"DESIGN FOR SYSTEM AVAILABILITY IMPROVEMENT THROUGH REDUNDANCY AND MAINTENANCE"

TO BE SUBMITTED AS MAJOR PROJECT IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF

MASTERS IN TECHNOLOGY

Submitted by

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CERTIFICATE

This is to certify that the dissertation entitled **Design for System Availability Improvement Through Redundancy and Maintenance** in the partial fulfillment of the requirements for the reward of the degree of Masters in Technology, Delhi Technological University (Formerly Delhi College of Engineering, University of Delhi), is an authentic record of the candidate's own work carried out by him under my guidance**.** The information and data enclosed in this thesis is original and has not been submitted elsewhere for honoring of any other degree**.**

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ACKNOWLEDGEMENT

Research is a higher concept. It brings to test our patience, vigor and dedication. Every result arrived is a beginning for a higher achievement. My project is a small drop in an ocean. It needs the help of friends and guidance of experts in the field, to achieve something new.

I found my pen incompetent to express my thanks to my supervisor Dr. Girish Kumar, Assoc. Professor, DTU under whose kind and worthy guidance and supervision I had the opportunity to carry out this work. It was only due to his advice, thoughtful comments, constructive criticism, and continuous vigil over the progress of my work with personal interest that it has taken this shape. He has been a great source of encouragement.

To get an opportunity to carry out the project work in the well-equipped, ever developing laboratories in our institution, I would like to pay my deep sense of thankfulness to HOD, Department of Mechanical Engineering, DTU.

I would especially like to acknowledge my gratitude to all my dear friends for their consistent support, valuable suggestions from time to time to make this project worthy.

With a silent prayer to the almighty I take this opportunity to express my gratitude to all those who have supported me in completing my second semester project work as a part of my degree program.

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DECLARATION

I, **Ashish Ranjan**, hereby certify that the work which is being presented in this thesis entitled "**Design for System Availability Improvement through Redundancy and Maintenance**", is submitted, in the partial fulfillment of the requirements for degree of Master of Technology at Delhi Technological University is an authentic record of my work carried under the supervision of **Dr. Girish Kumar**. I have not submitted the matter embodied in this report for the award of any other degree or diploma it has not been directly copied from any source without giving its proper reference.

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ABSTRACT

In this project system availability is improved through redundancy and maintenance. For system modeling, Markovian approach is used. The effect of redundancies on system models is studied by increasing the level of redundancies on various components. For system model development, binary states are considered at component level.

System rate diagram is developed considering the states and transitions. Transition leads to change of states due to failure or repair. Subsequently, mathematical model of the rate diagram is formulated in terms of rate of change of probabilities of the respective states. Further, set of rate equations is solved by Ranga Kutta method in MATLAB. For proposed methodology is illustrated by a power plant system. This work will be useful to the practicing power plant engineers for improving the power plant availability; also this will be helpful for system designers in designing the system with availability considerations. The importance of improving system availability can be analysis by considering critical system like aircrafts wherein failure not only impacts business financially but also can lead to fatal accidents.

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LIST OF ABBREVIATIONS

Sr. No.	Terms	
1	MTF	Mean Time to Failure
2	MTR	Mean Time to Repair
3	MTBF	Mean Time Between Failure
4	MDT	Mean Down Time
5	MTBM	Mean Time Between Maintenance
6	DUC	Device Under Control
7	MRP	Markov Renewal Process
8	SMP	Semi Markov Process
9	MAP	Markov Arrival Process
10	TPM	Total Productive Maintenance
11	PM	Preventive Maintenance
12	LHS	Left Hand Side
13	RHS	Right hand Side

LIST OF SYMBOL

Sr. No.	Terms	
1	K	Failure rate
2	U	Repair rate
3	Y	Transition state
4	T	Time
5	O	Operating
6	F	Failed
7	S	Steady
8	NF	Not-Feasible
9	P(t)	Probability of a particular state at time t

CONTENTS

CHAPTER 1

INTRODUCTION

This chapter gives an overview of the problem and highlights issues that are relevant to the system availability.

1.1 Motivation / Relevance

The idea behind presenting this work is improving the downtime that any industrial system undergoes that hampers its productivity.

1.2 Overview

Availability is defined as the probability that the system is operating properly when it is requested for use [1]. In other words, availability is the probability that a system is not failed or undergoing a repair action when it needs to be used. In simple mathematical terms, availability is the ratio of the time that the system is available for use to the total time. Various attempts are made to increase the availability of the system.

Availability of system is improved by repairing the component before they fail and providing a component in parallel to the component which has a high tendency of failure so that even if the primary component fails the other one would replace it and system can continue functioning. In today world, the most part of the operating cost of the system or component is basically the cost incurred during maintenance.

1.3 Current status of work

Availability analysis in the literature is mainly restricted to simple series system. However in modern industries, systems are complex and critical in nature. This requires their higher availabilities. However, the time to failure of mechanical systems follow a Weibull distribution.

Another limitation of the work done until now is the analysis of only a single to three component system. Limitation of the literature also extends to the fact that only binary level of failure is considered which is although simple but lacks accuracy. The analysis of a four components system incorporating maintenance and redundancy through Markov model has been attempted in this work.

1.4 Organization of Report

The work presented in this thesis has been organized in seven chapters. Chapter 2 deals with the review of the literature mainly on two aspects. First the application areas/field for system availability assessment and improvement and secondly the various methodologies used for assessment and improvement.

Chapter 3 discusses the basic terminology involved in availability analysis and various types of redundancies and different maintenance policies. Chapter 4 provides overview of the approaches to be used for the modeling of the system and its analysis. Chapter 5 deals with the system description, development of the system model and its analysis. Chapter 6 presents the results and analysis. Finally, chapter 7 concludes the thesis and gives the future direction for the work.

CHAPTER 2

LITERATURE REVIEW

This chapter deals with the review of the literature and highlight issues that are relevant to system availability. It analyzes the work already done in this field and the gaps in research works.

2.1 Availability Analysis - Literature

A literature dealing with availability of system and operation research has been reported. Mostly the work is based on certain distribution or various models, so the approach of analysis of system is basically theoretical.

Jindal (2012) discussed behavioral analysis of a single unit system with server failure. The author discussed availability analysis of two unit system, in which one can work in reduced capacity a single unit Redundant System having imperfect switch over device with a single repair facility. [2]

Chen and Trivedi (2007) studied systems with major preventive maintenance (PM) and formulated general expressions for system availability under general failure, repair, and maintenance distributions. Authors also developed models considering both major and minor PM activities, where simulations and analytical approaches were respectively employed. [3]

Taneja and Minocha (2005) discussed the reliability of an ash handling plant. System is described as having three pumps to evaluate various parameters of availability and system reliability. Authors analyzed the system reliability and optimization analysis considering hot standby condition. [4]

Narmada and Varghese (1997) introduced the concept of a ‘base-state’, useful for finding all the key parameters of the system under steady state conditions. The authors presented an analytical approach for finding optimum interchange time of units for giving rest to the operative unit. [5]

Chan & Asgarpoor (2006) presented a method to find the optimum maintenance policy for a component considering random failures and failures due to deterioration. [6]

Barabady (2005) identified the critical and sensitive subsystems or components of the system that need more attention for improvement along with studying the criticality and sensitivities of the components of the system for continuous improvement. [7]

Kurien (2011) proposed a discrete event simulation model using time between successive failures of the sub system wherein live data of a trainer aircraft from fleet operation is used for the purpose of operation. The research helped in identifying complexities of aging repairable system. [8]

Zhao (2006) discussed the imperfect status of repairable component in series system. He proposed the presence of alternating renewable process in the failure pattern of repairable component implying that the failed component is repaired. [9]

Lev (2001) studied the fuzzy reliability of repairable system in context of probability wherein he identified the time dependent availability and unavailability in context of probability described by necessity distribution functions. [10]

Wang (2013) presented the analysis in terms of cost of a machine repairable system with several work station wherein the most feasible state is analysis for overall compatibility of a machine repairable system. [11]

Hokstad (2005) discussed the failure intensity process and reliability and maintenance model formulation which provides framework for analysis of repairable and non repairable items, preventive as well as corrective maintenance and is applicable for dormant failure. [12]

Ansell (2007) studied practical aspects of modeling repairable systems using Cox's proportional hazard methods which present the work as emiparametric allowing weak assumptions about the form of hazard function. [13]

Lal, Bhatia, Reddy (1999) developed a methodical scheme based on theory of boolean algebra and Markov and simultaneously introduced a new numerical approach for evaluating transient computation of Markovian system of equations obtained by using supplementary variable technique. The authors incorporated different numerical methods including Finite Difference Methods, Lagrange's interpolation method and Simpson's one-third method. [14]

Jain & Gupta (2007) incorporated common cause breakdown giving the major crash on the system performance. The authors dealt with the availability analysis of a redundant system comprising of N-non-identical components and S warm standby components under the care of single repair facility. [15]

2.2 Research Gaps

After going through the literature review in the section 2.1, following research gaps are identified:

- Availability improvement through redundancy at component level has not been attempted.
- Availability improvement through redundancy and maintenance is not reported in the literature.
- Further there are limited literature available applying Markovian approach for availability modeling with redundancy and maintenance.

Based on the above research gaps, following objectives are formulated:

1. To improve system availability through redundancy at component level.

2. To develop a availability model with redundancy and maintenance.

3. To apply Markovian approach for availability modeling and analysis.

CHAPTER 3

AVAILABILITY AND MAINTENANCE THEORIES

This chapter deals with theories required for modeling for system and provide an overview availability, maintenance and redundancy of the system.

3.1 AVAILABILITY THEORIES

This section introduces basis concepts of availability and related terminology.

3.1.1 Availability Overview

Availability is defined as the probability that the system is available to be utilized when it is requested to use. Mathematically, it is the ratio of the total time that the system is functional to the total time that the system is requested for use. [16]

System availability depends up on the availability of various other sub systems like hardware, software, humans, interfaces and the process itself. Availability issues deal with mainly three major factors [17] for:

- Escalating time to failure,
- Lessening downtime because of repairs or scheduled maintenance
- Cost effective manner to achieve above points.

As availability grows, the capacity for making money increases because the equipment is in service a larger percent of time.

As stated earlier, availability represents the probability that the system is capable of conducting its required function when it is called upon given that it is not failed or undergoing a repair action. Therefore, it is a function of reliability and maintanability. Not only is availability a function of reliability, but it is also a function of maintainability. Given below is a table showing the relation between availability, reliability and maintainability.

Table 3.1: **Relation of R-A-M**

Reliability	**Maintainability**	**Availability**
Constant	Decreases	Decreases
Constant	Increases	Increases
Increases	Constant	Increases
Decreases	Constant	Decreases

Refer table 3.1, if the reliability is held constant, even at a high value, this does not directly imply a high availability. As the time to repair increases, the availability decreases. Even a system with a low reliability could have a high availability if the time to repair is short. [22]

Commonly used terms in reliability theory are defined in the following manners

- **Mean Time To Failure** (MTTF)

  Mean time to Failure is the average time interval connecting two successive failures. Often referred to as "uptime" in the IT industry, the length of time that a system is online between outages or failures can be thought of as the "time to failure" for that system.

- **Mean Time To Repair** (MTTR)

  Mean Time to Repair (MTTR) is the time desirable to revamp a futile hardware module. In an equipped system, repair normally means replacing a failed hardware part. Thus, hardware MTTR can definitely be viewed as mean time to reinstate a failed hardware module.

- **Mean Time Between Failure** (MTBF)

  Mean Time between Failure (MTBF) is a reliability term used to make available the quantity of failures per million hours for a product. This is the most common inquiry about a product’s life span, and is important in the decision-making process of the end user.

It is quite clear from the above definitions that Mean time between failure if the sum of both means time to failure and mean time to repair. [23]

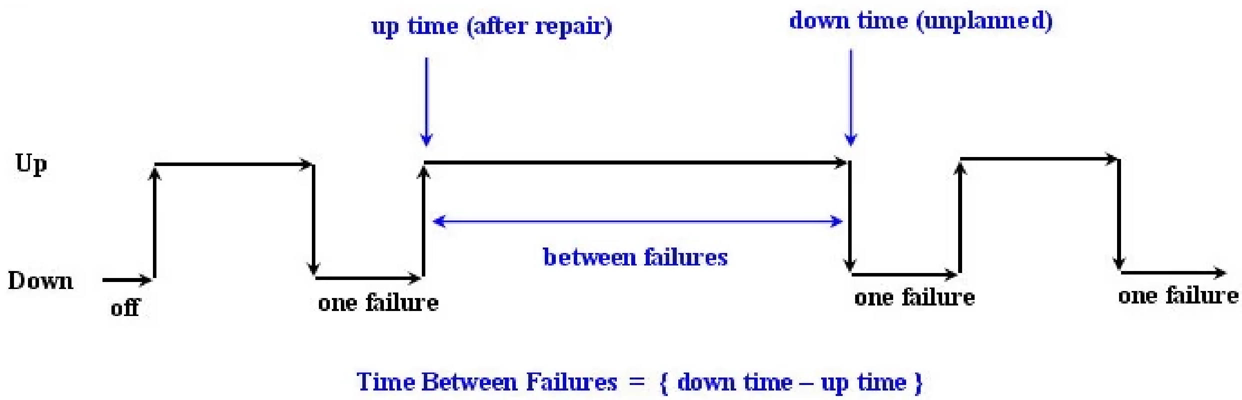


Fig 3.1: **Mean Time before Failure**

$$MTBF = MTTF + MTTR$$

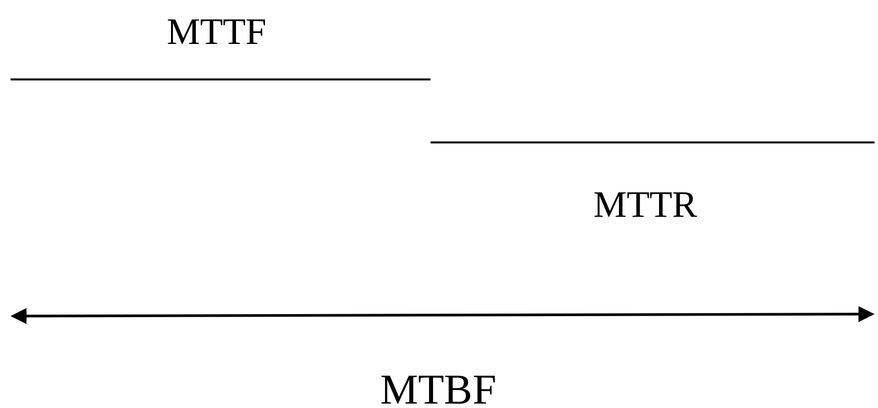


Fig 3.2: **MTBF Calculation**

- **Mean Down Time**

  In decision-making management, *mean down time* (MDT) is the average time that a system is out of use. This includes all time related with repair, counteractive and preventive maintenance; self imposed downtime, and any logistics or organizational delays.

- **Mean Time Between Maintenance** (MTBM)

  Mean Time Between Maintenance (MTBM) is a gauge of the reliability taking into account the safeguarding strategy, which is the total number of life units exhausted by a given time, divided by the total number of maintenance events (planned and unscheduled) performed on that item.

- **Mean Active Maintenance Time**

  Overall average time required to carry out a maintenance action in order to get the system back to running.

3.1.2 Types of Availability

Classification of Availability is purely flexible and is totally dependent on the type of downtime used for checking the behavior of the system. So availability is classified into six basic types depending on the span of time of failure. [24]

Table 3.2 – **Availability Types**

3.1.2.1 Instantaneous (or Point) Availability
3.1.2.2 Steady State Availability
3.1.2.3 Average Uptime Availability (or Mean Availability)
3.1.2.4 Inherent Availability
3.1.2.5 Achieved Availability
3.1.2.6 Operational Availability

3.1.2.1.Instantaneous/Point Availability

Instantaneous availability, as the name suggests, is the type of availability that deals with the availability of a system that whether it will be available at a specific point of time or not.

Let T be any specific point of time when the availability of the system is to be determined. So for any time t (t < T), the system can either be failure or in maintenance state but it doesn't matter as long as the system is available for operation at time T. Inherent availability deals with the probability of system operation and functioning at the requisite level in an ideal environment without any consideration of maintenance.

A series of failure and repairs are shown in the image below and a combination of which states the system availability at a specific point of time i.e. T

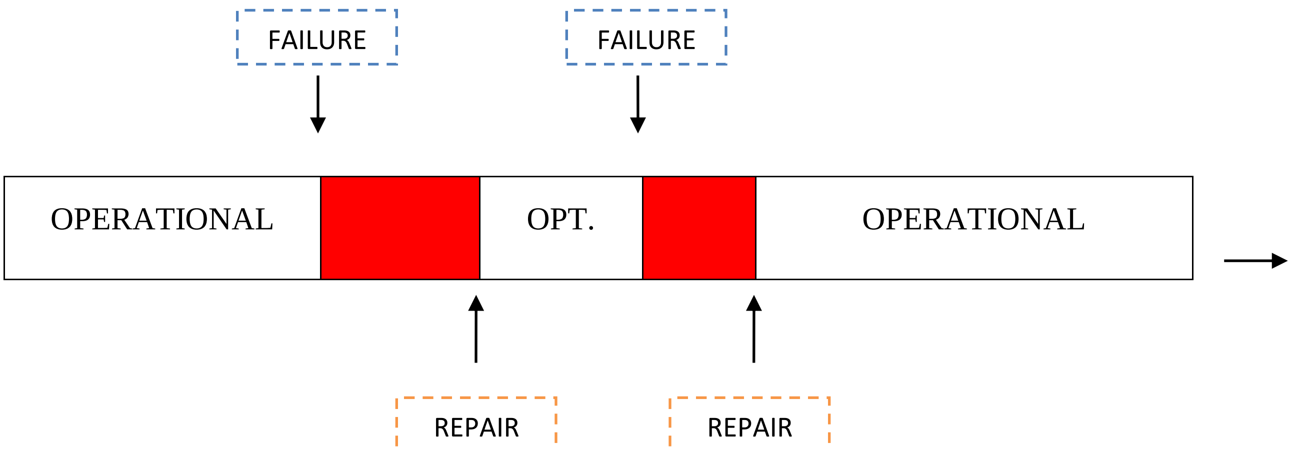


Fig 3.3: **Point Availability**

3.1.2.2 Steady State Availability

Steady state availability of the system is the limit applied to the availability of the system as the time approaches infinity. It is basically the availability of the system when the system has reached a steady state which also implies it to be portrayed as Mean Availability. Mathematically steady state availability is denoted by

$$A(\infty) = \lim_{t \to \infty} A(t)$$

So, Steady state availability is asymptotic availability and so it can be plotted graphically and a relation with Point availability can be established. Given below is the graphical representation of steady state availability.

3.1.2.3 **Average Uptime Availability** (or Mean Availability)

This type of availability is the simplest one to understand. It is basically the mean of the integrated time that the system is available throughout for utilization. Mathematically it is shown as under

$$\underline{A(t)} = \frac{1}{t} \int_0^t A(u).du$$

For systems that have periodical maintenance, availability may be zero at regular periodical intervals. In these cases, mean availability is a more meaningful measure than point availability. Telecommunication companies are the best example that uses such type of availability in their day to day behavior in order to keep a track on the amount of time their system is available for utilization by the customers.

3.1.2.4 **Inherent Availability**

Inherent availability is the possibility that the system will behave ideal and will be available at a given tip of time under affirmed support environment. It excludes logistics time, waiting or administrative downtime, and preventive maintenance downtime including corrective maintenance downtime. When the system fails under any condition the main point that occurs is how fast the system can recover to the initial stage.

Mathematically, it is calculated by the ratio of mean time to failure to the sum of the means of the time to failure and repair.

$$\text{Inherent Availability} = \frac{MTTF}{MTTF+MTTR}$$

The above given equation is valid only for a single component but considering a system of components then Mean time before Failure is taken into account.

$$\text{Availability} = \frac{MTBF}{MTBF+MTTR}$$

- It assumes that the manpower and spare parts are 100% available without any delays.
- It is basically derived from the analysis of an engineering design.
- It excludes logistics time, waiting or administrative downtime, and preventive maintenance downtime.
- It is expected level of availability for performance of corrective maintenance only.

3.1.2.5 Achieved Availability

Achieved availability is analogous to inherent availability but only preventive maintenance is also included.

It is the chance of providing satisfactory operation at a specific point of time operating under suitable support environment. The achieved availability is from time to time referred to as the availability seen by the maintenance section (includes both corrective and preventive maintenance but does not comprise logistic, supply or administrative delays).

Mathematically, Achieved availability can be calculated as the ratio of the mean time flanked by maintenance actions to the sum of the means of the time connecting maintenance action and the mean maintenance downtime.

$$\text{Achieved Availability} = \frac{MTBM}{MTBM + Mean}$$

Where, Mean =

$$Maintenance\ downtime \Big/ (no.of\ system\ failures + no.of\ PMs\ downing\ systems)$$

- Downtime only includes corrective maintenance and active preventive maintenance time i.e. wrenches time.
- Does not include logistic and administrative time.
- Similar to inherent availability regarding the operative status as well as the conditions for operation.

3.1.2.6 Operational Availability

Operational availability compasses the any design and support system aspects and provides a unique indicator of the capability of the system to deliver its functions/mission whenever called upon at any given point of time.

It is the real average availability that the system persists over a period of time and includes all sources of downtime like logistics, preventive maintenance, administrative, etc. The formerly discussed availability classifications are estimates based on models of the system breakdown and downtime distributions. In many cases, operational availability cannot be controlled by the manufacturer due to variation in location, resources and other factors that are the sole province of the end user of the product.

Mathematically, Operational availability is the relative amount of the uptime of the operation to the total time.

$$\text{Operational Availability} = \frac{Functional\ time}{total\ time}$$

Logistic planners, design engineers and maintainability engineers can collaboratively estimate the repair needs of the system, required personnel, spares, maintenance tasks, repair procedures, support equipment and other resources. Only when all downtime causes are addressed will you be able to paint a realistic picture of your system's availability in actual operation.

3.2. MAINTENANCE THEORIES

This section attempts to detail the traditional division into types of maintenance. It is more practical to apply another concept: the maintenance model. Different models of maintenance defined as a mixture of different types of maintenance in the proportions necessary for each equipment.

3.2.1. Maintenance Overview

Maintainability is the relative costs of fixing, updating, extending, operating and servicing an entity over its lifetime. An entity with relatively low costs in these areas is considered maintainable whereas an entity with high costs may be considered non-maintainable or "high maintenance." [25]

The results obtained from the evaluation process help the organization to determine whether its information systems are effective and efficient or otherwise. The process of monitoring, evaluating, and modifying of existing information systems to make required or desirable improvements may be termed as System maintenance. System maintenance is an ongoing activity, which covers a wide variety of activities, including removing program and design errors, updating documentation and test data and updating user support. [26] For the purpose of convenience, maintenance may be categorized into three classes, namely:

- Corrective Maintenance
- Adaptive Maintenance
- Perfective Maintenance.

- **Corrective Maintenance**: - This type of maintenance implies removing errors in a program, which might have crept in the system due to faulty design or wrong assumptions. Thus, in corrective maintenance, processing or performance failures are repaired.

- **Adaptive Maintenance**: - In adaptive maintenance, program functions are changed to enable the information system to satisfy the information needs of the user. This type of maintenance may become necessary because of organizational changes which may include:

  a) Change in the organizational procedures,
  b) Change in organizational objectives, goals, policies, etc.
  c) Change in forms,
  d) Change in information needs of managers.
  e) Change in system controls and security needs, etc.

- **Perfective Maintenance**: - Perfective maintenance means adding new programs or modifying the existing programs to improve the presentation of the information organization. This type of maintenance undertaken to respond to user's additional needs which may be due to the changes within or outside of the organization. Outside changes are primarily environmental changes, which may in the absence of system maintenance; render the information system ineffective and inefficient. These environmental changes include:

  a) Changes in governmental policies, laws, etc.,
  b) Economic and competitive conditions, and
  c) New technology.

Maintainability deals with period of how long it takes to achieve (ease and speed) the maintenance actions compared to a datum. The datum includes maintenance is executed by personnel having particular skill levels, using prearranged procedures and possessions, at each prescribed stage of maintenance.

The solution figure of merit for maintainability is frequently the MTTR and a limit for the utmost repair time. Qualitatively it points to the effortlessness with which hardware or software is restored to a operation state. Quantitatively it has probability and is calculated based on the total downtime for maintenance as well as all time for: diagnosis, trouble shooting, tear-down, removal/substitute, active revamp time, corroboration testing that the repair is adequate, delays for logistic movements, and organizational maintenance delays. [27]

$$M(t) = 1 - \exp\left({}^{-t}/_{MTTR}\right)$$

Note the simple, easy to use criteria shown above, is frequently expressed in exponential repair times. A better and more accurate formula requires use of a different equation for the very cumbersome log-normal distributions of repair times describing maintenance times which are skewed to the right. The maintainability issue is to achieve short repair times for keeping availability high so that downtime of productive equipment is minimized for cost control when availability is critical.

The system availability is also improved by Maintenance or in simple words repair of the existing system. The maintenance strategies are optimized so that the productivity of the plant is maintained using cost-effective maintenance techniques. There are four principles that are critical for a reliability centered maintenance program i.e. the primary objective is to preserve system function, identify failure modes that can affect the system function, prioritize the failure mode, select effective and applicable tasks to control the failure modes.

The overview of basic maintenance management process is given below and is followed to keep the system moving.

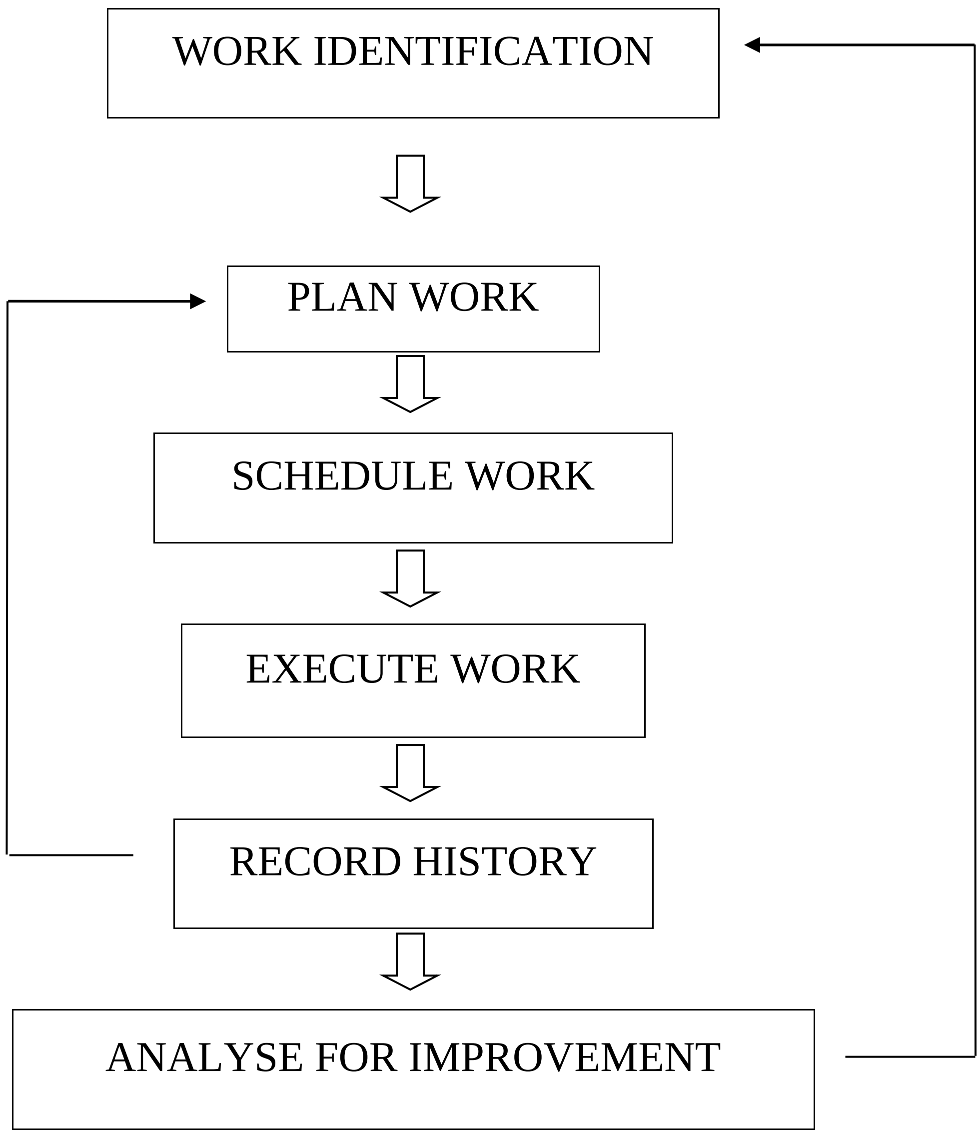


Fig 3.4: **Maintenance Management Process**

3.2.2. CLASSIFICATION OF MAINTENANCE

Maintainability or maintenance policies can be classified on the type of repair that can be done on the system. [28] Maintenance policies are classified into the following types

Table 3.3: **Types of Maintenance**

3.2.2.1	Reactive Maintenance
3.2.2.2	Preventive Maintenance
3.2.2.3	Predictive Maintenance
3.2.2.4	Unplanned Maintenance
3.2.2.5	Opportunistic Maintenance
3.2.2.6	Total Productive Maintenance
3.2.2.7	Zero Hours Maintenance (Overhaul)

3.2.2.1 Reactive Maintenance

Reactive maintenance (breakdown maintenance) is a form of repair that is done when equipment has already broken down. Reactive maintenance focuses on restoring the equipment to its normal operating condition. The broken-down equipment is returned to working within service specifications by replacing or repairing faulty parts and components.

- **Advantages** of Reactive Maintenance
  - Lower initial costs
  - Fewer staffs needed
  - No planning required
- **Disadvantages** of Reactive Maintenance
  - Difficult to control budgets
  - Shorter life expectancy of assets
  - Safety issues
  - Time consuming
  - Inefficient use of resources

- Collateral Damage
- Repeat issues

3.2.2.2 Preventive Maintenance

Preventive maintenance is maintenance that is regularly performed on a piece of equipment to lessen the likelihood of it failing. Preventive maintenance is performed while the equipment is still working, so that it does not break down unexpectedly. [29] Preventive maintenance is planned so that any required resources are available.

- **Advantages** of Preventive Maintenance
  - Less risk factor
  - Follows a schedule
  - Longer equipment life
  - Money saving
  - Less energy wasting

- **Disadvantages** of Preventive Maintenance
  - More money upfront
  - Over maintenance
  - More workers

3.2.2.3 Predictive Maintenance

Predictive maintenance uses a number of apparatus and techniques to observe the condition of your machines and equipment to predict when problems are going to occur by identifying the symptoms of wear and other failures. Also known as reliability centered maintenance and condition base maintenance it seeks to make our maintenance more economically efficient by allowing us to use components within the machines that would be replaced at regular intervals under preventative maintenance programs for far longer, sometimes several times their expected life spans.

Advantages of Predictive maintenance

- Provides increased component operational life and availability
- Allows for preemptive corrective actions

- Results in decrease in equipment and/or process downtime
- Lowers costs for parts and labor
- Provides better product quality

- **Disadvantages** of Preventive maintenance

  - Increases investment in diagnostic equipment
  - Increases investment in staff training
  - Savings potential is readily seen by management

3.2.2.4 Unplanned Maintenance

Any maintenance activity for which a pre-determined job procedure is not documented, or for which all labour, materials, tools, and equipment required to carry out the task are not estimated, and their availability assured before commencement of the task.

Unplanned maintenance differs from unscheduled maintenance in that the latter may have been planned for a particular fiscal year but not yet scheduled for a particular day.

Because this maintenance type is both unplanned and unscheduled this method of performing maintenance activities is highly inefficient. Time needs to be spent investigating and determining the problem as well as determining a maintenance plan to get the equipment fixed quickly. Time is also likely to be spent waiting for parts, supplies or other personnel to complete the maintenance task.

If no maintenance planning is undertaken then this style of maintenance becomes the default maintenance style. This is because the planned and predictive maintenance styles described later need an investment in planning before they can be successfully utilized.

3.2.2.5 Opportunistic Maintenance

Opportunity maintenance is a form of preventive maintenance based upon “convenient” replacement of equipment items or components by taking the advantage of the unplanned or planned shutdown of a system where we have suitable maintenance resources already on location.

The objective of opportunistic maintenance is to improve system availability and reduce production loss; however, the key to success is being able to determine when a component should be replaced during its useful working life to gain a cost-effective improvement. [21]

Opportunistic maintenance is considered effective for an oil and gas asset due to the high-level of dependency presented by the different systems. For example, considering an offshore platform, a failure event in the separation system is likely to shut down other parts of platform such as the oil export system. Thus, when a downtime opportunity is created by the failed component, the maintenance team may take the opportunity while at the facility to perform preventive maintenance for other components satisfying a pre-specified decision rule. As a result, substantial cost can be saved when compared to awaiting the regular maintenance schedule of the opportune maintained item(s).

3.2.2.6 Total Productive Maintenance

Total productive maintenance is a complete system for maintenance of equipment that aims at achieving an optimal production environment devoid of defects, downtime, stoppages and accidents. [30]

One distinct advantage of total productive maintenance is that it empowers the shop floor to work in a concerted manner to ensure that machines are functioning at their optimal performance. In fact, in a lean production setup that is practicing TPM, you find

Once a high degree of stability is established using the 5S program, an organization can start implementing the total productive maintenance in earnest. Total productive maintenance has eight pillars that are aimed at proactively establishing reliability of machines. One point that has to be made here is that people are centre of this system and must be continuously trained to identify and eliminate waste.

- Autonomous maintenance
- Planned maintenance
- Quality maintenance

- Focused improvement
- Early equipment maintenance
- Education and training
- Health, Safety and Environment
- TPM in office functions

Factors to govern TPM over other maintenances can be seen from below mentioned advantages of total productive maintenance

- Operators feel responsible for their machines, equipment becomes more reliable
- Maintenance can be scheduled when production activities are few
- Defect reduction & consequent profit improvement
- New equipment achieves full potential in a shorter period of time
- Employees gain the necessary skills to enable them solve problems within the organization

3.2.2.7 **Zero Hours Maintenance** (Overhaul)

The set of tasks whose goal is to review the equipment at scheduled intervals before appearing any failure, either when the reliability of the equipment has decreased considerably so it is risky to make forecasts of production capacity . This review is based on leaving the equipment to zero hours of operation, that is, as if the equipment were new. These reviews will replace or repair all items subject to wear. The aim is to ensure, with high probability, a good working time fixed in advance.

3.3 REDUNDANCY THEORIES

This section deals with the overview of the theories and importance of introduction of a redundant component in a system and the classification and types of redundancy.

3.3.1 REDUNDANCY OVERVIEW

Load sharing is a form of redundancy with dependent components, *i.e.* the breakdown of one constituent affects the likelihood of failure for the additional component(s). In this issue, we will discuss another form of redundancy, namely standby. This article describes the three types of standby configurations and presents an example analysis for a system with one active and one standby component.

What is too often forgotten in reliability analysis of redundant systems is that extra hardware is required to couple the individual components into a well functioning redundant configuration. Even when components can be directly coupled without additional hardware, failure modes of one component could represent a too big load for the redundant components to handle, thus leading to system failure. Both the extra hardware and 'overload' failures represent extra failure possibilities which can be accounted for by a virtual series component. [31] When a single component does not supply the required reliability extra components can be added that are not severely essential for the standard functioning of the system but are able to take over the functional task of other components upon failure, thus extending the system's lifetime. Usually these redundant components are identical to the one(s) they backup, however this is not necessarily.

Redundancy and maintenance form a very strong combination to create reliable systems. When broken components are detected and repaired/replaced at a much higher rate than the combined failure rate of the surviving components, a dramatic increase in system reliability and availability can be achieved. This because broken components normally will be repaired before the system fails.

Redundancy is defined as an addition of information, resource and time to the existing product or system than required for its optimum performance. Redundancy is of following types:

- **Resource Redundancy:** Resource redundancy is made up of two parts; software redundancy and hardware redundancy. Software redundancy talks about addition of software in form of program or patch to undertake a task of fault detection. Hardware redundancy talks about addition of hardware for identifying or modifying defects. [32]
- **Information Redundancy:** As the same suggest information redundancies provide extra information to implement given function of error detection.
- **Time Redundancy:** As the same suggest time redundancies provide additional time to fault detection.

3.3.2 CLASSIFICATION OF REDUNDANCY

Redundant components can be fully activated (active), partially activated (standby) or switched off completely (passive). Standby redundancy is typically functional when the components' startup time is inappropriately extended. Based on these properties, redundancy can be classified into following types:

Table 3.4: **Types of Redundancy**

3.3.2.1. Active Redundancy
3.3.2.2. Standby Redundancy
3.3.2.3. Passive Redundancy

3.3.2.1 Active Redundancy

In active redundancy, as the name implies, all the items that are for the time being available are operated, but the system can continue to provide the required service with as few as m out of n of them operating. The items are then said to be in m-out-of-n active parallel redundancy.

Redundancy is often used to improve system reliability or availability in the absence of more reliable single items. Thus, a busy office manager might decide to have two photocopiers, not because the load is too great for only one machine even at peak times but simply because no manufacturer seems to make machines that fail less than three times a month, and no service operation will promise to come and fix it the same day in time for the last postal collection. Frequently, in a predominantly series system there is one item which is significantly less reliable than the rest. Such items are the first candidates for redundancy. The improvement is dramatic, but of course the cost is high.

3.3.2.2 Standby Redundancy

Under standby redundancy, the redundant components do not share any of the load, and they start operating only when active components fail. In standby redundancy, the components are divided into two types, Active and Standby. The standby components have two failure distributions, one for when they are in standby (quiescent distribution) and one for when they operate (active distribution). [33]

In stand-by redundancy, any items beyond the required number m are shut down whether failed or not. In both cases the redundant sub-system is regarded as failed only when less than m items remain for the moment in working order. Standby redundancy, moreover known as Backup Redundancy is when you have an indistinguishable secondary unit to back up the main unit. The secondary unit typically does not monitor the system, but is there just as a spare. The standby unit is not usually kept in sync with the primary unit, so it must reconcile its input and output signals on takeover of the Device under Control (DUC). This approach does lend itself to give a “bump” on transfer, meaning the secondary may send control signals to the DUC that are not in sync with the last control signals that came from the primary unit.

We also need a third party to be the watchdog, which monitors the system to make a decision when a swap over circumstance is met and command the system to switch control to the standby unit and a voter, which is the component that decides when to switch over and which unit is given control of the DUC.

3.3.2.3 Passive Redundancy

Passive redundancy is a system where the Backup device isn't doing anything. It is probably on and ready, but its not performing any jobs until started when its needed. An example of that could be two independent play out devices in a control room. The backup playout device isn't doing anything but its turned on and ready to play. Another example could be redundant transmitters where you have one transmitter ready if another transmitter stops working. Then there must be a control unit that detects that Main has a problem, shuts Main down, switches the inputs and outputs and tells Backup to start.

Here we also find *N*+1 redundancy. If we have a transmitter station with a series of transmitters, then there could be one Backup which can replace any of the other transmitters. If one of the Main transmitters fail, then the control unit must detect which transmitter have fails, make sure to send the correct signal to the input of the Backup transmitter, tell the Backup which frequency it must tune to, switch the outputs and start the Backup.

Note that the terms active and passive redundancy is used differently in different articles about redundancy. Other authors may also use different categories, defining a category called One-to-One where each device always have a spare device where the spare device typically is operated in active redundancy mode.

CHAPTER 4

MODELLING METHODOLOGIES

This section deals with the introduction to the various system modeling techniques used to model the system and proceed with the analytical aspects of the system. This section brings forwards the analysis of the system using various modeling techniques and the advantages of each of them over one another. These system modeling techniques include Markov analysis, Monte Carlo simulation, etc.

A system is a compilation of subsystems, assemblies and/or components prearranged in a precise design in order to accomplish desired functions with satisfactory presentation and reliability. The types of workings, their quantities, their qualities and the approach in which they are agreed within the system have a straight effect on the system's reliability. Therefore, in addition to the reliability of the components, the relationship between these components is also considered and decisions as to the choice of components can be made to improve or optimize the overall system reliability, maintainability and/or availability. This section also clarifies the number of iterations required to reach the target value. Iteration comprises of addition of a redundant component in the system.

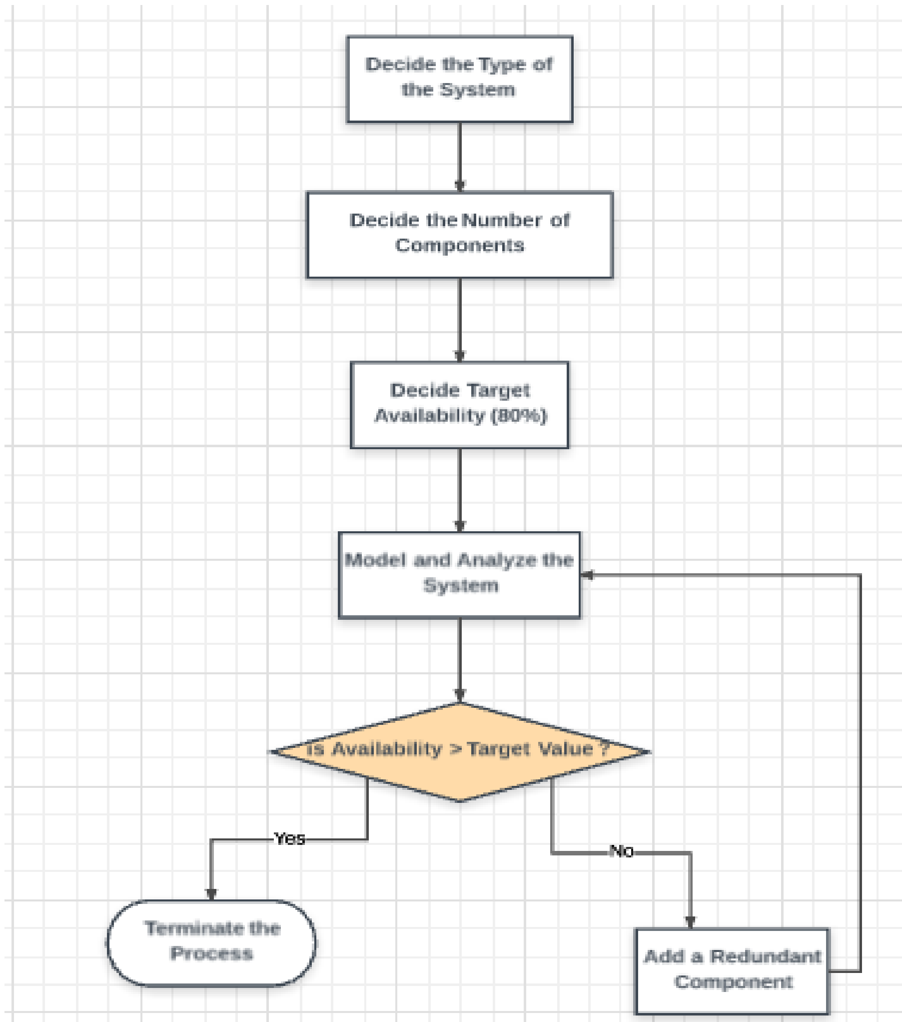


Fig 4.1: **Decision Flowchart**

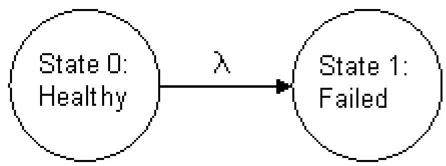
Modeling techniques to be discussed under this section are given in the table below.

4.1.Markov Analysis

4.2.Semi – Markov Analysis

4.1. MARKOV ANALYSIS

For any known system, a Markov model consists of a list of the potential states of that system, the probable changeover paths flanked by those states, and the speed parameters of those transitions. In reliability analysis the transitions frequently consist of failures and maintenance. [34] When a Markov model is decrypted graphically, each state is typically denoted as a "bubble", with arrows denoting the changeover paths between states, as depicted in the figure underneath for a single component that has just two states: healthy and failed.



We denote $P_j(t)$ as the probability of the system being in State j at time t. If the device is recognized to be vigorous at some preliminary time t = 0, the original probabilities of the two states are $P_0(0) = 1$ and $P_1(0) = 0$. After that the probability of State 0 reduces at the steady rate l, which means that if the system rests in State 0 at any known time, the chance of making the transition to State 1 during the subsequent augmentation of time dt is ldt. Consequently, in general probability that the changeover from State 0 to State 1 will happen during a exact incremental period of time dt is known by multiplying the probability of being in State 0 at the commencement of that interval and the probability of the transition during a period dt known that it was in State 0 at the commencement of that growth. This depicts the incremental transform dP_0 in probability of State 0 at any time provided, so we have the primary relation

$$dP_0 = -(P_0)(\lambda dt)$$

Dividing LHS and RHS by dt, we come across with the following simple differential equation:

$$\frac{dP_0}{dt} = -\lambda P_0$$

This signifies that a changeover path from a specified state to any other state decreases the chance of the foundation state at a rate equivalent to the transition speed restriction multiplied by the existing probability of the state. Now, since the whole likelihood of both states must equal 1, it follows that the probability of State 1 must amplify at the similar rate that the chance of State 0 is decreasing. Thus the equations for this simple model are given below

$$\frac{dP_0}{dt} = -\lambda P_0 \qquad \frac{dP_1}{dt} = \lambda P_0 \qquad P_0 + P_1 = 1$$

The elucidation of these equations, with the original situation $P_0(0) = 1$ and $P_1(0) = 0$, is

$$P_0(t) = e^{-\lambda t} \qquad P_1(t) = 1 - e^{-\lambda t}$$

The outline of this solution explains why transitions with steady rates are occasionally called “exponential transitions”, since the changeover times are exponentially dispersed. Also, it’s clear that the entire probability of all the states is preserved. Probability basically “flows” from one state to a different one. [35]

The state equation for each state equates the rate of change of the probability of that state (dP/dt) with the “probability flow into and out of” that state. The total probability flow into a given state is the sum of all transition rates into that state, each multiplied by the chance of the state at the source of that transition. The probability flow out of the given state is the sum of all transitions out of the state multiplied by the probability of that given state. [36]

4.2. SEMI – MARKOV ANALYSIS

The semi-Markov process is constructed by the so called Markov renewal process that is a special case the two-dimensional Markov sequence. The Markov renewal process is defined by the transition probabilities matrix, called the renewal kernel and a first allocation or by an additional distinctiveness which are corresponding to the renewal kernel. The counting process corresponding to the semi-Markov process allows determining concept of the process regularity. In the paper are also shown the other methods of determining the semi-Markov process. [37]

The main difference between an MRP and a semi-Markov process is that the former is defined as a two-tuple of states and times, whereas the latter is the actual random process that evolves over time and any realization of the process has a defined state for any given time. The entire process is not Markovian, i.e., memory less, as happens in a CTMC. Instead the process is Markovian only at the specified jump instants. This is the rationale behind the name, Semi-Markov. In many applications, the influx of customers to a service center is not well described by restitution processes. The interval between successive arrivals is correlated, while renewal processes have self-governing inter arrival times. A natural generalization is the class of SMP, which when specifically applied to the arrival of customers is called MRP or MAP. Arrivals to any one station correspond to departures from some other station. In order to evade perplexity, we use the terms SMP or MRP here.

CHAPTER 5

SYSTEM MODELING

This chapter of the report deals with the description of the models used for the analysis along with the brief introduction about the various steps involved in the same. This section also clarifies the various assumptions taken into consideration in order to move ahead with the analysis of the system.

5.1. SYSTEM DESCRIPTION

This section describes the layout of the system used for the analysis of the model.

5.1.1. Four Components System

The Four Components system to be used in this project is a **Rankine Cycle**.

The Rankine cycle is the fundamental operating cycle of all power plants where an operating fluid is continuously evaporated and condensed. The selection of operating fluid depends mainly on the available temperature range. [38] The Rankine cycle operates in the following steps:

- **Isobaric Heat Transfer**. High pressure liquid enters the boiler from the feed pump and is heated to the saturation temperature. Further addition of energy causes evaporation of the liquid until it is fully converted to saturated steam.
- **Isentropic Expansion**. The vapor is expanded in the turbine, thus producing work which may be converted to electricity. In practice, the expansion is limited by the temperature of the cooling medium and by the erosion of the turbine blades by liquid entrainment in the vapor stream as the process moves further into the two-phase region. Exit vapor qualities should be greater than 90%.
- **Isobaric Heat Rejection**. The vapor-liquid mixture leaving the turbine is condensed at low pressure, usually in a surface condenser using cooling water. In well designed and maintained condensers, the pressure of the vapor is well below atmospheric pressure, approaching the saturation pressure of the operating fluid at the cooling water temperature.

- **Isentropic Compression**. The pressure of the condensate is raised in the feed pump. Because of the low specific volume of liquids, the pump work is relatively small and often neglected in thermodynamic calculations.

The Rankine cycle describes the procedure by which steam-operated heat engines usually sets up in thermal power generation plants produces power. The heat sources used in these power plants are usually nuclear fission or the combustion of fossil fuels such as coal, natural gas, and oil.

The operational fluid in a Rankine cycle follows a closed loop and is reused again and again. The water vapour with condensed droplets frequently seen billowing from power stations is created by the cooling and represents the means for waste heat to exit the system, allowing for the addition of heat that can then be converted to useful work. Cooling towers function as large heat exchangers by absorbing the latent heat of vaporization of the operational fluid and at the same time evaporating cooling water to the atmosphere. While a lot of substances could be used as the operational fluid in the Rankine cycle, water is the typical fluid due to its favorable properties like its non-toxic feature and non-reactive chemistry, available in abundance and comparatively low cost as well as its favorable thermodynamic properties for the overall analysis. [39]

5.1.2. Assumptions and System Specifications

Assumptions taken under consideration for the following Markov analysis:

- Two components cannot fail at the same time.
- A component and its redundant pair cannot be
  - Both operating at the same time.
  - One in failed and other in steady state simultaneously
  - Both at steady state at the same time.
- A component cannot fail if it is under steady state.
- A component under failed state will undergo repair to either operating or steady state according to situation.
- The transition probabilities for a given beginning state of the system sum to one.
- The probabilities apply to all participants in the system.
- The transition probabilities are constant over time.
- The states are independent over time.

All the components undergo failure in a specified amount of time that is used to evaluate Failure rate i.e. failure per hour and in a similar way Repair rate.

The failure rates and repair rates to be used in Markov analysis is evaluated as inverse of failure and repair time respectively. The following rates are taken into consideration after reference of analysis of failure rate. [18] [19] [20]

Table 5.1: **List of Values**

Failure rate	(Failures per hour)
k1	**0.0000285**
k2	**0.00002**
k3	**0.000015384**
k4	**0.000028**
k5	**0.000031**
k6	**0.000026**
k7	**0.000018**

Repair rate		(Repairs per hour)
u1	u5	**0.000177**
u2	u6	**0.000138**
u3	u7	**0.000216**
u4		**0.000143**

5.2. MODELING OF THE SYSTEM

This phase of the project deals with the actual interpretation of all the data, theories, assumption and analysis to bring out result in modeling of a four components system. Firstly, simple Markov model with four components in series is used. Once the target of availability is not achieved we start adding redundant components over the components until and unless the target is not achieved.

5.2.1. Model 1 - Four Components System

Components in simple Markov model can only be under 2 transition states i.e. either operating or failed.

Total number of possible states for the model

$$= 2 \times 2 \times 2 \times 2 = 16$$

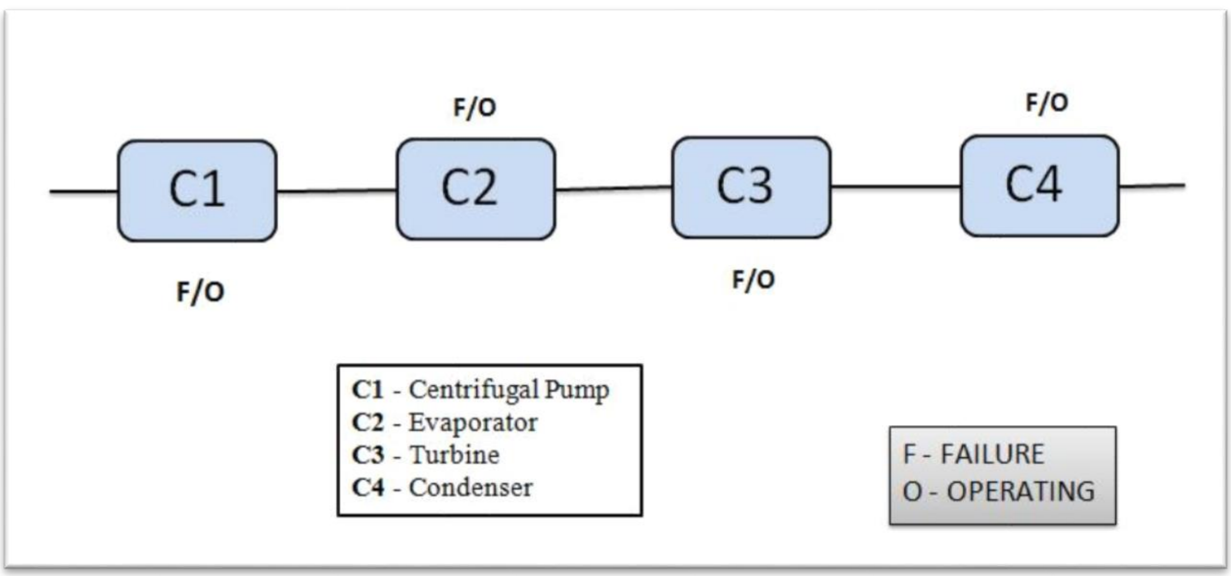


Fig. 5.1: **Four components System (Model 1)**

Out of these 16 possible transition states, details of the feasible and non-feasible ones are given in table 5.3.

Table 5.3: **System State (Model 1)**

CASES	Comp 1	Comp 2	Comp 3	Comp 4	Feasible/Non-Feasible
1	O	O	O	O	FEASIBLE
2	O	O	O	F	FEASIBLE
3	O	O	F	O	FEASIBLE
4	O	F	O	O	FEASIBLE
5	O	F	F	O	NF
6	O	F	O	F	NF
7	O	O	F	F	NF
8	O	F	F	F	NF
9	F	O	O	O	FEASIBLE
10	F	O	O	F	NF
11	F	O	F	O	NF
12	F	F	O	O	NF
13	F	F	F	O	NF
14	F	F	O	F	NF
15	F	O	F	F	NF
16	F	F	F	F	NF

From table 5.3, the feasible states are selected to decide the current status of a state when it undergoes failure or repair from one transition state to another. Data of transition from one state to another is stored in table 5.4.

Table 5.4: **System State with Feasible transition (Model 1)**

CASES	Comp 1	Comp 2	Comp 3	Comp 4	Transition To	Transition From
1	O	O	O	O	2,3,4,5	2,3,4,5
2	F	O	O	O	1	1
3	O	F	O	O	1	1
4	O	O	F	O	1	1
5	O	O	O	F	1	1

The flow chart showing all the states and the states that it is transforming to and also the states it is transforming from.

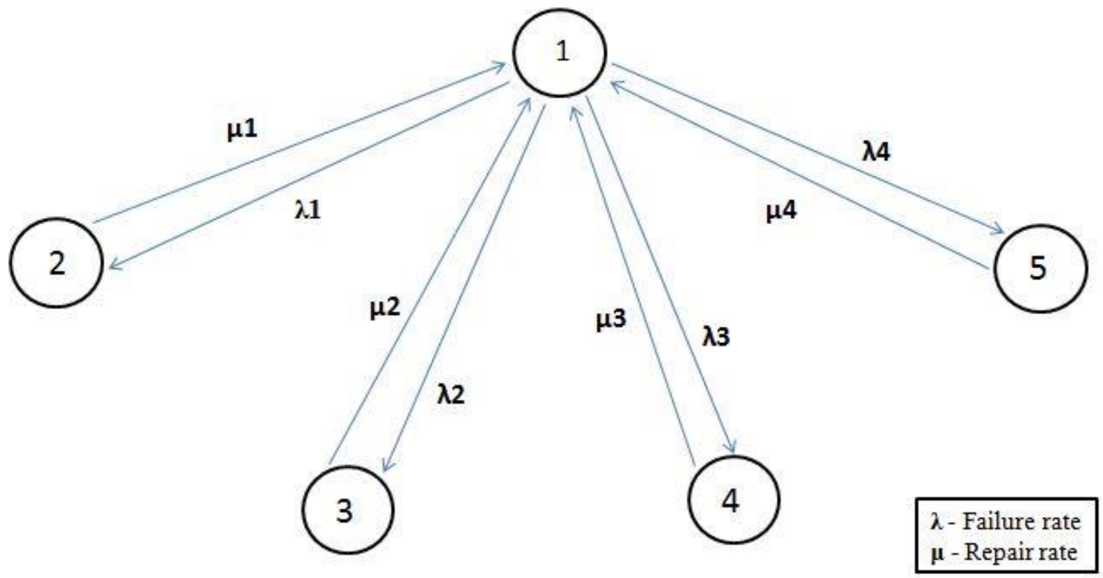


Fig. 5.2: **State transition diagram (Model 1)**

The above table and data are used to form a system of differential equations for Markov analysis and then solving the same in MATLAB to calculate the availability of the system and then plot a graph of availability with time.

MATLAB program is taken into consideration for the above system of differential equation to get individual solution for all the variables in terms of time and to simulate the system for a specified amount of time, (in our case 50,000 hrs).

The program is run by using the command window and simulated for

Time, t = 50,000 hrs

Availability is the sum of probability of all the system that have not undergone failure at all. **Availability of the first model is simply the probability of 'state 1' alone.** The Graph of Availability versus Time is plotted.

```
[T,Y] = ode45(@model1,[0 50000],[1 0 0 0 0])

plot (T,Y(:,1),'-')
```

The Markov model is subjected to initial value condition with respect to time. At the beginning of the analysis, the system is considered to be in state 1.

$$\mathbf{y1\ (0) = 1}$$

The probability of different states changes with time and probability of other states starts increasing with time and after sometime becomes approximately constant.

$$y2\ (0) = y3\ (0) = y4\ (0) = y5\ (0) = 0$$

And probability of all the transition states should be equal to unity as mentioned above

$$\mathbf{y1 + y2 + y3 + y4 + y5 = 1}$$

5.2.2. Model 2 – Single redundant system

Second model in Markov analysis of 4 component system introduces a redundant component on the first component in the model i.e. centrifugal pump. Introduction of redundancy adds a new 'steady state' on the components connected in parallel. The components in parallel are in 3 transition states i.e. either operating or steady or failed.

Total number of possible states for the model

$$= \mathbf{3 \times 3 \times 2 \times 2 \times 2 = 72}$$

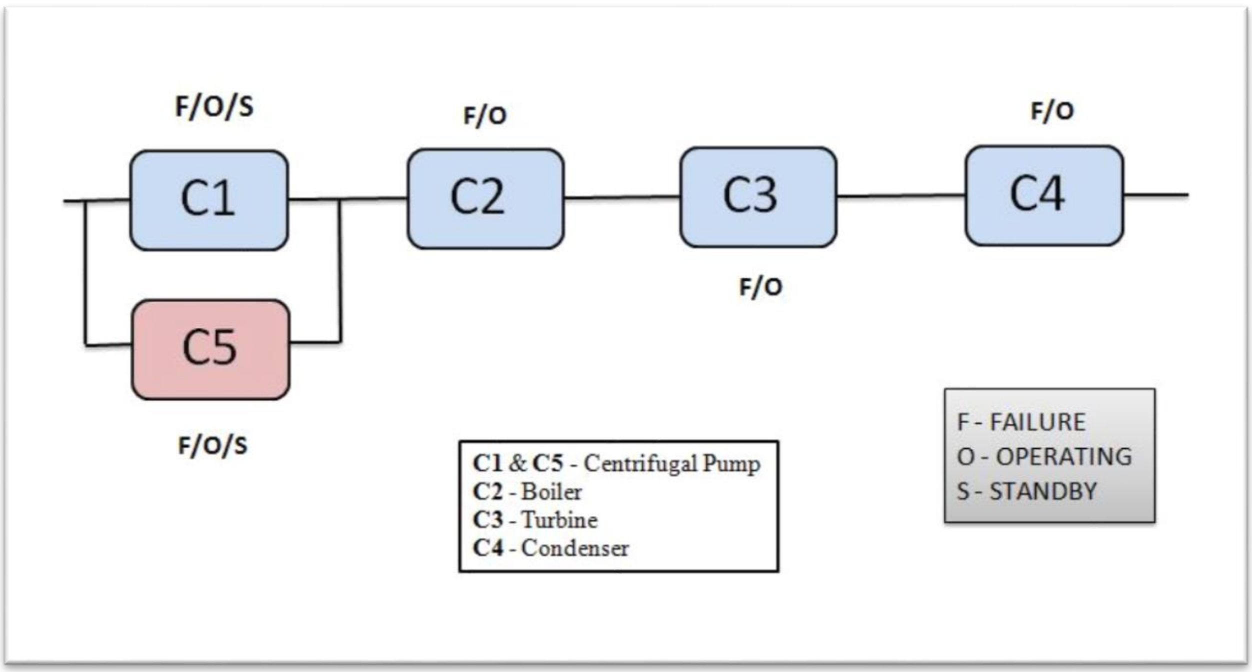


Fig. 5.3: **Single Redundancy Model (Model 2)**

Out of these 72 possible transition states, the non-feasible one would be eliminated afterwards. Feasible states for model 2 i.e. redundancy for component 1 are derived. From the possible 72 states, feasible states are 17 and these are listed in table

Table 5.5: **Transition State (Model 2)**

CASES	Comp 1	Redun 5	Comp 2	Comp 3	Comp 4	Transition To	Transition From
1	O	F	O	O	O	13,2,3,4,5	2,3,4,13,14
2	O	F	F	O	O	1,6	1,
3	O	F	O	F	O	1,7	1
4	O	F	O	O	F	1,8	1
5	O	S	O	O	O	9,6,7,8	1,6,7,8
6	O	S	F	O	O	5	2,5
7	O	S	O	F	O	5	3,5
8	O	S	O	O	F	5	4,5
9	F	O	O	O	O	13,10,11,12,14	5,10,11,12,13
10	F	O	F	O	O	9,15	9
11	F	O	O	F	O	9,16	9
12	F	O	O	O	F	9,17	9
13	F	F	O	O	O	1,9	1,9
14	S	O	O	O	O	1,15,16,17	9,15,16,17
15	S	O	F	O	O	14	10,14
16	S	O	O	F	O	14	11,14
17	S	O	O	O	F	14	12,14

The component under failed state in parallel can undergo repair to transform into a steady state while still the other redundant pair is operating.

‘**State 5**’ is considered as the state at the beginning of the process wherein component 1 is operating and component 5 is in steady state.

The flow chart showing all the states and the states that it is transforming to and also the states it is transforming from is drawn which will be further used to develop differential equations to evaluate the availability of the system by Markov analysis.

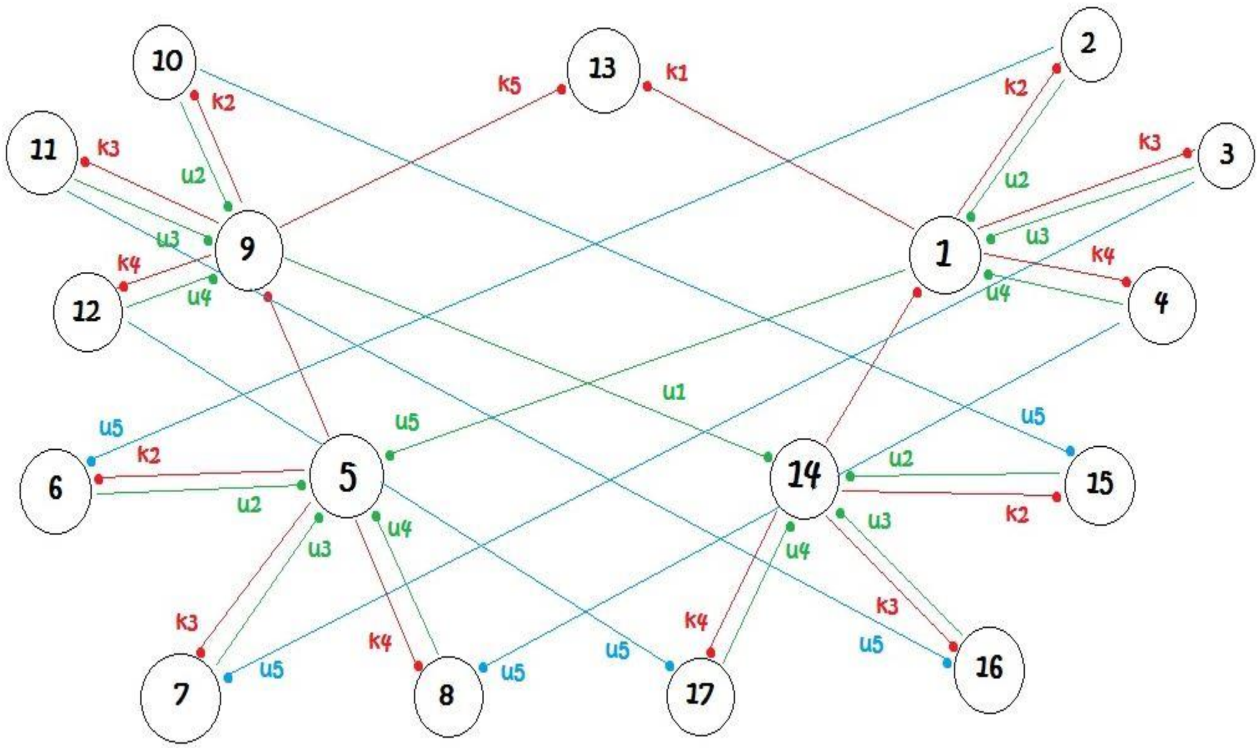


Fig. 5.4: **State transition diagram (Model 2)**

The above table and data are used to form a system of differential equations for Markov analysis and then solving the same in MATLAB to calculate the availability of the system and then plot a graph of availability with time.

<u>System of differential equations in Markov analysis for 5 Components redundant model</u>

MATLAB program is taken into consideration for the above system of differential equation to get individual solution for all the variables in terms of time and to simulate the system for a specified amount of time, (in our case 50,000 hrs).

The program is run by using the command window and simulated for

Time, t = 50,000 hrs

Availability of the Second Markov model is evaluated by summation of all the states that haven't undergone failure at any point of time i.e. state 1, 5, 9 and 14.

Availability = y1 + y5 + y9 + y14

The Graph of Availability versus Time is plotted.

The Markov model is subjected to initial value condition with respect to time. At the beginning of the analysis, the system is considered to be in state 5.

y5 (0) = 1

The probability of different states changes with time and probability of other states starts increasing with time and after sometime becomes approximately constant.

And probability of all the transition states should be equal to unity as mentioned above

y1 + y2 + y3 +. . . . + y17 = 1

5.2.3. Model 3 - Double Redundant Markov Model

Third model in Markov analysis of 4 component system introduces a redundant component on the first and second components in the model i.e. centrifugal pump and evaporator. Introduction of redundancy adds a new 'steady state' on the components connected in parallel. The components in parallel are in 3 transition states i.e. either operating or steady or failed.

Total number of possible states for the model

$$= \mathbf{(3 \times 3) \times (3 \times 3) \times 2 \times 2 = 324}$$

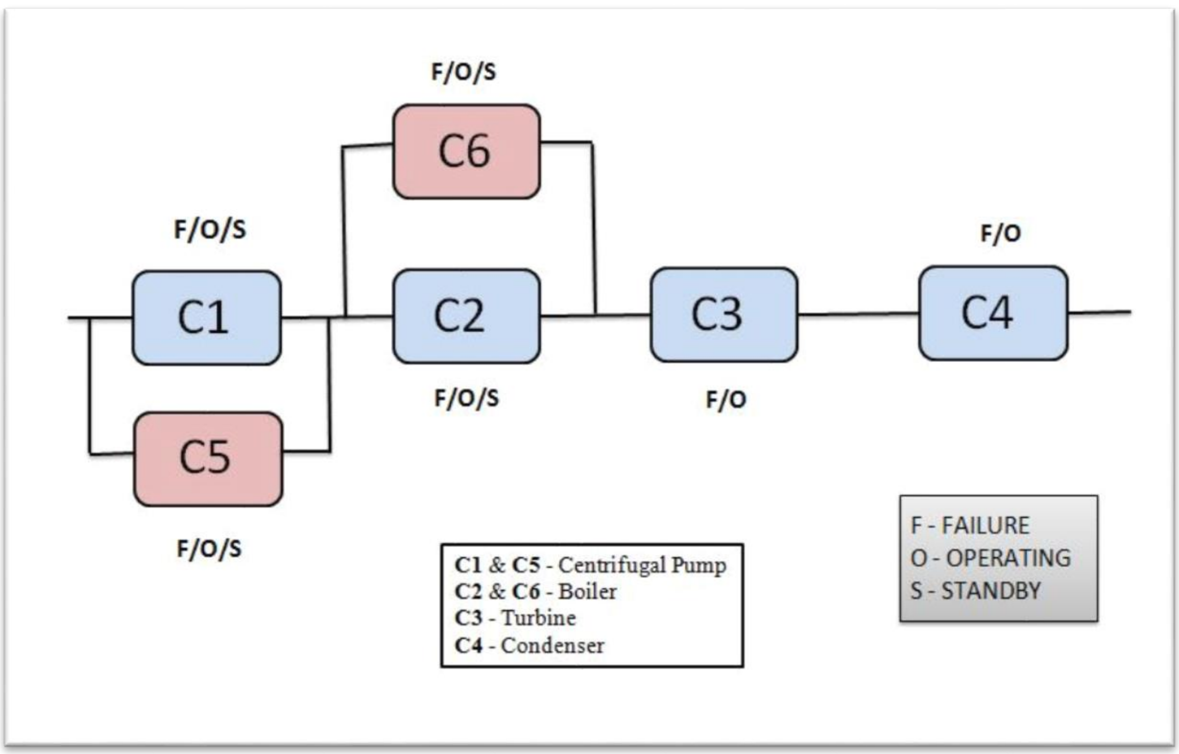


Fig. 5.5: **Double redundancy model (Model 3)**

Out of these 324 possible transition states, the states which are non-feasible are to be eliminated afterwards as those are not compatible for analysis.

From the list of the feasible states, we now consider the conditions that we had assumed earlier to decide feasibility. The feasible states are selected to decide the current status of a state when it undergoes failure or repair from one transition state to another.

Data of transition from one state to another is stored in table 5.6.

Table 5.6: **Transition State (Model 3)**

	C1	R5	C2	R6	C3	C4	TRANSITION TO						TRANSITION FROM					
CASE							**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**
1	O	F	O	F	O	O	40	10	2	3	14	4	40	10	2	3	44	11
2	O	F	O	F	F	O			1		15	5			1			
3	O	F	O	F	O	F				1	16	6				1		
4	O	F	O	S	O	O	41	7	5	6	17		41		5	6	47	1
5	O	F	O	S	F	O			4		18				4			2
6	O	F	O	S	O	F				4	19					4		3
7	O	F	F	O	O	O	42	11	8	9	20	10	42	4	8	9	50	10
8	O	F	F	O	F	O		12	7		21				7			
9	O	F	F	O	O	F		13		7	22					7		
10	O	F	F	F	O	O		1			23	7		1				7
11	O	F	S	O	O	O	43		12	13	24	1	43	7	12	13	54	
12	O	F	S	O	F	O			11		25			8	11			
13	O	F	S	O	O	F				11	26			9		11		
14	O	S	O	F	O	O	27	23	15	16		17		23	15	16	1	24
15	O	S	O	F	F	O			14			18			14		2	
16	O	S	O	F	O	F				14		19				14	3	
17	O	S	O	S	O	O	30	20	18	19					18	19	4	14
18	O	S	O	S	F	O			17						17		5	15
19	O	S	O	S	O	F				17						17	6	16
20	O	S	F	O	O	O	33	24	21	22		23	7	17	21	22	23	
21	O	S	F	O	F	O		25	20				8	20				
22	O	S	F	O	O	F		26		20			9	20				
23	O	S	F	F	O	O		14				20	10	14	20			
24	O	S	S	O	O	O	37		25	26		14	11	20	25	26		
25	O	S	S	O	F	O			24				12	21	24			
26	O	S	S	O	O	F				24			13	22	24			
27	F	O	O	F	O	O	44	36	28	29	40	30	14	28	29	36	37	40
28	F	O	O	F	F	O	45		27			31	27					
29	F	O	O	F	O	F	46			27		32	27					
30	F	O	O	S	O	O	47	33	31	32	41		17	27	31	32	41	
31	F	O	O	S	F	O	48		30				28	30				
32	F	O	O	S	O	F	49			30			29	30				
33	F	O	F	O	O	O	50	37	34	35	42	36	20	30	34	35	36	42
34	F	O	F	O	F	O	51	38	33				33					
35	F	O	F	O	O	F	52	39		33			33					
36	F	O	F	F	O	O	53	27				33	27	33				

37	F	O	S	O	O	O	54		38	39	43	27	24	33	38	39	43	
38	F	O	S	O	F	O	55		37				34	37				
39	F	O	S	O	O	F	56			37			35	37				
40	F	F	O	F	O	O	1				27	41	1	27				
41	F	F	O	S	O	O	4				30		4	30	40			
42	F	F	F	O	O	O	7	43			33		7	33				
43	F	F	S	O	O	O	11				37		11	37	42			
44	S	O	O	F	O	O		53	45	46	1	47	27	45	46	53	54	
45	S	O	O	F	F	O			44			48	28	44				
46	S	O	O	F	O	F				44		49	29	44				
47	S	O	O	S	O	O		50	48	49	4		30	44	48	49		
48	S	O	O	S	F	O			47				31	45	47			
49	S	O	O	S	O	F				47			32	46	47			
50	S	O	F	O	O	O		54	51	52	7	53	33	47	51	52	53	
51	S	O	F	O	F	O		55	50				34	50				
52	S	O	F	O	O	F		56		50			35	50				
53	S	O	F	F	O	O		44				50	36	44	50			
54	S	O	S	O	O	O			55	56	11	44	37	50	55	56		
55	S	O	S	O	F	O			54				38	51	54			
56	S	O	S	O	O	F				54			39	52	54			

The component under failed state in parallel can undergo repair to transform into a steady state while still the other redundant pair is operating.

'**State 17**' is considered as the state at the beginning of the process wherein component 1 and 2 are operating and component 5 and 6 are in steady state. table showing all the states and the states that it is transforming to and also the states it is transforming from is drawn which will be further used to develop differential equations to evaluate the availability of the system by Markov analysis.

The above table and data are used to form a system of differential equations for Markov analysis and then solving the same in MATLAB to calculate the availability of the system and then plot a graph of availability with time.

System of differential equations in Markov analysis for 6 Components redundant model

MATLAB program is taken into consideration for the above system of differential equation to get individual solution for all the variables in terms of time and to simulate the system for a specified amount of time, (in our case 50,000 hrs).

The program is run by using the command window and simulated for

Time, t = 50,000 hrs

Availability of the double redundant Markov model is evaluated by summation of all the states that haven't undergone failure at any point of time i.e. States 1, 4, 7, 11, 14, 17, 20, 24, 27, 30, 33, 37, 44, 47, 50 and 54. So, mathematically it is represented as

Availability = y1 + y4 + y7 + y11 + y14 + y17 + y20 + y24 + y27 + y30 + y33 + y37 + y44 + y47 + y50 + y54

The Markov model is subjected to initial value condition with respect to time. At the beginning of the analysis, the system is considered to be in state 17.

y17 (0) = 1

The probability of different states changes with time and probability of other states starts increasing with time and after sometime becomes approximately constant.

And probability of all the transition states should be equal to unity as mentioned above

y1 + y2 + y3 +. . . . + y55 + y56 = 1

5.2.4. Model 4 - Three Redundant System

Fourth model in Markov analysis of 4 component system introduces a redundant component on the first, second and third components in the model i.e. centrifugal pump, evaporator and turbine. Introduction of redundancy adds a new 'steady state' on the components connected in parallel. The components in parallel are in 3 transition states i.e. either operating or steady or failed.

Total number of possible states for the model

$$= \mathbf{(3 \times 3) \times (3 \times 3) \times (3 \times 3) \times 2 = 1458}$$

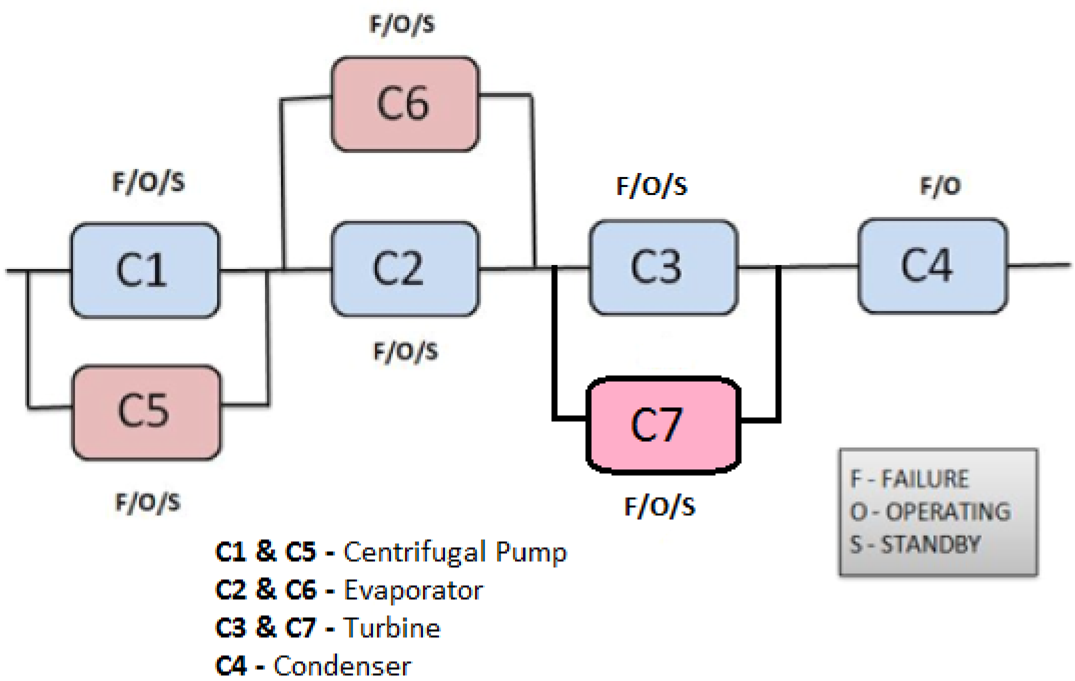


Fig. 5.6: **Triple redundant component (Model 4)**

Out of these 1458 possible transition states, 176 states are found to be feasible and have been used to create the transition table for the system. The component under failed state in parallel can undergo repair to transform into a steady state while still the other redundant pair is operating.

On analysing the table, '**State 52'** is considered as the state at the beginning of the process wherein component 1,2 and 3 are operating and component 5,6 and 7 are in steady state. table showing all the states and the states that it is transforming to and also the states it is transforming from is drawn which will be further used to develop differential equations to evaluate the availability of the system by Markov analysis.

The feasibility table and data are used to form a system of differential equations for Markov analysis and then solving the same in MATLAB to calculate the availability of the system and then plot a graph of availability with time.

System of differential equations in Markov analysis for 7 Components redundant model

MATLAB program is taken into consideration for the above system of differential equation to get individual solution for all the variables in terms of time and to simulate the system for a specified amount of time, (in our case 50,000 hrs).

The program is run by using the command window and simulated for

Time, t = 50,000 hrs

Availability of the fourth Markov model i.e. triple redundant model is evaluated by summation of all the states that haven't undergone failure at any point of time i.e. 1, 3, 5, 8, 10, 12, 14, 17, 19, 21, 23, 26, 32, 34, 36, 39, 41, 43, 45, 48, 50, 52, 54, 57, 59, 61, 63, 66, 72, 74, 76, 79, 81, 83, 85, 88, 90, 92, 94, 97, 99, 101, 103, 106, 112, 114, 116, 119, 137, 139, 141, 144, 146, 148, 150, 153, 155, 157, 159, 162, 168, 170, 172, 175. Mathematically it is represented in the following form:

Availability = y1 + y3 + y5 + y8 + y10 + y12 + y14 + ... + y162 + y168 + y170 + y172 + y175

CHAPTER – 6

RESULTS AND DISCUSSION

This section deals with the evaluation of system availability for the models developed in the previous chapter.

6.1. Four Components series model (Model 1) - Results

For the model 1, results are obtained as per the mathematical model developed in the section 5.2.1 and using the transition rates for the components as per table 5.2. A MATLAB code as listed in appendix A1 is used for the results. The variation of probability of all the different transition states and the system availability with respect to time is shown in the figure 6.1.

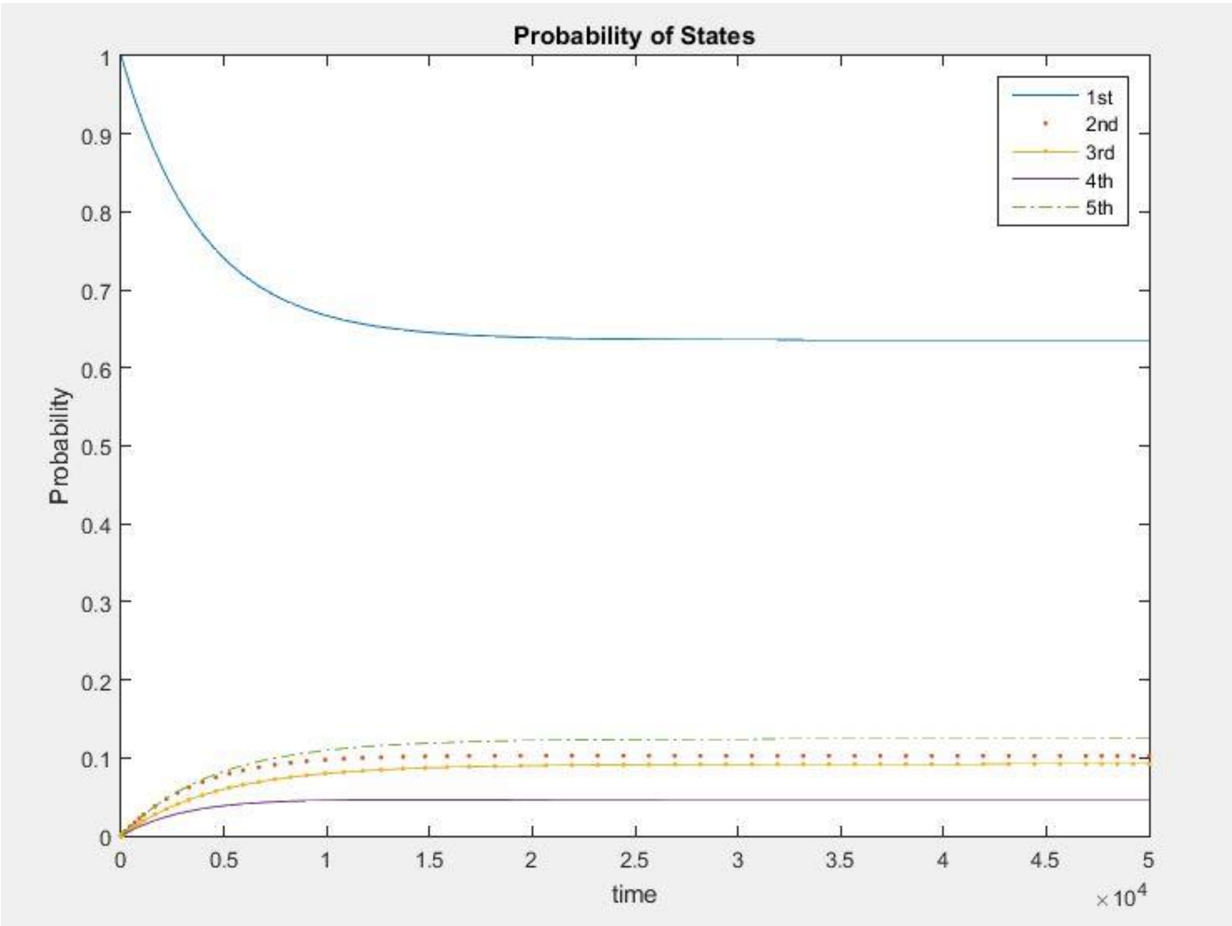


Fig 6.1: **Graphical representation for model 1**

Fig 6.1 shows the results in graphical form for 50,000 hours. The probability values for all the 4 states and system availability values are shown in the graphical form. After analysis from figure 6.1, the availability of the system in the first Markov model comes out to be **0.6358** i.e. the system is available to the user for **63.58%** of the total time.

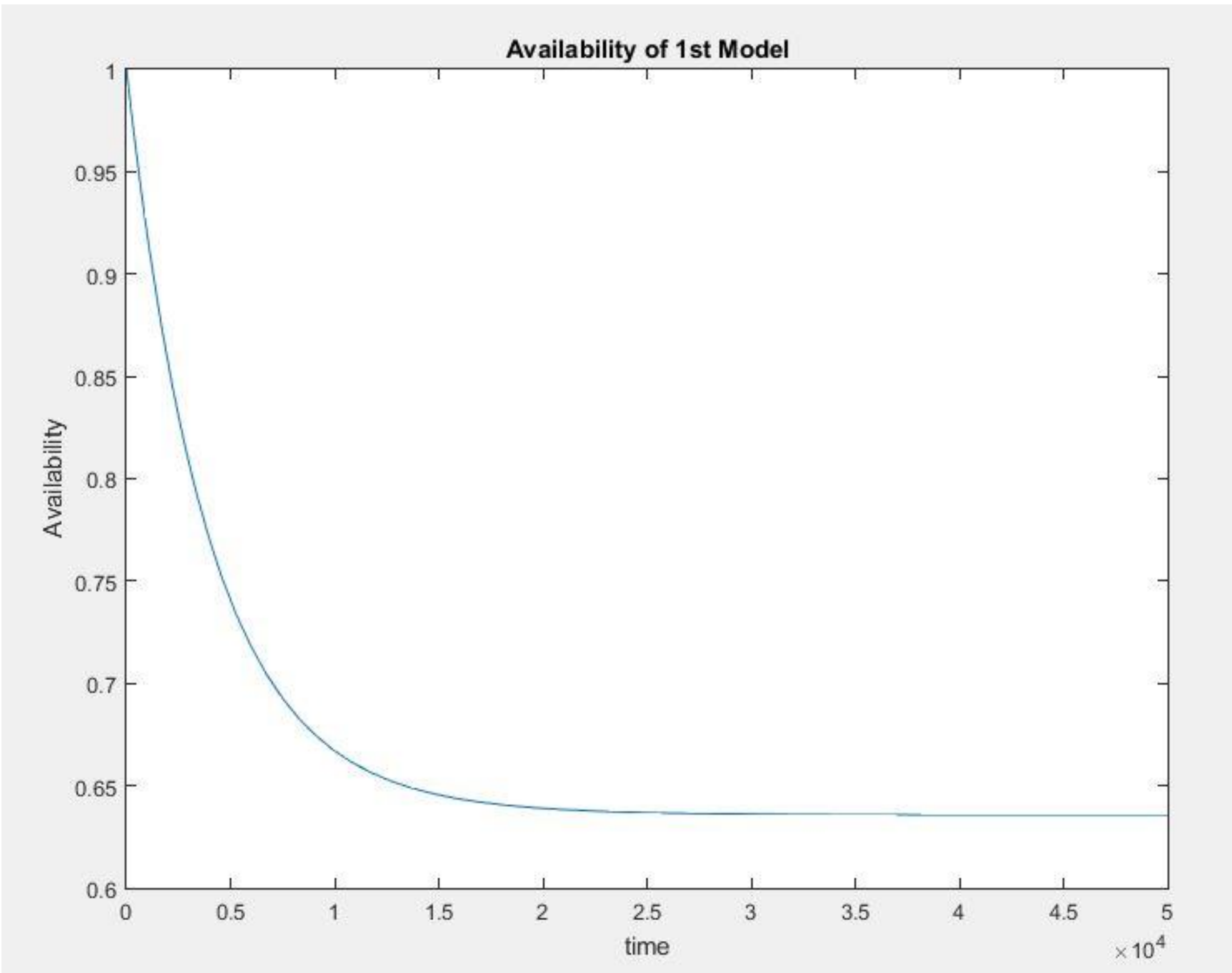


Fig 6.2: **System Availability (Model 1)**

6.2. Markov Model With Single Redundancy (Model 2) - Results

For the single redundant model, results are obtained as per the mathematical model developed in the section 5.2.2 and using the transition rates for the components as per table 5.2. A MATLAB code as listed in appendix A2 is used for the results. Given below is the Plot of Availability versus Time for single redundant model.

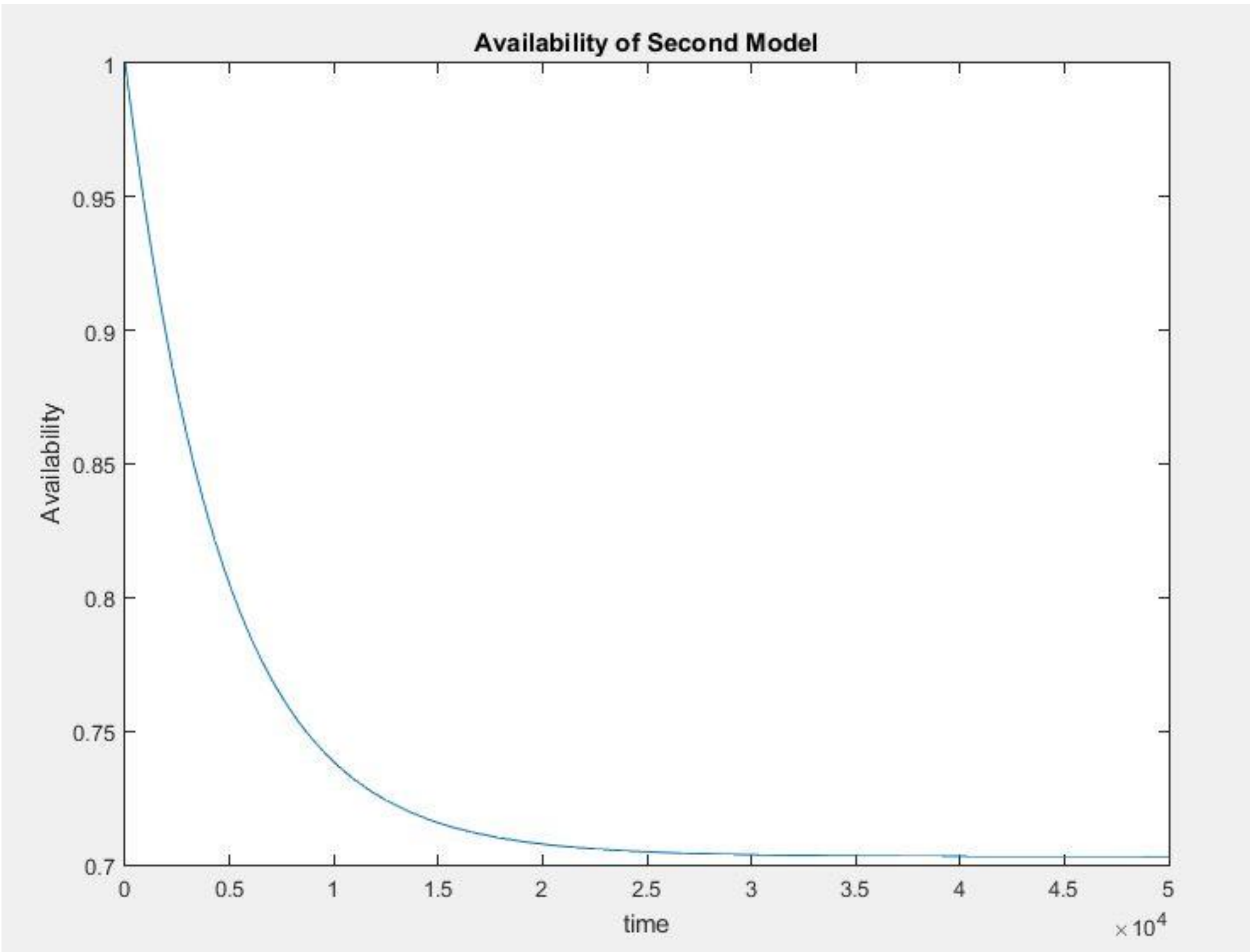


Fig 6.3: **System Availability (Model 2)**

After analysis from figure 6.3, the availability of the system in the second Markov model comes out to be **0.7031** i.e. the system is available to the user for **70.31%** of the total time.

6.3. Double Redundant Markov Model (Model 3) - Result

For the third model i.e. double redundant model, results are obtained as per the mathematical model developed in the section 5.2.3 and using the transition rates for the components as per table 5.2. A MATLAB code as listed in appendix A3 is used for the results. For the double redundant Markov model, plot of availability versus time is given below.

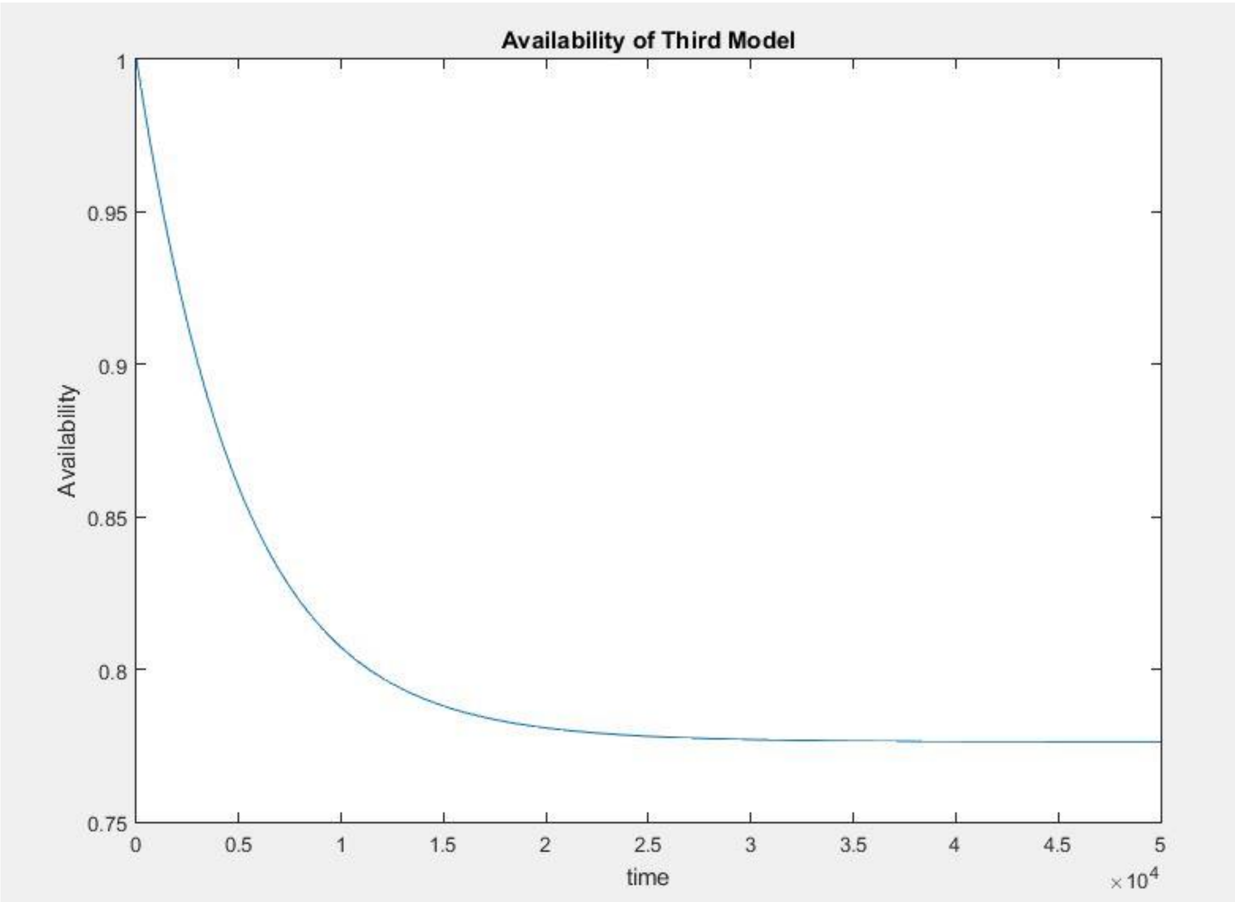


Fig 6.4: **Graphical representation of System Availability (Model 3)**

Referring to figure 6.4, the availability of the system in the second Markov model comes out to be **0.7763** i.e. a user can avail the system for **77.63%** of the total time.

6.4. Markov Model with Three Redundant System

For the triple redundant model, results are obtained as per the mathematical model developed in the section 5.2.4 and using the transition rates for the components as per table 5.2. A MATLAB code as listed in appendix A4 is used for the results. The Graph of Availability versus Time is plotted.

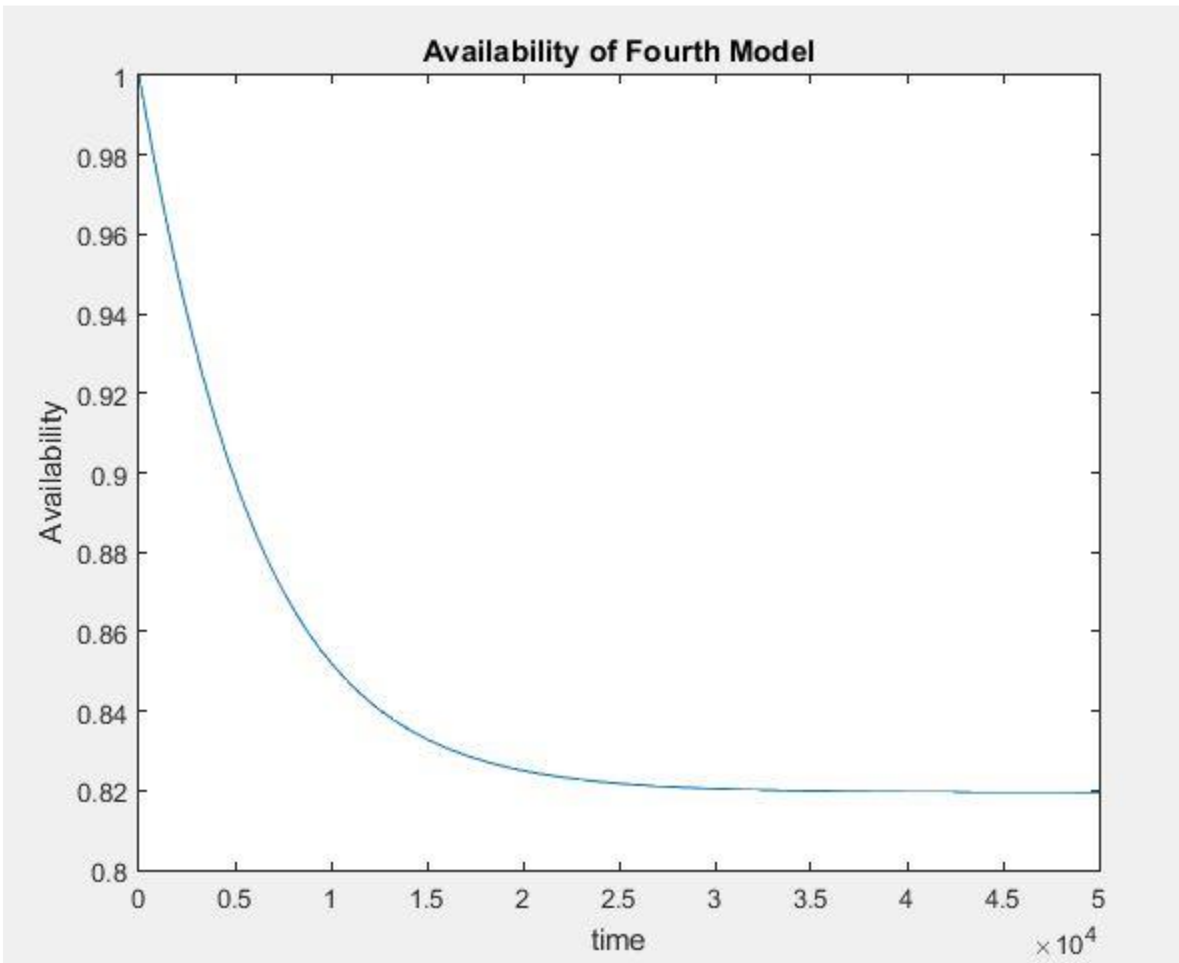


Fig 6.5: **System Availability of Triple redundant model (Model 4)**

Referring to plot 5, the availability of the system in the third Markov model comes out to be **0.8168** i.e. the system is available to the user for **81.68%** of the total time.

CHAPTER – 7

CONCLUSION & FUTURE SCOPE OF WORK

This section puts forward the conclusion and observations of the report along with the areas that can be work upon in near future

7.1. Conclusion

The project aimed at improving the availability of the system by adding components in parallel and by maintenance i.e. repair of the failure states. The improvement is achieved in the three subsidiary models by adding a redundant on the first, second and third components and the iterations are stopped once the initial target of system availability is achieved.

The summary of the system availabilities of Markov models as obtained under different conditions & redundancies is given in the table below.

Table 7.1: **Availability Summary**

	AVAILABILITY (%)
Model 1	**63.58**
Model 2	**70.31**
Model 3	**77.63**
Model 4	**81.68**

Introduction of a single redundancy improves the availability of the system by **10.585%** as compared to the system without any redundancy and adding in another redundancy i.e. Model 3 improves it further by 10.41% i.e. a total of **22.098%** improvement from the first model. Further addition of another redundant component on the turbine component increases the availability of the system by 5.21% i.e. a total of **28.468%.**

Addition of a redundancy provides the system with larger number of available states that haven't undergone failure at all which signifies that availability of the system is indeed improving. The main reason that the availability is increasing is the increase in the number of available states starting from 1 available state in the first model, 16 in the second, 64 in the double redundant model and 256 in the final model.

A chart showing the comparison of the availability of all the systems is given below.

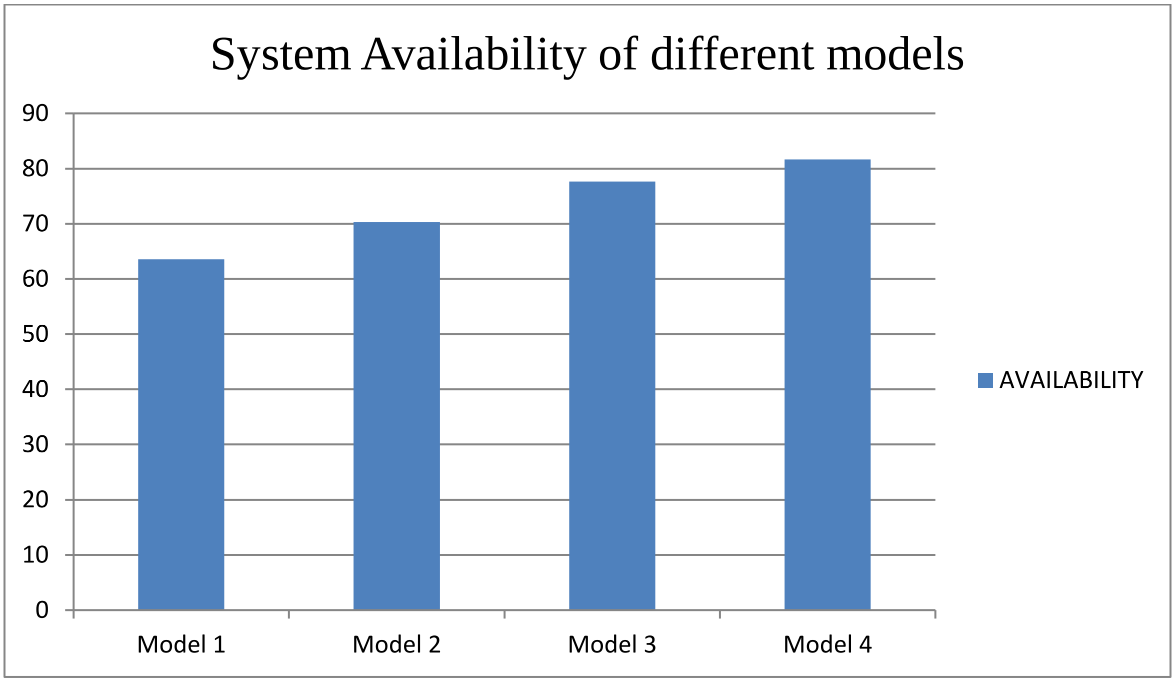


Fig 7.1: **System Availability summary**

7.2. Future scope of work

Following are the areas that are open for exploration and have potential to bring out fruitful results.

- System model with redundancy on all components can be studied. However, that may involve very high level of states that will lead to high computational efforts.
- This study can be extended to analysis under budgetary constraint.
- The work on redundancy optimization can also be explored.

CHAPTER - 8

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APPENDIX 1

SYSTEM EQUATION & COMMAND WINDOW FOR MODEL 1

System of differential equations in markov analysis for simple four components model

$$\frac{dy1}{dt} = -(\mathrm{k1} + \mathrm{k2} + \mathrm{k3} + \mathrm{k4}) * \mathrm{y}(1) + \mathrm{u1} * \mathrm{y}(2) + \mathrm{u2} * \mathrm{y}(3) + \mathrm{u3} * \mathrm{y}(4) + \mathrm{u4} * \mathrm{y}(5)$$

$$\frac{dy2}{dt} = -u1 * y(2) + k1 * y(1)$$

$$\frac{dy3}{dt} = -u2 * y(3) + k2 * y(1)$$

$$\frac{dy4}{dt} = -u3 * y(4) + k3 * y(1)$$

$$\frac{dy5}{dt} = -u4 * y(5) + k4 * y(1)$$

Where y1, y2, y3, y4 and y5 represents transition states 1,2,3,4 and 5 respectively

MATLAB program for the first Markov model

```
function dydt = model1(t,y,k1,k2,k3,k4,u1,u2,u3,u4)

k1=0.0000285;k2=0.00002;k3=0.000015384;k4=0.000028;
u1=0.000177;u2=0.000138;u3=0.000216;u4=0.000143;

dydt =
 [-(k1+k2+k3+k4)*y(1)+ u1*y(2)+ u2*y(3)+ u3*y(4)+ u4*y(5);
       -u1*y(2)+ k1*y(1);
       -u2*y(3)+ k2*y(1);
       -u3*y(4)+ k3*y(1);
       -u4*y(5)+ k4*y(1);]
```

APPENDIX 2

SYSTEM EQUATION & COMMAND WINDOW FOR MODEL 2

MATLAB program for the Second Markov model

```
function dydt = model2(t,y,k1,k2,k3,k4,k5,u1,u2,u3,u4,u5)

k1=0.0000285;k2=0.00002;k3=0.000015384;k4=0.000028;
k5=0.000031;u1=0.000177;u2=0.000138;u3=0.000216;
u4=0.000143;u5=0.000177;
dydt = [-(k2+k3+k4+k1+u5)*y(1) +
u2*y(2)+u3*y(3)+u4*y(4)+u1*y(13)+k5*y(14);
    -(u2+u5)*y(2)+k2*y(1);
    -(u3+u5)*y(3)+k3*y(1);
    -(u4+u5)*y(4)+k4*y(1);
    -(k2+k3+k4+k1)*y(5)+u2*y(6)+u3*y(7)+u4*y(8)+u5*y(1);
    -(u2)*y(6)+u5*y(2)+k2*y(5);
    -(u3)*y(7)+u5*y(3)+k3*y(5);
    -(u4)*y(8)+u5*y(4)+k4*y(5);
    -
(k2+k3+k4+k5+u1)*y(9)+u2*y(10)+u3*y(11)+u4*y(12)+u5*y(13)+k1*y(
5);
    -(u1+u2)*y(10)+k2*y(9);
    -(u1+u3)*y(11)+k3*y(9);
    -(u1+u4)*y(12)+k4*y(9);
    -(u1+u5)*y(13)+k1*y(1)+k5*y(9);
    -(k5+k2+k3+k4)*y(14)+u5*y(9)+u2*y(15)+u3*y(16)+u4*y(17);
    -(u2)*y(15)+u5*y(10)+k2*y(14);
    -(u3)*y(16)+u5*y(11)+k3*y(14);
    -(u4)*y(17)+u5*y(12)+k4*y(14);
       ]
```

COMMAND WINDOW

```
[T,Y] = ode45(@model2,[0 50000],[0 0 0 0 1 0 0 0 0 0 0 0
0 0 0 0 0])


          Plot(T,Y(:,1)+Y(:,5)+Y(:,9)+Y(:,14),'-')
```

APPENDIX 3

SYSTEM EQUATION & COMMAND WINDOW FOR MODEL 3

MATLAB program for the second Markov model

```
function dydt = test3(t,y,k1,k2,k3,k4,k5,k6,u1,u2,u3,u4,u5,u6)
k1=0.0000285;k2=0.00002;k3=0.000015384;k4=0.000028;
k5=0.000031;k6=0.000026;u1=0.000177;u2=0.000138;
u3=0.000216;u4=0.000143;u5=0.000177;u6=0.000138;

dydt = [-
(k1+k2+k3+k4+u5+u6)*y(1)+u1*y(40)+u2*y(10)+u3*y(2)+u4*y(3)+k5*y(
44)+k6*y(11);
    -(u3+u5+u6)*y(2)+k3*y(1);
    -(u4+u5+u6)*y(3)+k4*y(1);
    -
(k1+k2+k3+k4+u5)*y(4)+u1*y(41)+u3*y(5)+u4*y(6)+k5*y(47)+u6*y(1);
    -(u3+u5)*y(5)+k3*y(4)+u6*y(2);
    -(u4+u5)*y(6)+k4*y(4)+u6*y(3);
    -
(k1+k6+k3+k4+u5+u2)*y(7)+u1*y(42)+u6*y(10)+u3*y(8)+u4*y(9)+k2*y(
4)+k5*y(50);
    -(u2+u3+u5)*y(8)+k3*y(7);
    -(u2+u4+u5)*y(9)+k4*y(7);
    -(u2+u6+u5)*y(10)+k2*y(1)+k6*y(7);
    -
(k1+k3+k4+u5+k6)*y(11)+u1*y(43)+u2*y(7)+u3*y(12)+u4*y(13)+k5*y(5
4);
    -(u3+u5)*y(12)+u2*y(8)+k3*y(11);
    -(u4+u5)*y(13)+u2*y(9)+k4*y(11);
    -
(k1+k2+k3+k4+u6)*y(14)+u2*y(23)+u3*y(15)+u4*y(16)+u5*y(1)+k6*y(2
4);
    -(u3+u6)*y(15)+k3*y(14)+u5*y(2);
    -(u4+u6)*y(16)+k4*y(14)+u5*y(3);

-(k1+k2+k3+k4)*y(17)+u3*y(18)+u4*y(19)+u5*y(4)+u6*y(14);
    -(u3)*y(18)+u5*y(5)+k3*y(17)+u6*y(15);
    -(u4)*y(19)+u5*y(6)+k4*y(17)+u6*y(16);
```

```
  -
(k1+k6+k3+k4+u2)*y(20)+u5*y(7)+u6*y(23)+u3*y(21)+u4*y(22)+k2*y(17);
    -(u2+u3)*y(21)+u5*y(8)+k3*y(20);
    -(u2+u4)*y(22)+u5*y(9)+k4*y(20);
    -(u2+u6)*y(23)+u5*y(10)+k2*y(14)+k6*y(20);
    -(k1+k6+k3+k4)*y(24)+u5*y(11)+u2*y(20)+u3*y(25)+u4*y(26);
    -(u3)*y(25)+u5*y(12)+u2*y(21)+k3*y(24);
    -(u4)*y(26)+u5*y(13)+u2*y(22)+k4*y(24);
    -
(k5+k2+k3+k4+u1+u6)*y(27)+u5*y(40)+u2*y(36)+u3*y(28)+u4*y(29)+k1*y(14
)+k6*y(37);
    -(u1+u3+u6)*y(28)+k3*y(27);
    -(u1+u4+u6)*y(29)+k4*y(27);
    -
(k5+k2+k3+k4+u1)*y(30)+u5*y(41)+u6*y(27)+u3*y(31)+u4*y(32)+k1*y(17);
    -(u1+u3)*y(31)+u6*y(28)+k3*y(30);
    -(u1+u4)*y(32)+u6*y(29)+k4*y(30);
    -
(k5+k6+k3+k4+u1+u2)*y(33)+u5*y(42)+u6*y(36)+u3*y(34)+u4*y(35)+k1*y(20
)+k2*y(30);
    -(u1+u2+u3)*y(34)+k3*y(33);
    -(u1+u2+u4)*y(35)+k4*y(33);
    -(u1+u2+u6)*y(36)+k2*y(27)+k6*y(33);
    -
(k5+k6+k3+k4+u1)*y(37)+u5*y(43)+u2*y(33)+u3*y(38)+u4*y(39)+k1*y(24);
    -(u1+u3)*y(38)+u2*y(34)+k3*y(37);
-(u1+u4)*y(39)+u2*y(35)+k4*y(37);
    -(u1+u5+u6)*y(40)+k1*y(1)+k5*y(27);
    -(u1+u5)*y(41)+u6*y(40)+k1*y(4)+k5*y(30);
    -(u1+u5+u2)*y(42)+k1*y(7)+k5*y(33);
    -(u1+u5)*y(43)+u2*y(42)+k1*y(11)+k5*y(37);
    -
(k5+k2+k3+k4+u6)*y(44)+u1*y(27)+u2*y(53)+u3*y(45)+u4*y(46)+k6*y(54);
    -(u6+u3)*y(45)+u1*y(28)+k3*y(44);
    -(u6+u4)*y(46)+u1*y(29)+k4*y(44);
    -(k5+k2+k3+k4)*y(47)+u1*y(30)+u6*y(44)+u3*y(48)+u4*y(49);
    -(u3)*y(48)+u1*y(31)+u6*y(45)+k3*y(47);
    -(u4)*y(49)+u1*y(32)+u6*y(46)+k4*y(47);
    -
(k5+k6+k3+k4+u2)*y(50)+u1*y(33)+u6*y(53)+u3*y(51)+u4*y(52)+k2*y(47);
    -(u2+u3)*y(51)+u1*y(34)+k3*y(50);
```

```
    -(u2+u4)*y(52)+u1*y(35)+k4*y(50);
    -(u2+u6)*y(53)+u1*y(36)+k2*y(44)+k6*y(50);
    -(k5+k6+k3+k4)*y(54)+u1*y(37)+u2*y(50)+u3*y(55)+u4*y(56);
    -(u3)*y(55)+u1*y(38)+u2*y(51)+k3*y(54);
    -(u4)*y(56)+u1*y(39)+u2*y(52)+k4*y(54);
    ]
```

COMMAND WINDOW

```
[T,Y] = ode45(@test3,[0 500],[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0])


plot(T,Y(:,1)+Y(:,4)+Y(:,7)+Y(:,11)+Y(:,14)+Y(:,17)+Y(:,20)+Y(:,2
4)+Y(:,27)+Y(:,30)+Y(:,33)+Y(:,37)+Y(:,44)+Y(:,47)+Y(:,50)+Y(:,54)
,'-')
            title('Availability of Third Model')
                        xlabel('time')
                    ylabel('Availability')
```

APPENDIX 4

COMMAND WINDOW FOR MODEL 4

[T,Y] = ode45(@test4,[0 500],[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0])

Plot(T,Y(:,1)+Y(:,3)+Y(:,5)+Y(:,8)+Y(:,10)+Y(:,12)+Y(:,14)+Y(:,17)+Y(:,19)+Y(:,21)+Y(:,23)+Y(:,26)+Y(:,32)+Y(:,34)+Y(:,36)+Y(:,39)+Y(:,41)+Y(:,43)+Y(:,45)+Y(:,48)+Y(:,50)+Y(:,52)+Y(:,54)+Y(:,57)+Y(:,59)+Y(:,61)+Y(:,63)+Y(:,66)+Y(:,72)+Y(:,74)+Y(:,76)+Y(:,79)+Y(:,81)+Y(:,83)+Y(:,85)+Y(:,88)+Y(:,90)+Y(:,92)+Y(:,94)+Y(:,97)+Y(:,99)+Y(:,101)+Y(:,103)+Y(:,106)+Y(:,112)+Y(:,114)+Y(:,116)+Y(:,119)+Y(:,137)+Y(:,139)+Y(:,141)+Y(:,144)+Y(:,146)+Y(:,148)+Y(:,150)+Y(:,153)+Y(:,155)+Y(:,157)+Y(:,159)+Y(:,162)+Y(:,168)+Y(:,170)+Y(:,172)+Y(:,175),'-')

Title ('Availability of Fourth Model')

xlabel ('time')

ylabel ('Availability')