173)	([0.666,0.713],0.113,0.287)	([0.773,0.893],0.111,0.284)	([0.68,0.94],0.117,0.297)	([0.333,0.547],0.062,0.158)
SH_8	([0.32,0.56],0.064,0.186)	([0.333,0.5],0.059,0.151)	([0.893,1],0.15,0.379)	([0.773,0.893],0.112,0.285)	([0.44,0.56],0.049,0.126)

Table 5.12 Results of overall risk indices

Failure causes	SH_1	SH_2	SH_3	SH_4	SH_5	SH_6	SH_7	SH_8
SH_1	0	0.632	0.305	0.634	0.316	0.255	0.546	0.548
SH_2	0	0	0.005	0.131	0	0	0	0.053
SH_3	0	0.332	0	0.387	0.068	0.101	0.251	0.301
SH_4	0.156	0.286	0.214	0	0.102	0.115	0.143	0.157

SH_5	0.078	0.394	0.135	0.342	0	0.053	0.270	0.281
SH_6	0.08	0.457	0.230	0.418	0.116	0	0.345	0.347
SH_7	0.063	0.150	0.073	0.138	0.025	0.038	0	0.099
SH_8	0.042	0.180	0.100	0.130	0.013	0.018	0.076	0

Table 5.13 Ranking of failure causes by the proposed methodology

Failure causes	Leaving outranking flow	Entering outranking flow	Net out ranking flow	Risk ranking
SH_1	0.462	0.060	0.402	1
SH_2	0.027	0.347	-0.320	8
SH_3	0.206	0.152	0.054	4
SH_4	0.168	0.311	-0.143	5
SH_5	0.222	0.092	0.130	3
SH_6	0.285	0.083	0.202	2
SH_7	0.084	0.233	-0.149	6
SH_8	0.080	0.255	-0.175	7

5.5 RANKING OF FAILURE CAUSES OF VARIOUS CRITICAL SUBSYSTEMS OF PAPER PLANT

Similarly using the above explained methodology critical ranking is performed for all the critical subsystem identified by using MARKOV approach as explained in Chapter IV by drawing the root cause analysis diagram for all the system to identify the most critical failure cause which will help the maintenance person to adopt the best maintenance planning in the industry (Figure 5.3-5.6).

5.5.1 Blower subsystem of Feeding System

Table 5.14 Critical ranking of failure causes of Blower subsystem

Component	Failure causes	Ranking
Cyclone separator	Lining wear	10
	Foreign objects lodged in valve	1
	Incoming air velocity too high	11
	Incoming air velocity too low	9
	Improper drive train adjustment	5
Motor	Windings burnt	3
	Blade wear/ damage	6
	Lack of lubrication	2
	Seals damaged	4
	Shaft vibration	8
	Loose vanes	7

5.5.2 Digester Subsystem of Pulping System

Table 5.15 Critical ranking of failure causes of digester subsystem

Component	Failure causes	Ranking
Chip feeder	valve malfunctioning	7
	Broken internals	3
Air flow controller	valve malfunctioning	5
Temperature controller	Fuse Failure	11
	Mechanical Binding	2
Pressure time cycle controller	Broken internals	1
	Valve Failure	6
steam flow controller	valve malfunctioning	4
Top relief valve	valve malfunctioning	7
Blow line	Clogging	10
	Mechanical Binding	9

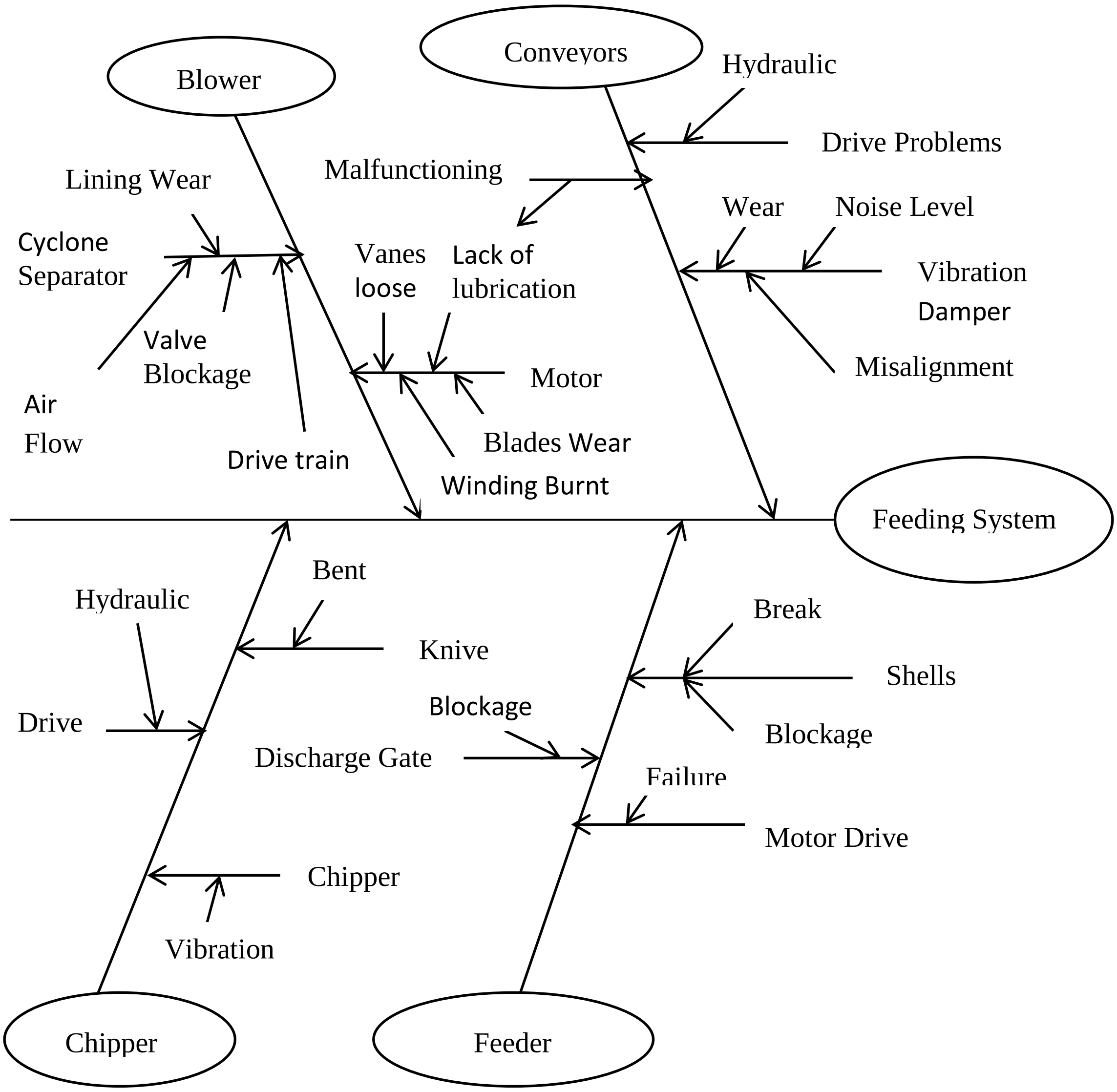


Figure 5.3 Root cause analysis of feeding system

5.4.3 Cleaner Subsystem of Bleaching and Washing System

Table 5.16 Critical ranking of failure causes of cleaner subsystem

Component	Failure cause	Ranking
Mat	Mechanical Binding	3
	Mat Scale	4
Jet flow	Speed	5
	Head	6
	Pressure drop	1
Orifice Valve	Valve Malfunctioning	2

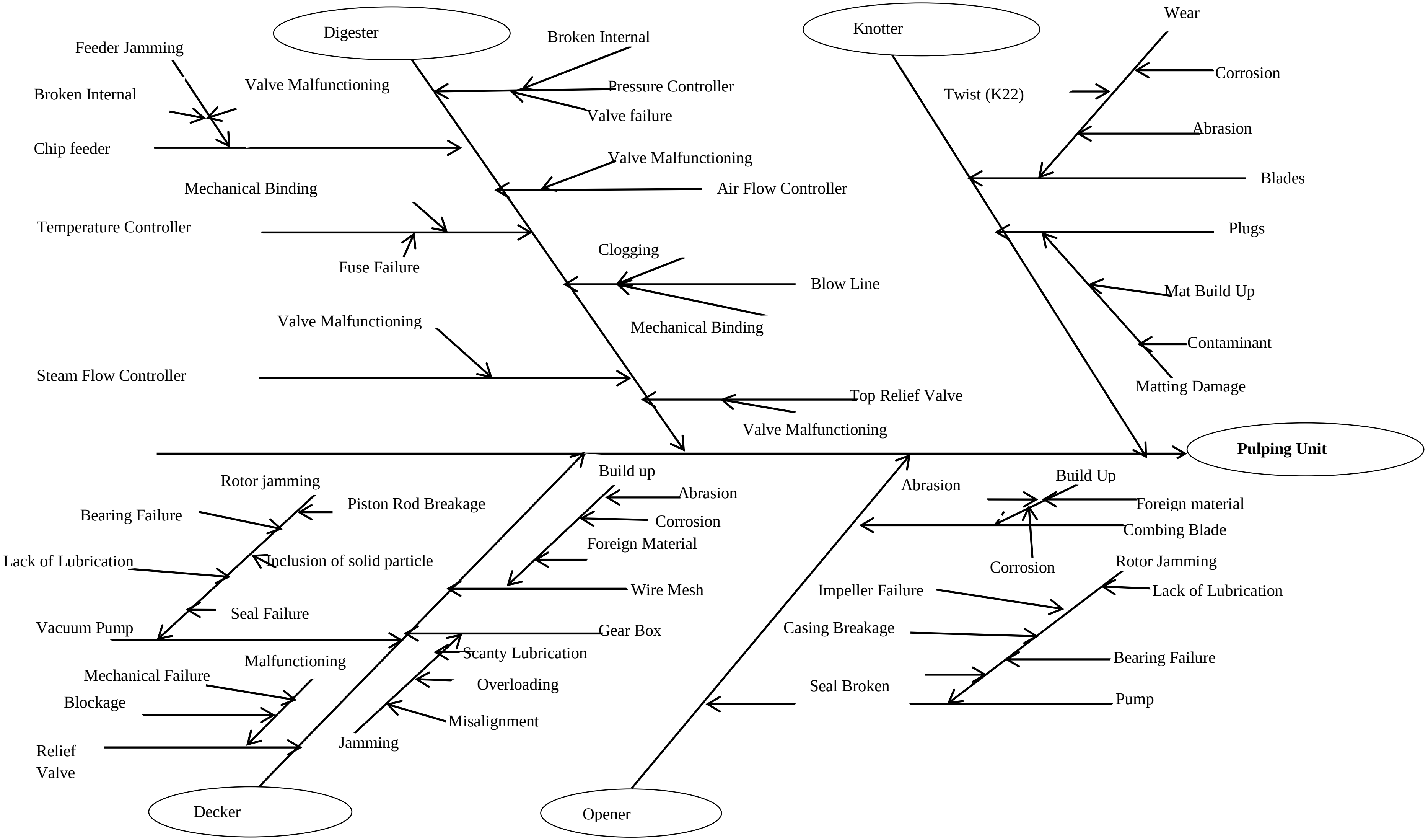


Figure 5.4 Root Cause Analysis of Pulping System

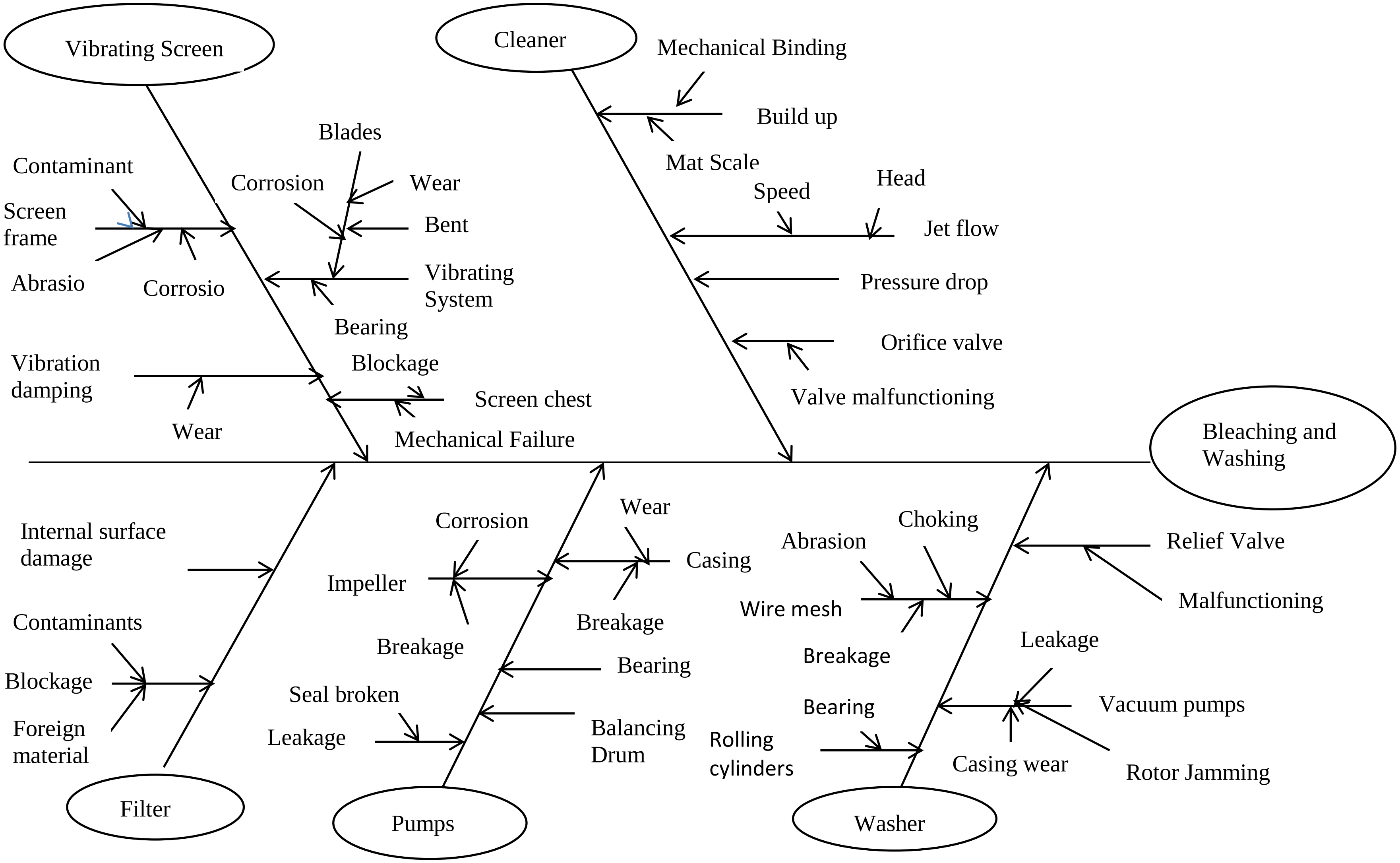


Figure 5.5 Root cause analysis of Bleaching and washing system

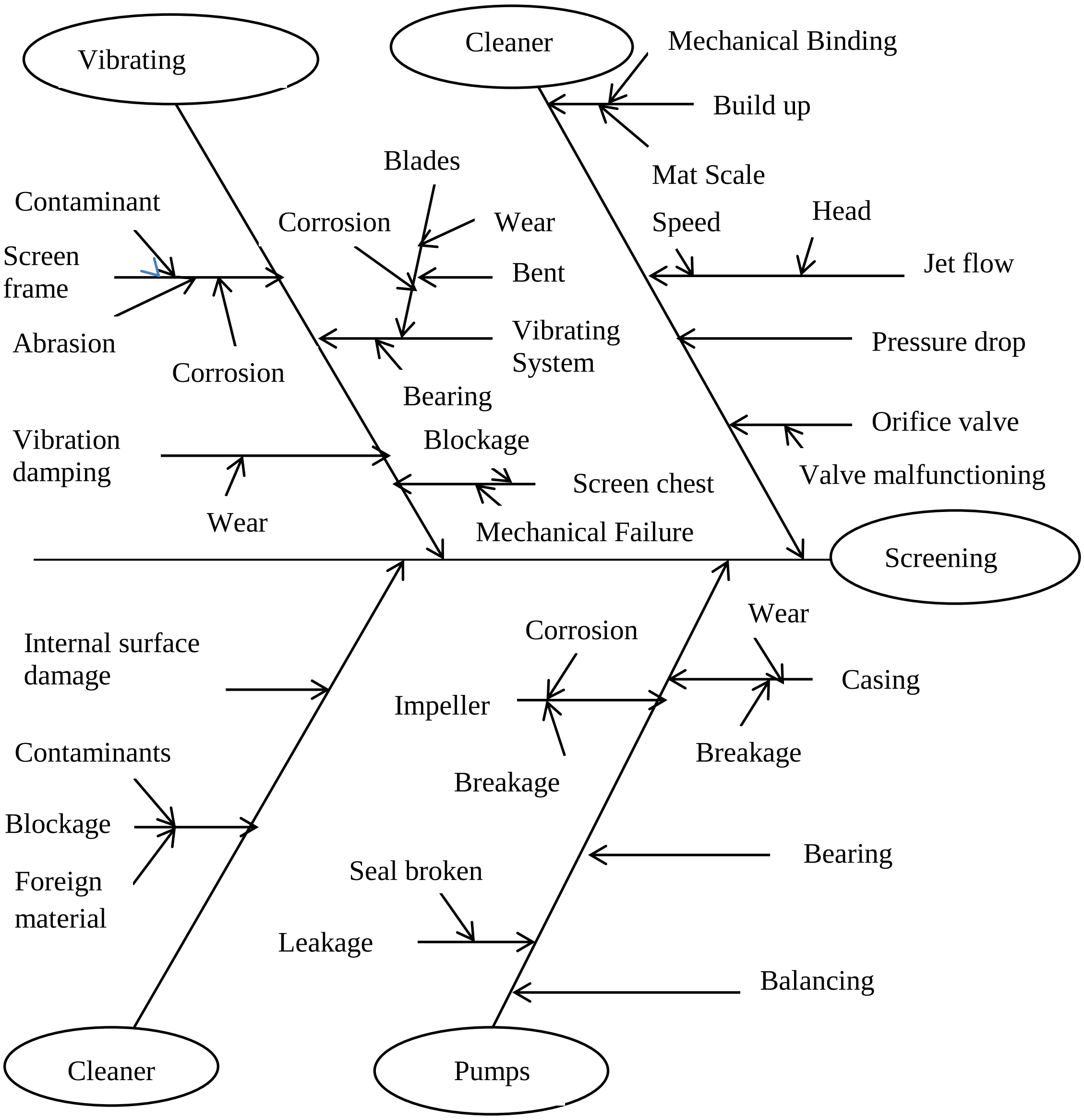


Figure 5.6 Root Cause Analysis of Screening System

5.5.4 Vibrating Screen Subsystem of Screening System

Table 5.17 Critical ranking of failure causes of Vibrating Screen

Component	Failure causes	Ranking
Screen Frame	Abrasion	10
	Contaminants	1
	Corrosion	4
Vibrating System	Blades wear	9
	Blades bent	6
	Lack of lubrication	8
	Bearing failure	3

Vibration damping	Wear	5
Screen chest	Blockage	6
	Mechanical failure	2

Concluding Remarks

In a production system, the failure mode rating and criticality analysis is a particularly complex task because it requires the use of subjective judgments, uncertain data and approximate system models. The results depend on the analysts/experts judgement and the quality of the information derived from different sources. The traditional FMCEA methodology used for the purpose has several well-known weaknesses. Taking into account the deficiencies, a multi criteria decision making approach based on integrated cloud model and PROMETHEE II has been proposed. The criticality analysis is performed by incorporating a number of criteria and by giving different degree of importance to each criteria. The proposed method uses cloud model to describe the fuzziness and randomness of linguistic assessment information and deal with uncertainty and multi-granularity linguistic scale to assess the risk of failure causes and also determines the weights of the decision makers objectively based on uncertainty degree and divergence degree which avoids the imprecise subjective randomness of assigning weights to the decision maker. Furthermore in the proposed model ranking of the failure causes is performed using PROMETHEE II which is a simple and easily comprehensible approach in comparison to other multi-criteria decision making approaches and produces complete ranking of alternatives. Thus it will help the maintenance managers in greatly reducing, if not eliminates, their concern of dealing with imprecise quantitative data for maintenance decision making.

CHAPTER VI

RESOURCE ALLOCATION AND PROFIT ANALYSIS

6.1 INTRODUCTION

The main objective of an industrial system is to produce profitable goods from the limited available resources and same is true for the process industry (Paper plant considered). The profit margin and its distribution for the improvement of plant performance, managerial expertise and staff welfare play an important role in the direction of industrial growth. In a plant, higher output and without losing quality results in large profit. To achieve high production goal, one has to ensure the maximum possible availability of various operating systems in the plant. The aim of achieving high system availability demands performance evaluation, behavioural analysis and scientific maintenance planning. The present maintenance system improves by allocating more funds, skilled manpower, better machines and methods. It is cyclic chain i.e. more the profit, better the maintenance funds allocation, better will be the system availability achieving higher production goals and hence improving further the profit.

To achieve economic and reliable performance of each system in the plant, the required steps are: use of large safety factors, reduce the complexity of the system, increase the use of reliable components and schedules for repair are the effective means of ensuring high plant availability. The maintenance cost and resources allocated for the various departments are analysed. Then the effort needed for its maintenance has been expressed as a function of input variables i.e. component cost and maintenance manpower cost. The multiple constraint function has been imposed on the objective function and dynamic programming using Lagrange's multiplier has been used to reduce the dimensions of the problem. Subject to single dimension constraint, the resource allocation for each unit in the plant is worked out followed by economic analysis chart. The minimum run point of no loss/ no profit is determined. The chart also guides the management to take corrective and timely action for the optimal utilization of available resources.

6.2 DEVELOPMENT OF RESOURCE ALLOCATION MODEL

The paper plant normally consists of K stages in series under constraints such as availability of maintenance resources and manpower. The problem is treated as a multi-stage decision problem and at any stage (say j), a decision is made regarding resources to be allocated to the activity (let it be c_j). The decision at the K^{th} stage is made on the basis of allocation made at the previous K-1 stages. The optimum allocation depends on the total quantity of resources available for allocation to K stages. If stage j, comprises X_j components with reliability p_j, then the resource allocated at the j^{th} stage will be

$$x_j = \left(c_j / R_1\right)$$

$$c_j = R_1 x_j$$

Where R_1 is coefficient of component cost and its value differs from plant to plant.

The availability of successful operation of stage j is given by the following expression:

$$A_j\left(c_j\right) = 1 - \left(1 - p_j\right)^{c_j/R_1}$$

Where c_j is the resource allocated to stage j.

At present paper plant is consisting of 5 systems, therefore overall optimum availability of the system is given by:

$$A_{v(opt)} = A_1 A_2 ....A_5 = \prod_{j=1}^{5} A_j\left(c_j\right)$$

Where A_1, A_2,……. A_5 denote the availabilities of all five systems of plant

$$A_{v(opt)} = \prod_{j=1}^{5}\left[1 - \left(1 - p_j\right)^{c_j/R_1}\right] \qquad (6.1)$$

$$\ln A_{v(opt)} = \ln A_1 + \ln A_2 + \ln A_3 + \ln A_4 + \ln A_5 = \sum_{j=1}^{5} \phi_j\left(c_j\right) = Z$$

where $\varphi_j\left(c_j\right) = \ln A_j\left(c_j\right) = \ln\left[1 - \left(1 - p_j\right)^{c_j/R_1}\right]$

The plant management is always interested in maximizing the profit.

$$Maximize \;\; Z = \sum_{j=1}^{5} \varphi_j\left(c_j\right), \;\; c_j \succ o$$

$$subject \; to \; \sum_{j=1}^{5} c_j x_j \le c_1$$

and $\sum_{j=1}^{5} m_j \bar{c}_j \le c_2$

and $c_1 > c_2$

$\bar{c}_j \alpha c_j$

Where c_1 is the maintenance cost (excluding manpower), c_2 is the available manpower budget for maintenance and $\bar{c}_j$ is the manpower cost for stage j. The number of subsystems (x_j) and maintenance manpower required for stage j (m_j) are known.
Since, the maintenance manpower employed for stage j (m_j) depends upon the number of subsystems at the stage j (x_j), therefore the manpower cost for stage j ($\bar{c}_j$) is directly proportional to resources allocated to stage j (c_j).
$\bar{c}_j = R_2 c_j$

where R_2 is defined as the coefficient of manpower cost and its value lies in between 0 to 1, subject to the plant size.

Introducing Lagrange's multiplier (£$_L$) the problem becomes following:

$$Maximize\ Z = \sum_{j=1}^{5} \varphi_j\left(c_j\right) - \lambda_L \sum_{j=1}^{5} m_j c_j R_2 \ \left(c_j > 0\right) \tag{6.2}$$

Subject to

$$\sum_{j=1}^{5} c_j x_j \le c_1$$

Therefore, the resulting recursive equation for the n stage problem is as follows:

$$f_n\left(\in\right) = Max.\left[\left\{\ln\left[1-\left(1-p_j\right)^{c_j/R_1}\right]\right\}\right] - \lambda_L m_n \in R_2 + f_{n-1}\left(\in - c_n x_n\right) \tag{6.3}$$

Where

P_j= Availability at stage j

$c_j = \in / x_j$

∈= total resources available

m_n= Manpower for the concerned system

R_1=Coefficient of component cost

R_2=Coefficient of manpower cost

$£_L$=Lagrange’s multiplier

For the operation of the plant cost data have been obtained from the concerned plant personnel and help is taken of the accounts books. The missing data have been taken by utilizing the experience of the experts. Then the, estimates are made regarding the allocation of optimum capital to each stage, so as to achieve maximum system availability. For the paper plant coefficient for component cost (R_1) and coefficient for manpower cost (R_2) are suggested by the plant personnel, and then values are 4.0 and 0.7 respectively.

6.3 RESOURCE ALLOCATION TO SYSTEMS

Values of the maximum possible steady state availability for respective stages, have been taken from the detailed behavioural analysis performed in Chapter III,IV and the considered data is given in Table 6.1. Starting with the first stage, the results have been obtained for each stage for the given values of the state function and using the recursive equation 6.3. The values of resource allocation ($\in_0$) for which the state function is maximum, has been determined by considering a particular value of Lagrange’s multiplier and is shown by bold region in Table 6.2 to 6.6. These values have been checked against the available resources. Then, a new value of £ is chosen and the allocation is repeated. This process is continued until the given constraints are satisfied. Table 6.2 to 6.6 gives computed results of allocated money for different values of Lagrange’s multiplier.

The various allocations for appropriate values of $£_L$ are calculated in the following manner and values are entered in Table 6.7.

The optimum allocation values ($\in_0$) for each stage (1 to 5) for various values of $£_L$ are noted from Tables 6.2 to 6.6 respectively and entered in Table 6.7.

Maintenance cost is calculated by summation of all optimum allocation values corresponding to particular value of $£_L$.

Manpower cost for different values of $£_L$ is calculated using the following formula:

$$\text{Manpower cost}=\sum_{system\ 1}^{system\ 5} \frac{optimum\ allocation\ (\in_0)}{Number\ of\ subsystems\ (x_j)} \times manpower\ (m_n) \qquad (6.4)$$

The optimum overall availability i.e. $A_{v(opt.)}$, is obtained using the following formula:

$$A_{v(opt)} = \prod_{j=1}^{5} \left[1 - \left(1 - p_j\right)^{\frac{\in_0}{x_j R_1}} \right] \tag{6.5}$$

Thus, all values of optimum allocation, Maintenance cost, Manpower cost and optimum overall availability are calculated using above said formulas and illustrated in Table 6.7.

Table 6.7 clearly reveals that a decrease in the value of £ increases the availability leading to the requirement of more money both for maintenance and manpower. Hence, subject to the available resources, an optimum value of £ is selected, so as to allocate money for each stage for achieving optimum system availability i.e. for maximum profit with availability factor conditions.

$$£_L = \frac{\left[\left(1 - p_j\right)^{c_j/R_1} \right] \ln(1 - p_j)^{-R_1}}{R_2 m_n [1 - (1 - p_j)^{c_j/R_1}} \tag{6.7}$$

The second derivative of the recursive function i.e. $d^2 fn(\in)/dc_j^2$ is negative for $c_j > 0$. It implies that relation given by equation (6.7) is the condition of maximum availability for the allocated money.

Table 6.1 Data input table for Paper Plant

S.No	Name of system	System availability	Number of subsystems	Manpower	Permitted range of maintenance cost	Permitted range of manpower cost
1	Feeding	0.93	3	2	100-200	50-150
2	Pulping	0.94	5	4		
3	Bleaching and Washing	0.95	6	4		
4	Screening	0.92	4	3		
5	Paper making unit	0.87	7	5		

Table 6.2 Allocation table for Feeding System

Feeding					
$£_L$=0.001		**$£_L$=0.002**		**$£_L$=0.003**	
$\in$	$f(\in)$	$\in$	$f(\in)$	$\in$	$f(\in)$
1	-1.61702	1	-1.61842	1	-1.61982
2	-1.02995	2	-1.03275	2	-1.03555
3	-0.72651	3	-0.73071	3	-0.73491
4	-0.53685	4	-0.54245	4	-0.54805
5	-0.40779	5	-0.41479	5	-0.42179
6	-0.31571	6	-0.32411	6	-0.33251
7	-0.24804	7	-0.25784	7	-0.26764
8	-0.19735	8	-0.20855	8	-0.21975
9	-0.15889	9	-0.17149	9	-0.18409
10	-0.12945	10	-0.14345	10	-0.15745
11	-0.10682	11	-0.12222	11	-0.13762
12	-0.08937	12	-0.10617	12	-0.12297
13	-0.07592	13	-0.09412	13	-0.11232
14	-0.06558	14	-0.08518	14	-0.10478
15	-0.05767	15	-0.07867	15	-0.09967
16	-0.05167	16	-0.07407	16	-0.09647
17	-0.04719	17	-0.07099	17	-0.09479
18	-0.04389	18	-0.06909	18	**-0.09429**
19	-0.04155	19	-0.06815	19	-0.09475
20	-0.03996	20	**-0.06796**	20	-0.09596
21	-0.03897	21	-0.06837	21	-0.09777
22	-0.03846	22	-0.06926	22	-0.10006
23	**-0.03833**	23	-0.07053	23	-0.10273
24	-0.03851	24	-0.07211	24	-0.10571
25	-0.03893	25	-0.07393	25	-0.10893
26	-0.03955	26	-0.07595	26	-0.11235
27	-0.04032	27	-0.07812	27	-0.11592
28	-0.04122	28	-0.08042	28	-0.11962

29	-0.04222	29	-0.08282	29	-0.12342
30	-0.0433	30	-0.0853	30	-0.1273
31	-0.04444	31	-0.08784	31	-0.13124
32	-0.04563	32	-0.09043	32	-0.13523
33	-0.04687	33	-0.09307	33	-0.13927
34	-0.04813	34	-0.09573	34	-0.14333
35	-0.04943	35	-0.09843	35	-0.14743
36	-0.05074	36	-0.10114	36	-0.15154
37	-0.05207	37	-0.10387	37	-0.15567
38	-0.05342	38	-0.10662	38	-0.15982
39	-0.05478	39	-0.10938	39	-0.16398
40	-0.05614	40	-0.11214	40	-0.16814
41	-0.05751	41	-0.11491	41	-0.17231
42	-0.05889	42	-0.11769	42	-0.17649
43	-0.06027	43	-0.12047	43	-0.18067
44	-0.06166	44	-0.12326	44	-0.18486
45	-0.06305	45	-0.12605	45	-0.18905
46	-0.06444	46	-0.12884	46	-0.19324
47	-0.06583	47	-0.13163	47	-0.19743
48	-0.06722	48	-0.13442	48	-0.20162
49	-0.06862	49	-0.13722	49	-0.20582
50	-0.07002	50	-0.14002	50	-0.21002
51	-0.07141	51	-0.14281	51	-0.21421
52	-0.07281	52	-0.14561	52	-0.21841
53	-0.07421	53	-0.14841	53	-0.22261
54	-0.07561	54	-0.15121	54	-0.22681
55	-0.07701	55	-0.15401	55	-0.23101
56	-0.0784	56	-0.1568	56	-0.2352
57	-0.0798	57	-0.1596	57	-0.2394
58	-0.0812	58	-0.1624	58	-0.2436
59	-0.0826	59	-0.1652	59	-0.2478
60	-0.084	60	-0.168	60	-0.252

61	-0.0854	61	-0.1708	61	-0.2562
62	-0.0868	62	-0.1736	62	-0.2604
63	-0.0882	63	-0.1764	63	-0.2646
64	-0.0896	64	-0.1792	64	-0.2688
65	-0.091	65	-0.182	65	-0.273
66	-0.0924	66	-0.1848	66	-0.2772
67	-0.0938	67	-0.1876	67	-0.2814
68	-0.0952	68	-0.1904	68	-0.2856
69	-0.0966	69	-0.1932	69	-0.2898
70	-0.098	70	-0.196	70	-0.294
71	-0.0994	71	-0.1988	71	-0.2982
72	-0.1008	72	-0.2016	72	-0.3024
73	-0.1022	73	-0.2044	73	-0.3066
74	-0.1036	74	-0.2072	74	-0.3108
75	-0.105	75	-0.21	75	-0.315
76	-0.1064	76	-0.2128	76	-0.3192
77	-0.1078	77	-0.2156	77	-0.3234
78	-0.1092	78	-0.2184	78	-0.3276
79	-0.1106	79	-0.2212	79	-0.3318
80	-0.112	80	-0.224	80	-0.336
81	-0.1134	81	-0.2268	81	-0.3402
82	-0.1148	82	-0.2296	82	-0.3444
83	-0.1162	83	-0.2324	83	-0.3486
84	-0.1176	84	-0.2352	84	-0.3528
85	-0.119	85	-0.238	85	-0.357
86	-0.1204	86	-0.2408	86	-0.3612
87	-0.1218	87	-0.2436	87	-0.3654
88	-0.1232	88	-0.2464	88	-0.3696
89	-0.1246	89	-0.2492	89	-0.3738
90	-0.126	90	-0.252	90	-0.378
91	-0.1274	91	-0.2548	91	-0.3822
92	-0.1288	92	-0.2576	92	-0.3864

93	-0.1302	93	-0.2604	93	-0.3906
94	-0.1316	94	-0.2632	94	-0.3948
95	-0.133	95	-0.266	95	-0.399
96	-0.1344	96	-0.2688	96	-0.4032
97	-0.1358	97	-0.2716	97	-0.4074
98	-0.1372	98	-0.2744	98	-0.4116
99	-0.1386	99	-0.2772	99	-0.4158
100	-0.14	100	-0.28	100	-0.42

Table 6.3 Allocation table for Pulping System

Pulping					
£$_L$=0.001		**£$_L$=0.002**		**£$_L$=0.003**	
$\in$	$f(\in)$	$\in$	$f(\in)$	$\in$	$f(\in)$
1	-2.033646	1	-2.036446	1	-2.039246
2	-1.411162	2	-1.416762	2	-1.422362
3	-1.074719	3	-1.083119	3	-1.091519
4	-0.854424	4	-0.865624	4	-0.876824
5	-0.697045	5	-0.711045	5	-0.725045
6	-0.578879	6	-0.595679	6	-0.612479
7	-0.487292	7	-0.506892	7	-0.526492
8	-0.414753	8	-0.437153	8	-0.459553
9	-0.356412	9	-0.381612	9	-0.406812
10	-0.30897	10	-0.33697	10	-0.36497
11	-0.27008	11	-0.30088	11	-0.33168
12	-0.23802	12	-0.27162	12	-0.30522
13	-0.211491	13	-0.247891	13	-0.284291
14	-0.189491	14	-0.228691	14	-0.267891
15	-0.171233	15	-0.213233	15	-0.255233
16	-0.156092	16	-0.200892	16	-0.245692
17	-0.143562	17	-0.191162	17	-0.238762
18	-0.133232	18	-0.183632	18	-0.234032
19	-0.124763	19	-0.177963	19	-0.231163

20	-0.117875	20	-0.173875	20	**-0.229875**
21	-0.112334	21	-0.171134	21	-0.229934
22	-0.107944	22	-0.169544	22	-0.231144
23	-0.104538	23	**-0.168938**	23	-0.233338
24	-0.101979	24	-0.169179	24	-0.236379
25	-0.100145	25	-0.170145	25	-0.240145
26	-0.098937	26	-0.171737	26	-0.244537
27	-0.098268	27	-0.173868	27	-0.249468
28	**-0.098064**	28	-0.176464	28	-0.254864
29	-0.098262	29	-0.179462	29	-0.260662
30	-0.098806	30	-0.182806	30	-0.266806
31	-0.099651	31	-0.186451	31	-0.273251
32	-0.100755	32	-0.190355	32	-0.279955
33	-0.102084	33	-0.194484	33	-0.286884
34	-0.103608	34	-0.198808	34	-0.294008
35	-0.1053	35	-0.2033	35	-0.3013
36	-0.107139	36	-0.207939	36	-0.308739
37	-0.109105	37	-0.212705	37	-0.316305
38	-0.111181	38	-0.217581	38	-0.323981
39	-0.113352	39	-0.222552	39	-0.331752
40	-0.115606	40	-0.227606	40	-0.339606
41	-0.117932	41	-0.232732	41	-0.347532
42	-0.120321	42	-0.237921	42	-0.355521
43	-0.122763	43	-0.243163	43	-0.363563
44	-0.125253	44	-0.248453	44	-0.371653
45	-0.127783	45	-0.253783	45	-0.379783
46	-0.130349	46	-0.259149	46	-0.387949
47	-0.132946	47	-0.264546	47	-0.396146
48	-0.135569	48	-0.269969	48	-0.404369
49	-0.138216	49	-0.275416	49	-0.412616
50	-0.140882	50	-0.280882	50	-0.420882
51	-0.143566	51	-0.286366	51	-0.429166

52	-0.146266	52	-0.291866	52	-0.437466
53	-0.148978	53	-0.297378	53	-0.445778
54	-0.151702	54	-0.302902	54	-0.454102
55	-0.154437	55	-0.308437	55	-0.462437
56	-0.157179	56	-0.313979	56	-0.470779
57	-0.159929	57	-0.319529	57	-0.479129
58	-0.162686	58	-0.325086	58	-0.487486
59	-0.165449	59	-0.330649	59	-0.495849
60	-0.168216	60	-0.336216	60	-0.504216
61	-0.170988	61	-0.341788	61	-0.512588
62	-0.173763	62	-0.347363	62	-0.520963
63	-0.176542	63	-0.352942	63	-0.529342
64	-0.179323	64	-0.358523	64	-0.537723
65	-0.182107	65	-0.364107	65	-0.546107
66	-0.184893	66	-0.369693	66	-0.554493
67	-0.187681	67	-0.375281	67	-0.562881
68	-0.19047	68	-0.38087	68	-0.57127
69	-0.193261	69	-0.386461	69	-0.579661
70	-0.196053	70	-0.392053	70	-0.588053
71	-0.198846	71	-0.397646	71	-0.596446
72	-0.20164	72	-0.40324	72	-0.60484
73	-0.204435	73	-0.408835	73	-0.613235
74	-0.20723	74	-0.41443	74	-0.62163
75	-0.210026	75	-0.420026	75	-0.630026
76	-0.212823	76	-0.425623	76	-0.638423
77	-0.21562	77	-0.43122	77	-0.64682
78	-0.218417	78	-0.436817	78	-0.655217
79	-0.221215	79	-0.442415	79	-0.663615
80	-0.224013	80	-0.448013	80	-0.672013
81	-0.226811	81	-0.453611	81	-0.680411
82	-0.22961	82	-0.45921	82	-0.68881
83	-0.232408	83	-0.464808	83	-0.697208

84	-0.235207	84	-0.470407	84	-0.705607
85	-0.238006	85	-0.476006	85	-0.714006
86	-0.240806	86	-0.481606	86	-0.722406
87	-0.243605	87	-0.487205	87	-0.730805
88	-0.246404	88	-0.492804	88	-0.739204
89	-0.249204	89	-0.498404	89	-0.747604
90	-0.252003	90	-0.504003	90	-0.756003
91	-0.254803	91	-0.509603	91	-0.764403
92	-0.257602	92	-0.515202	92	-0.772802
93	-0.260402	93	-0.520802	93	-0.781202
94	-0.263202	94	-0.526402	94	-0.789602
95	-0.266002	95	-0.532002	95	-0.798002
96	-0.268801	96	-0.537601	96	-0.806401
97	-0.271601	97	-0.543201	97	-0.814801
98	-0.274401	98	-0.548801	98	-0.823201
99	-0.277201	99	-0.554401	99	-0.831601
100	-0.280001	100	-0.560001	100	-0.840001

Table 6.4 Allocation table for Bleaching and Washing System

Bleaching and Washing					
£$_L$=0.001		**£$_L$=0.002**		**£$_L$=0.003**	
∈	f(∈)	∈	f(∈)	∈	f(∈)
1	-2.14543	1	-2.14823	1	-2.15103
2	-1.51554	2	-1.52114	2	-1.52674
3	-1.17205	3	-1.18045	3	-1.18885
4	-0.94505	4	-0.95625	4	-0.96745
5	-0.78131	5	-0.79531	5	-0.80931
6	-0.65711	6	-0.67391	6	-0.69071
7	-0.55982	7	-0.57942	7	-0.59902
8	-0.4819	8	-0.5043	8	-0.5267
9	-0.4185	9	-0.4437	9	-0.4689
10	-0.36629	10	-0.39429	10	-0.42229

11	-0.32294	11	-0.35374	11	-0.38454
12	-0.2867	12	-0.3203	12	-0.3539
13	-0.25626	13	-0.29266	13	-0.32906
14	-0.23061	14	-0.26981	14	-0.30901
15	-0.20896	15	-0.25096	15	-0.29296
16	-0.19066	16	-0.23546	16	-0.28026
17	-0.1752	17	-0.2228	17	-0.2704
18	-0.16216	18	-0.21256	18	-0.26296
19	-0.15118	19	-0.20438	19	-0.25758
20	-0.14197	20	-0.19797	20	-0.25397
21	-0.13429	21	-0.19309	21	-0.25189
22	-0.12793	22	-0.18953	22	**-0.25113**
23	-0.12272	23	-0.18712	23	-0.25152
24	-0.11849	24	-0.18569	24	-0.25289
25	-0.11514	25	**-0.18514**	25	-0.25514
26	-0.11253	26	-0.18533	26	-0.25813
27	-0.11059	27	-0.18619	27	-0.26179
28	-0.10922	28	-0.18762	28	-0.26602
29	-0.10835	29	-0.18955	29	-0.27075
30	-0.10793	30	-0.19193	30	-0.27593
31	**-0.10789**	31	-0.19469	31	-0.28149
32	-0.10819	32	-0.19779	32	-0.28739
33	-0.10879	33	-0.20119	33	-0.29359
34	-0.10965	34	-0.20485	34	-0.30005
35	-0.11075	35	-0.20875	35	-0.30675
36	-0.11204	36	-0.21284	36	-0.31364
37	-0.11352	37	-0.21712	37	-0.32072
38	-0.11515	38	-0.22155	38	-0.32795
39	-0.11692	39	-0.22612	39	-0.33532
40	-0.11881	40	-0.23081	40	-0.34281
41	-0.12081	41	-0.23561	41	-0.35041
42	-0.1229	42	-0.2405	42	-0.3581

43	-0.12508	43	-0.24548	43	-0.36588
44	-0.12733	44	-0.25053	44	-0.37373
45	-0.12964	45	-0.25564	45	-0.38164
46	-0.13201	46	-0.26081	46	-0.38961
47	-0.13444	47	-0.26604	47	-0.39764
48	-0.1369	48	-0.2713	48	-0.4057
49	-0.13941	49	-0.27661	49	-0.41381
50	-0.14195	50	-0.28195	50	-0.42195
51	-0.14452	51	-0.28732	51	-0.43012
52	-0.14712	52	-0.29272	52	-0.43832
53	-0.14974	53	-0.29814	53	-0.44654
54	-0.15238	54	-0.30358	54	-0.45478
55	-0.15504	55	-0.30904	55	-0.46304
56	-0.15772	56	-0.31452	56	-0.47132
57	-0.16041	57	-0.32001	57	-0.47961
58	-0.16312	58	-0.32552	58	-0.48792
59	-0.16583	59	-0.33103	59	-0.49623
60	-0.16856	60	-0.33656	60	-0.50456
61	-0.17129	61	-0.34209	61	-0.51289
62	-0.17404	62	-0.34764	62	-0.52124
63	-0.17678	63	-0.35318	63	-0.52958
64	-0.17954	64	-0.35874	64	-0.53794
65	-0.1823	65	-0.3643	65	-0.5463
66	-0.18506	66	-0.36986	66	-0.55466
67	-0.18783	67	-0.37543	67	-0.56303
68	-0.19061	68	-0.38101	68	-0.57141
69	-0.19338	69	-0.38658	69	-0.57978
70	-0.19616	70	-0.39216	70	-0.58816
71	-0.19894	71	-0.39774	71	-0.59654
72	-0.20173	72	-0.40333	72	-0.60493
73	-0.20451	73	-0.40891	73	-0.61331
74	-0.2073	74	-0.4145	74	-0.6217

75	-0.21009	75	-0.42009	75	-0.63009
76	-0.21288	76	-0.42568	76	-0.63848
77	-0.21567	77	-0.43127	77	-0.64687
78	-0.21846	78	-0.43686	78	-0.65526
79	-0.22125	79	-0.44245	79	-0.66365
80	-0.22405	80	-0.44805	80	-0.67205
81	-0.22684	81	-0.45364	81	-0.68044
82	-0.22964	82	-0.45924	82	-0.68884
83	-0.23243	83	-0.46483	83	-0.69723
84	-0.23523	84	-0.47043	84	-0.70563
85	-0.23802	85	-0.47602	85	-0.71402
86	-0.24082	86	-0.48162	86	-0.72242
87	-0.24362	87	-0.48722	87	-0.73082
88	-0.24642	88	-0.49282	88	-0.73922
89	-0.24921	89	-0.49841	89	-0.74761
90	-0.25201	90	-0.50401	90	-0.75601
91	-0.25481	91	-0.50961	91	-0.76441
92	-0.25761	92	-0.51521	92	-0.77281
93	-0.26041	93	-0.52081	93	-0.78121
94	-0.26321	94	-0.52641	94	-0.78961
95	-0.26601	95	-0.53201	95	-0.79801
96	-0.26881	96	-0.53761	96	-0.80641
97	-0.27161	97	-0.54321	97	-0.81481
98	-0.2744	98	-0.5488	98	-0.8232
99	-0.2772	99	-0.5544	99	-0.8316
100	-0.28	100	-0.56	100	-0.84

Table 6.5: Allocation table for Screening System

Screening					
$£_L$=0.001		**$£_L$=0.002**		**$£_L$=0.003**	
$\in$	$f(\in)$	$\in$	$f(\in)$	$\in$	$f(\in)$
1	-1.92605	1	-1.92815	1	-1.93025
2	-1.31082	2	-1.31502	2	-1.31922
3	-0.98121	3	-0.98751	3	-0.99381
4	-0.76732	4	-0.77572	4	-0.78412
5	-0.61594	5	-0.62644	5	-0.63694
6	-0.50337	6	-0.51597	6	-0.52857
7	-0.41698	7	-0.43168	7	-0.44638
8	-0.34926	8	-0.36606	8	-0.38286
9	-0.29536	9	-0.31426	9	-0.33316
10	-0.25201	10	-0.27301	10	-0.29401
11	-0.21686	11	-0.23996	11	-0.26306
12	-0.18822	12	-0.21342	12	-0.23862
13	-0.16479	13	-0.19209	13	-0.21939
14	-0.1456	14	-0.175	14	-0.2044
15	-0.12986	15	-0.16136	15	-0.19286
16	-0.11698	16	-0.15058	16	-0.18418
17	-0.10646	17	-0.14216	17	-0.17786
18	-0.09791	18	-0.13571	18	-0.17351
19	-0.09101	19	-0.13091	19	-0.17081
20	-0.08548	20	-0.12748	20	-0.16948
21	-0.08111	21	-0.12521	21	**-0.16931**
22	-0.07772	22	-0.12392	22	-0.17012
23	-0.07515	23	**-0.12345**	23	-0.17175
24	-0.07329	24	-0.12369	24	-0.17409
25	-0.07201	25	-0.12451	25	-0.17701
26	-0.07124	26	-0.12584	26	-0.18044
27	**-0.07089**	27	-0.12759	27	-0.18429
28	-0.07091	28	-0.12971	28	-0.18851

29	-0.07123	29	-0.13213	29	-0.19303
30	-0.07181	30	-0.13481	30	-0.19781
31	-0.07262	31	-0.13772	31	-0.20282
32	-0.07362	32	-0.14082	32	-0.20802
33	-0.07478	33	-0.14408	33	-0.21338
34	-0.07608	34	-0.14748	34	-0.21888
35	-0.07749	35	-0.15099	35	-0.22449
36	-0.07901	36	-0.15461	36	-0.23021
37	-0.08061	37	-0.15831	37	-0.23601
38	-0.08229	38	-0.16209	38	-0.24189
39	-0.08402	39	-0.16592	39	-0.24782
40	-0.08581	40	-0.16981	40	-0.25381
41	-0.08765	41	-0.17375	41	-0.25985
42	-0.08952	42	-0.17772	42	-0.26592
43	-0.09143	43	-0.18173	43	-0.27203
44	-0.09336	44	-0.18576	44	-0.27816
45	-0.09532	45	-0.18982	45	-0.28432
46	-0.0973	46	-0.1939	46	-0.2905
47	-0.0993	47	-0.198	47	-0.2967
48	-0.10131	48	-0.20211	48	-0.30291
49	-0.10334	49	-0.20624	49	-0.30914
50	-0.10537	50	-0.21037	50	-0.31537
51	-0.10742	51	-0.21452	51	-0.32162
52	-0.10947	52	-0.21867	52	-0.32787
53	-0.11153	53	-0.22283	53	-0.33413
54	-0.1136	54	-0.227	54	-0.3404
55	-0.11567	55	-0.23117	55	-0.34667
56	-0.11774	56	-0.23534	56	-0.35294
57	-0.11982	57	-0.23952	57	-0.35922
58	-0.12191	58	-0.24371	58	-0.36551
59	-0.12399	59	-0.24789	59	-0.37179
60	-0.12608	60	-0.25208	60	-0.37808

61	-0.12817	61	-0.25627	61	-0.38437
62	-0.13026	62	-0.26046	62	-0.39066
63	-0.13235	63	-0.26465	63	-0.39695
64	-0.13444	64	-0.26884	64	-0.40324
65	-0.13653	65	-0.27303	65	-0.40953
66	-0.13863	66	-0.27723	66	-0.41583
67	-0.14073	67	-0.28143	67	-0.42213
68	-0.14282	68	-0.28562	68	-0.42842
69	-0.14492	69	-0.28982	69	-0.43472
70	-0.14702	70	-0.29402	70	-0.44102
71	-0.14911	71	-0.29821	71	-0.44731
72	-0.15121	72	-0.30241	72	-0.45361
73	-0.15331	73	-0.30661	73	-0.45991
74	-0.15541	74	-0.31081	74	-0.46621
75	-0.15751	75	-0.31501	75	-0.47251
76	-0.15961	76	-0.31921	76	-0.47881
77	-0.16171	77	-0.32341	77	-0.48511
78	-0.1638	78	-0.3276	78	-0.4914
79	-0.1659	79	-0.3318	79	-0.4977
80	-0.168	80	-0.336	80	-0.504
81	-0.1701	81	-0.3402	81	-0.5103
82	-0.1722	82	-0.3444	82	-0.5166
83	-0.1743	83	-0.3486	83	-0.5229
84	-0.1764	84	-0.3528	84	-0.5292
85	-0.1785	85	-0.357	85	-0.5355
86	-0.1806	86	-0.3612	86	-0.5418
87	-0.1827	87	-0.3654	87	-0.5481
88	-0.1848	88	-0.3696	88	-0.5544
89	-0.1869	89	-0.3738	89	-0.5607
90	-0.189	90	-0.378	90	-0.567
91	-0.1911	91	-0.3822	91	-0.5733
92	-0.1932	92	-0.3864	92	-0.5796

93	-0.1953	93	-0.3906	93	-0.5859
94	-0.1974	94	-0.3948	94	-0.5922
95	-0.1995	95	-0.399	95	-0.5985
96	-0.2016	96	-0.4032	96	-0.6048
97	-0.2037	97	-0.4074	97	-0.6111
98	-0.2058	98	-0.4116	98	-0.6174
99	-0.2079	99	-0.4158	99	-0.6237
100	-0.21	100	-0.42	100	-0.63

Table 6.6 Allocation table for Paper making System

Paper making unit					
$£_L=0.001$		**$£_L=0.002$**		**$£_L=0.003$**	
$\in$	$f(\in)$	$\in$	$f(\in)$	$\in$	$f(\in)$
1	-2.65886	1	-2.66236	1	-2.66586
2	-2.00498	2	-2.01198	2	-2.01898
3	-1.63834	3	-1.64884	3	-1.65934
4	-1.38905	4	-1.40305	4	-1.41705
5	-1.20385	5	-1.22135	5	-1.23885
6	-1.05903	6	-1.08003	6	-1.10103
7	-0.94195	7	-0.96645	7	-0.99095
8	-0.84505	8	-0.87305	8	-0.90105
9	-0.76346	9	-0.79496	9	-0.82646
10	-0.69386	10	-0.72886	10	-0.76386
11	-0.63388	11	-0.67238	11	-0.71088
12	-0.58177	12	-0.62377	12	-0.66577
13	-0.53621	13	-0.58171	13	-0.62721
14	-0.49615	14	-0.54515	14	-0.59415
15	-0.4608	15	-0.5133	15	-0.5658
16	-0.42947	16	-0.48547	16	-0.54147
17	-0.40165	17	-0.46115	17	-0.52065
18	-0.37688	18	-0.43988	18	-0.50288
19	-0.3548	19	-0.4213	19	-0.4878
20	-0.33509	20	-0.40509	20	-0.47509

21	-0.31748	21	-0.39098	21	-0.46448
22	-0.30175	22	-0.37875	22	-0.45575
23	-0.2877	23	-0.3682	23	-0.4487
24	-0.27515	24	-0.35915	24	-0.44315
25	-0.26395	25	-0.35145	25	-0.43895
26	-0.25398	26	-0.34498	26	-0.43598
27	-0.24512	27	-0.33962	27	-0.43412
28	-0.23726	28	-0.33526	28	**-0.43326**
29	-0.23032	29	-0.33182	29	-0.43332
30	-0.2242	30	-0.3292	30	-0.4342
31	-0.21884	31	-0.32734	31	-0.43584
32	-0.21418	32	-0.32618	32	-0.43818
33	-0.21015	33	**-0.32565**	33	-0.44115
34	-0.2067	34	-0.3257	34	-0.4447
35	-0.20378	35	-0.32628	35	-0.44878
36	-0.20134	36	-0.32734	36	-0.45334
37	-0.19936	37	-0.32886	37	-0.45836
38	-0.19779	38	-0.33079	38	-0.46379
39	-0.19659	39	-0.33309	39	-0.46959
40	-0.19575	40	-0.33575	40	-0.47575
41	-0.19523	41	-0.33873	41	-0.48223
42	-0.19501	42	-0.34201	42	-0.48901
43	**-0.19506**	43	-0.34556	43	-0.49606
44	-0.19536	44	-0.34936	44	-0.50336
45	-0.1959	45	-0.3534	45	-0.5109
46	-0.19665	46	-0.35765	46	-0.51865
47	-0.1976	47	-0.3621	47	-0.5266
48	-0.19874	48	-0.36674	48	-0.53474
49	-0.20005	49	-0.37155	49	-0.54305
50	-0.20152	50	-0.37652	50	-0.55152
51	-0.20313	51	-0.38163	51	-0.56013
52	-0.20488	52	-0.38688	52	-0.56888

53	-0.20675	53	-0.39225	53	-0.57775
54	-0.20874	54	-0.39774	54	-0.58674
55	-0.21084	55	-0.40334	55	-0.59584
56	-0.21304	56	-0.40904	56	-0.60504
57	-0.21534	57	-0.41484	57	-0.61434
58	-0.21772	58	-0.42072	58	-0.62372
59	-0.22017	59	-0.42667	59	-0.63317
60	-0.22271	60	-0.43271	60	-0.64271
61	-0.22531	61	-0.43881	61	-0.65231
62	-0.22797	62	-0.44497	62	-0.66197
63	-0.2307	63	-0.4512	63	-0.6717
64	-0.23348	64	-0.45748	64	-0.68148
65	-0.23631	65	-0.46381	65	-0.69131
66	-0.23919	66	-0.47019	66	-0.70119
67	-0.24211	67	-0.47661	67	-0.71111
68	-0.24507	68	-0.48307	68	-0.72107
69	-0.24808	69	-0.48958	69	-0.73108
70	-0.25111	70	-0.49611	70	-0.74111
71	-0.25418	71	-0.50268	71	-0.75118
72	-0.25728	72	-0.50928	72	-0.76128
73	-0.26041	73	-0.51591	73	-0.77141
74	-0.26356	74	-0.52256	74	-0.78156
75	-0.26674	75	-0.52924	75	-0.79174
76	-0.26994	76	-0.53594	76	-0.80194
77	-0.27317	77	-0.54267	77	-0.81217
78	-0.27641	78	-0.54941	78	-0.82241
79	-0.27967	79	-0.55617	79	-0.83267
80	-0.28294	80	-0.56294	80	-0.84294
81	-0.28624	81	-0.56974	81	-0.85324
82	-0.28954	82	-0.57654	82	-0.86354
83	-0.29287	83	-0.58337	83	-0.87387
84	-0.2962	84	-0.5902	84	-0.8842

85	-0.29954	85	-0.59704	85	-0.89454
86	-0.3029	86	-0.6039	86	-0.9049
87	-0.30627	87	-0.61077	87	-0.91527
88	-0.30964	88	-0.61764	88	-0.92564
89	-0.31303	89	-0.62453	89	-0.93603
90	-0.31642	90	-0.63142	90	-0.94642
91	-0.31982	91	-0.63832	91	-0.95682
92	-0.32323	92	-0.64523	92	-0.96723
93	-0.32664	93	-0.65214	93	-0.97764
94	-0.33006	94	-0.65906	94	-0.98806
95	-0.33349	95	-0.66599	95	-0.99849
96	-0.33692	96	-0.67292	96	-1.00892
97	-0.34035	97	-0.67985	97	-1.01935
98	-0.34379	98	-0.68679	98	-1.02979
99	-0.34724	99	-0.69374	99	-1.04024
100	-0.35068	100	-0.70068	100	-1.05068

Table 6.7 Allocations for different values of Lagrange's multipliers

	£ =0.001	**£=0.002**	**£=0.003**
Optimum allocation	23,28,31,27,43	20,23,25,23,33	18,20,22,21,28
Maintenance cost	152	124	109
Manpower cost	109.36	89.22	78.42
Optimum overall availability	89.96%	80.36%	72.39%

6.4 PROFIT ANALYSIS

The results given in Tables 6.7 guide process engineer to choose an appropriate level of maintenance according to his factory requirements. However, a certain minimum level must be maintained, so as to achieve minimum required profit. The analysis also indicates that system availability increases with the increases of maintenance and manpower cost. Profit increases with the increase of availability and fluctuates with the increase of the variable cost, i.e. maintenance cost + manpower cost.

- Earning of Sales (EOS) = Total cost x optimum overall availability, where total cost is assumed as 1000 units.
- Considering that the net sales are proportional to system availability (assuming fixed cost to be about 30% to the total cost), the relation for the cost of sales (C_s) is given as

C_s=maximum availability x (maintenance cost + manpower cost) + Fixed cost

- Profit=EOS-COS
- Break Even Point (BEP) = Fixed cost / [Total cost-(Maintenance cost + Manpower cost)]

Table 6.8 PROFIT ANALYSIS

	£=0.001	**£=0.002**	**£=0.003**
Optimum overall availability	89.96%	80.36%	72.39%
Earning of sales	899.6	803.6	723.9
Cost of sales	535.1	471.3	435.7
Profit	364.5	332.3	288.2
BEP	40.6%	38.13%	36.9%

Based on the results shown in Tables 6.8 economic production charts (cost of sales vs system availability) are plotted and breakeven point is determined and shown in Figure 6.1 to 6.3.

Figure 6.1 shows the economic production chart for paper plant indicating that the minimum run point of the plant is 40.6% (called BEP). Further, it is noted that if optimum overall availability is less than 40.6%, then there would be loss and if system availability is more than 40.6%, then there would be a profit margin, which further increases with increase in optimum overall availability.

Similarly, based on the information mentioned in Table 6.8 (for $£_L$ = 0.002), a graph is plotted as shown in Figure 6.2, which shows that B.E.P. is relatively low i.e. 38.13% at $£_L$= 0.002. It is evident that if optimum overall availability is less than 38.13%, then there would be loss and if system availability is more than 38.13%, then there would be a profit margin, which further increases with increase in optimum overall availability.

Similarly, based on the information presented in Table 6.8 (for £$_L$ = 0.003), a graph is plotted as shown in figure 6.3, which describes that B.E.P. is least i.e. 36.9% at £$_L$ = 0.003. Further, if optimum overall availability is less than 36.9%, then there would be loss and if system availability is more than 36.9%, then there would be a profit margin, which further increases with increase in optimum overall availability.

From the above discussions, it is evident that as £$_L$ increases, the value of B.E.P. decreases and it moves to the left. It implies that with increase in the value of £$_L$, no profit no loss point (B.E.P.) can be attained even at lower availability level. So, as £$_L$ increases, the profit margin also increases. The profit analysis presented herein will help the plant engineers to consider the application of optimization techniques in making a decision regarding allocation of maintenance resources to the plant concerned.

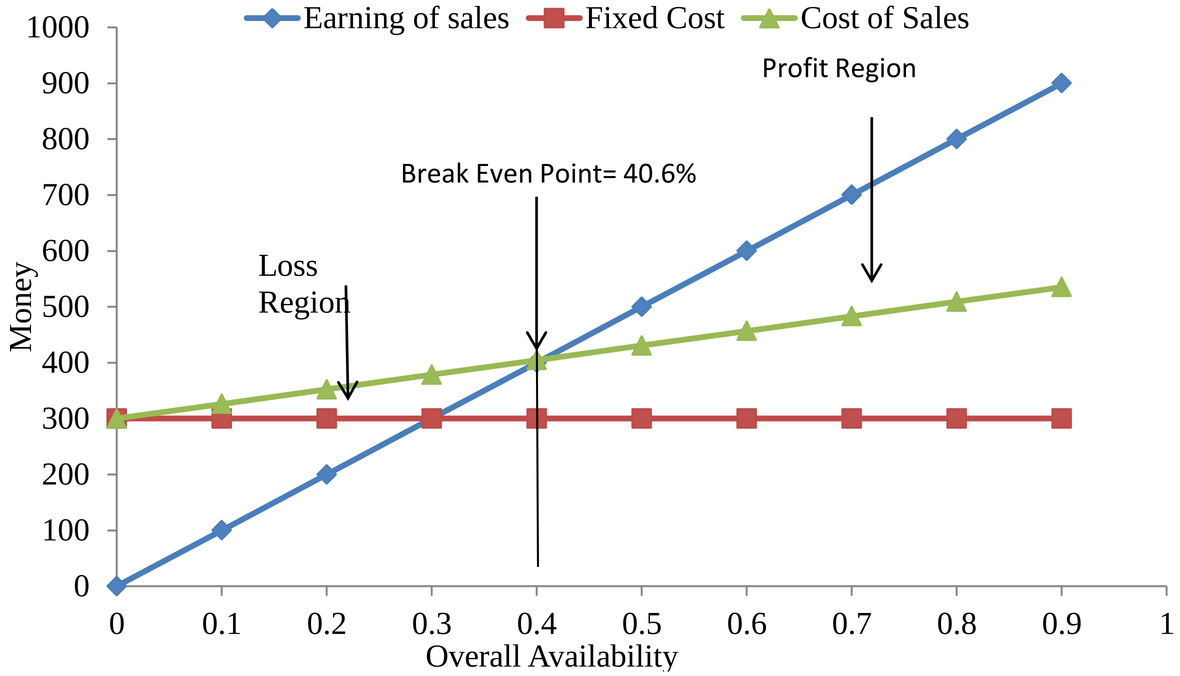


Figure 6.1 Allocated money vs. overall availability graph (£=0.001)

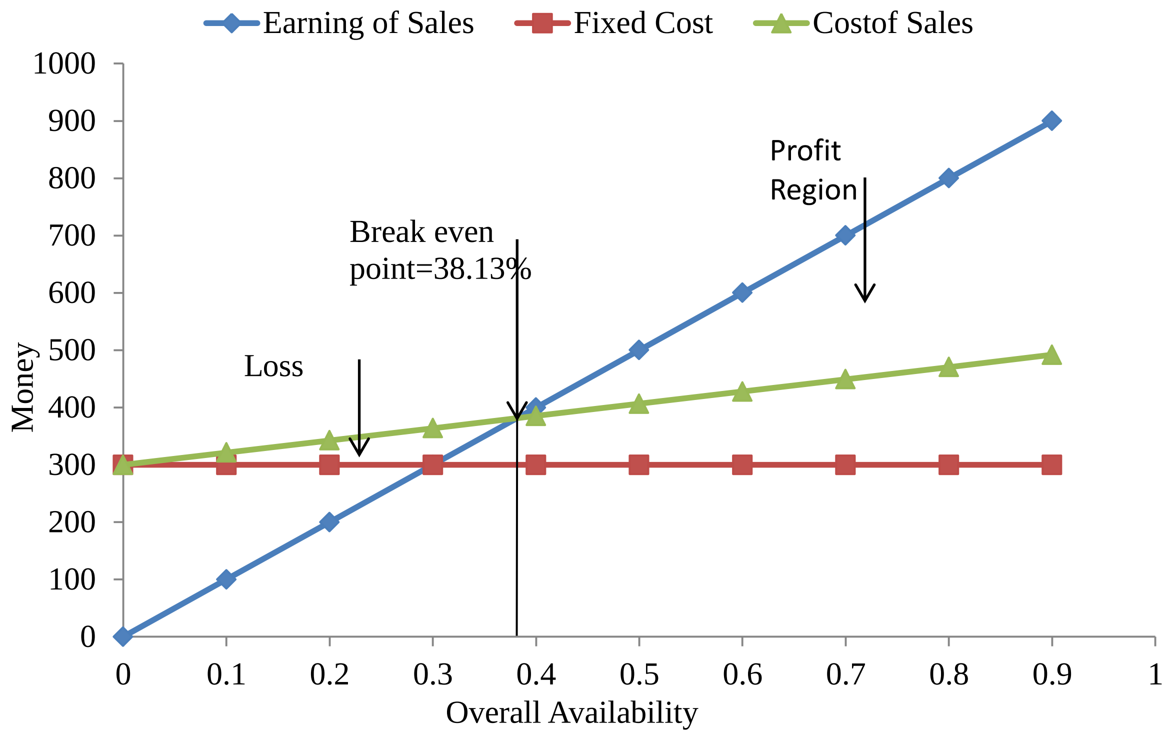


Figure 6.2 Allocated money vs. overall availability graph (£=0.002)

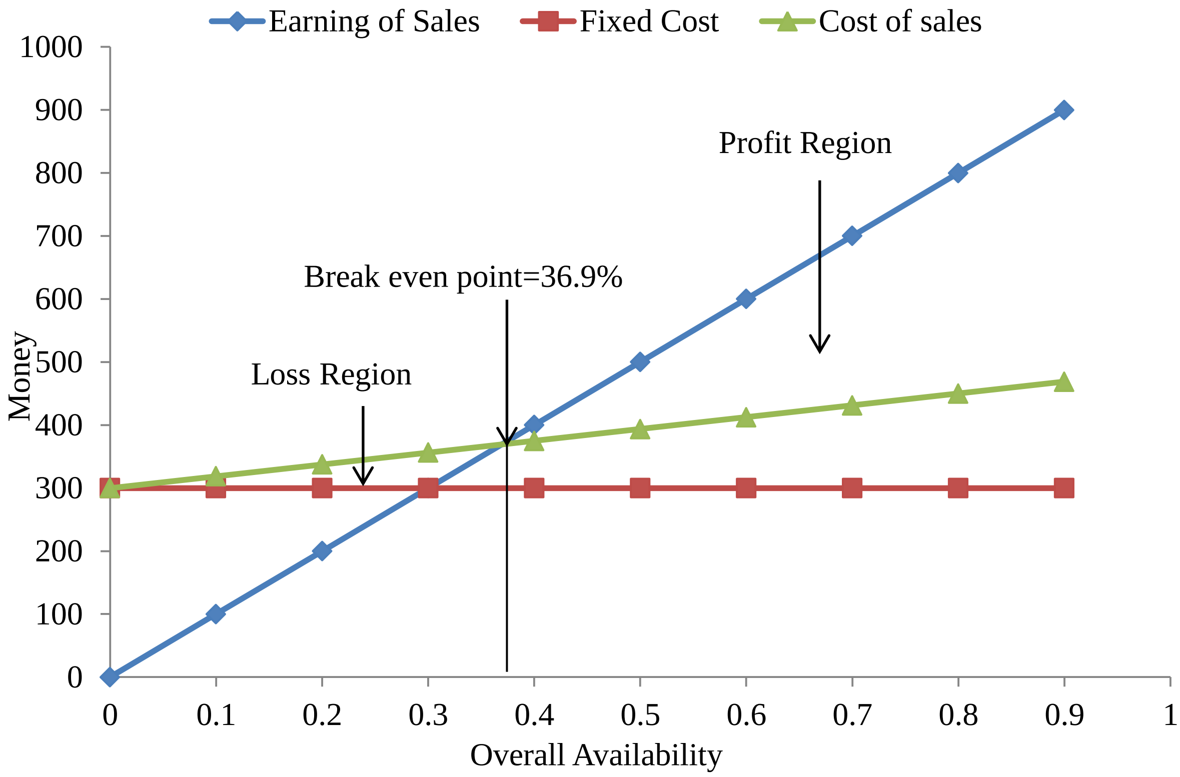


Figure 6.3 Allocated money vs. overall availability graph (£=0.003)

CHAPTER VII

CONCLUSION AND SCOPE FOR FUTURE WORK

7.1 CONCLUSION

The chapter presents a comprehensive summary of the major contributions made in previous chapter of this thesis. It also outlines the managerial implications for the purpose of implementation of recommendations in the industrial systems. Finally the suggestions for future work to extend the frontiers of the research reported in the thesis have been enumerated.

Repairable systems have become complex and expensive to operate and maintain. Increasing attention is being given to savings of cost during production, operation and maintenance of the repairable systems. A focused research attention is being accorded to the reliability based analysis and optimization of the maintenance and operational activities considered in recent years. The advances in technology, and growing complexity of technological systems, have increased the importance of reliability and maintainability manifold. This is especially true in the process industry, characterized by expensive specialized equipment and stringent environmental considerations. The job of reliability/maintenance engineers is more challenging in the process industries as they attempt to study, characterize measure and analyse the behaviour and performance of such systems.

The detailed literature on various issues related to reliability, availability and maintainability aspect of repairable systems have been studied. The literature was classified into different related categories such as reliability and availability modelling, Markov approach, maintenance planning and resource allocation. Literature review on the methodologies used in the research such as RCA, FMECA, AHP, integrated cloud model and PROMETHEE II have been discussed.

Root cause analysis (RCA) of all the systems of paper production plant was carried out which helped to provide comprehensive classification of causes related to anomalous performance of the subsystems/units. After the identification of critical components/units, the data related to failure and maintenance history of these components/units of various systems was collected from the log records of the paper production plant. The various performance parameters of systems such as availability, was computed for the various systems of the paper plant. The Markovian approach was used to analyse the behaviour and performance of the system. Sensitivity analysis of all systems has been performed to examine the effect of failure/repair times of each unit on systems performance parameters.

Taking note of limitations of traditional FMECA approach, a new methodology based on integrated cloud model and PROMETHEE II for evaluating the maintenance criticality for failure causes is also proposed in the thesis.

Research contributions of the present thesis are methodological in terms of real industrial applications. An attempt has been made to critically analyse RAM issues in industrial systems especially processing plants.

The significant research contributions of the study are summarized as follows:

1. The study provides comprehensive review of literature and identifies the contemporary issues related to the reliability, availability and maintainability (RAM) analysis in processing industries.
2. The qualitative analysis of systems of paper production plant using Root Cause Analysis (RCA) helped to create a knowledge base to deal with problems related to process/product unreliability by listing out all possible failure causes. The identification of failure causes further assisted in examining the failure history of the systems for further analysis.
3. The actual failure and repair data of a paper production plant was collected and using this data performance model for some systems of a paper plant have been developed using the probabilistic approach to evaluate system’s performance.
4. Steady state availability expressions have been derived and from the analysis, the decrease in availability is observed with increase in failure rates of various subsystems of paper production plant. Further, as the repair rates of various subsystems are increased, the availability is found to be increased. Thus, performance of Paper plant can be improved by increasing the repair rates and reducing the failure rates of various subsystems of all five systems. Desired level of performance has been established and feasible combination of failure and repair rates have been determined as given below

Table 7.1 Feasible combinations of failure and repair rates

Systems	Desired Availability	Failure Rates and Repair Rates
Feeding System	93%	Ψ_1=0.009, Φ_1=0.12, Ψ_2=0.05, Φ_2=0.3, Ψ_3=0.015, Φ_3=0.125
Pulping System	94%	Ψ_4=0.003, Φ_4=0.07, Ψ_5=0.006, Φ_5=0.3, Ψ_6=0.01, Φ_6=0.12, Ψ_7=0.004,0.006, Φ_7=0.2, 0.3, Ψ_8=0.0175, Φ_8=0.1
Bleaching and Washing System	95%	Ψ_9=0.004, Φ_9=0.2, Ψ_{10}=0.0039, Φ_{10}=0.25, Ψ_{11}=0.00725, Φ_{11}=0.4, Ψ_{12}=0.003, Φ_{12}=0.2, Ψ_{13}=0.0055, Φ_{13}=0.6, Ψ_{14}=0.0055, Φ_{14}=0.3
Screening System	92%	Ψ_{15}=0.004, Φ_{15}=0.25, Ψ_{16}=0.009, Φ_{16}=0.2 Ψ_{17}=0.008, Φ_{17}= 0.45, Ψ_{18}=0.006, Φ_{18}=0.6
Paper Production System	87%	Ψ_{19}=0.0038, Φ_{19}=0.085, Ψ_{20}=0.0050, Φ_{20}=0.16, Ψ_{21}=0.0013, Φ_{21}=0.35, Ψ_{22}=0.0012, Φ_{22}=0.054, Ψ_{23}=0.006, Φ_{23}=0.18, Ψ_{24}=0.005, Φ_{24}=0.16, Ψ_{25}=0.0045, Φ_{25}=0.24

5. It is further concluded that blower subsystem in the feeding system, digester subsystem in the pulping system, cleaner subsystem in bleaching and washing system, vibrating screen subsystem in screening system and steam handling subsystem in paper production system are most critical and require immediate attention in case of any breakdown; as the effect of their states nature/courses of action (failure/ repair rates) on the system availability is very high. Their high failure rates result in to sharp decrease in system availability.
6. To address the seriously debated disadvantages associated with traditional procedure for conducting FMECA, a new maintenance decision support system based on integrated cloud model and PROMETHEE II is proposed for determining maintenance criticality. This was evaluated by considering more number of criteria i.e. chance of failure, chance of non-detection, downtime length, spare parts criticality and safety factor than the Risk Priority Number (RPN) of traditional FMECA which is based on three criteria i.e. Chance of failure, chance of non-detection, and severity. The introduction of weighing

coefficient provides the system analyst more flexibility to decide which criteria is more important and needs to be given more importance. The use of cloud model helps the system managers to deal with uncertainty and imprecision related with the qualitative maintenance data more realistically. The proposed approach will help the system managers to plan suitable maintenance practices/strategies in more realistic manner for improving system performance.

7. For the desired availability level, to determine the profit margin, the available maintenance resources (manpower and money) have been allocated using dynamic programming method. The optimal values of stage allocations ($\in_0$) and state functions $f(\in_0)$ have also been achieved for given values of $£_L$ as shown in Table 7.2.

Table 7.2 Optimal values of stage allocations ($\in_0$) and state functions $f(\in_0)$.

Stage	**System**	**$£_L$=0.001**		**$£_L$=0.002**		**$£_L$=0.003**	
		$\in_0$	$f(\in_0)$	$\in_0$	$f(\in_0)$	$\in_0$	$f(\in_0)$
1	Feeding	23	-0.03833	20	-0.06796	18	-0.09429
2	Pulping	28	-0.098064	23	-0.168938	20	-0.229875
3	Bleaching and Washing	31	-0.10789	25	-0.18514	22	-0.25113
4	Screening	32	-0.07089	23	-0.12345	21	-0.16931
5	Paper Making	43	-0.19506	33	-0.32565	28	-0.43326

8. The graphs between overall availability and money allocated for given values of $£_L$ have been plotted and Break Even Points (B.E.P) have also been marked. The availability levels, for desired profit target are observed from the graphs. Also, the effect of $£_L$ on profit margin and B.E.P. has been analysed. Further, the minimum desired availability is available from B.E.P. in the graphs and for profit margin, the availability level must be maintained above B.E.P.

7.2 Limitation of Present Research work

The research work and method of analysis reported in this thesis possess some limitations as given below:

1. Due to mathematical complexities, availability is performed by assuming exponential distribution for failure and repair times.
2. In present work, failure and repair rates are assumed to be constant.
3. The performance analysis of each unit of a particular process industry is carried out by assuming the steady state conditions.
4. Too much calculation is contained in the implementation of the proposed Cloud and PROMETHEE II model to derive the critical ranking of failure causes.
5. In the present work we used fixed weight of decision maker's member for all the failure causes.

7.3 Scope for Future Research Work

The research work and method of analysis reported in this thesis can further be extended as given below:

1. The performance of process can be evaluated as a whole instead of evaluating the performance of various independent systems.
2. In present work, failure and repair rates are assumed to be constant, while the research work can be extended for variable repair and failure rates.
3. The time dependent differential equations may be tried to solve. So in future, the performance analysis can be done for transient behaviour of each unit of a particular process industry.
4. Too much calculation is contained in the implementation of the proposed Cloud and PROMETHEE II model to derive the critical ranking of failure causes. Therefore, a specialized software tool should be developed for the execution of the proposed risk evaluation approach for real applications.
5. In the proposed model we used fixed weight of decision maker's member for all the failure causes therefore in future research, it would be interesting to develop a method for assigning diverse weights to decision makers according to the failure cause to obtain more reliable risk ranking results.
6. For allocation of various resources i.e. manpower, material and money etc., the performance modeling can also be carried out as multi objective and multi constraint problem.

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LIST OF PUBLICATIONS OUT OF THESIS

1. List of Published Papers (04)

S. No	Title of the paper along with volume, Issue No, year of publication	Publisher	Impact factor	Refereed or Non-Refereed	Whether you paid any money or not for publication	Remarks
1	Critical ranking of steam handling unit by using integrated cloud model and extended PROMETHEE for maintenance purpose, Complex & Intelligent Systems, 7(1),2021.	Springer	5.277	Refereed	-	Science Citation Index Expanded
2	AHP-VIKOR-based methodology for determining maintenance criticality, International Journal of Productivity and Quality Management, 29(2), 2020	Inderscience	-	Refereed	-	SCOPUS
3.	Stochastic Modelling and Performance Analysis of Feeding Unit in Paper Plant, International Journal of Mathematics in Operational Research, 19(3), 302-316	Inderscience	-	Refereed	-	SCOPUS
4	A literature review on maintenance planning and resource	International Journal of Engineering Sciences Paradigms	-	Refereed	-	UGC

	allocation, International Journal of Engineering Sciences Paradigms and Researches (IJESPR) 48(special issue), 2019	and Researches (IJESPR)				

2. List of Accepted Papers in International Journals (01)

S. No	Title of the paper along with volume, Issue No, year of publication	Publisher	Impact factor	Referred or Non-Referred	Whether you paid any money or not for publication	Remarks
1	Availability analysis using Markovian approach and Maintenance Planning of a process industry, International Journal of Industrial and Systems Engineering	Inderscience	-	Refereed	-	SCOPUS

3. List of Communicated Papers (01)

S. No	Title of the paper	Journal Name	Publisher	Remarks	Status
1	Mathematical Modelling and Performance Analysis of Screening Unit in Paper Plant	International Journal of System Assurance Engineering and Management	Springer	Emerging Sources Citation Index	Under Revision

4. List of Papers in International/National Conferences (03)

S. No	Title of the paper	Conference Name	Publisher
1	Critical Ranking of Failure Causes of Opener Subsystem using TOPSIS	International Conference on Advances in Power Generation from Renewable Energy Resources (APGRES-2020)	-
2.	A literature review on maintenance policy optimization technique.	National Conference on Trends and Advances in Mechanical Engineering (TAME-2017)	-
3.	Criticality Analysis of Cleaner subsystem using Fuzzy AHP and PROMETHEE II	International Conference on Trends and Advances in Mechanical Engineering (TAME-2021)	-