DESIGN AND DEVELOPMENT OF DECISION SUPPORT SYSTEMS FOR A PROCESS PLANT

THESIS

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by

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I, hereby, declare that this thesis entitled **DESIGN AND DEVELOPMENT OF DECISION SUPPORT SYSTEMS FOR A PROCESS PLANT** by **Anil Kr. Aggarwal**, being submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy in DEPARTMENT OF MECHANICAL ENGINEERING under Faculty of Engineering & Technology of YMCA University of Science & Technology Faridabad, during the academic year 2016-2017, is a bonafide record of my original work carried out under guidance and supervision of **Dr. VIKRAM SINGH (SUPERVISOR), PROFESSOR & Dr. SANJEEV KUMAR (CO-SUPERVISOR), ASSOCIATE PROFESSOR, DEPARTMENT OF MECHANICAL ENGINEERING, YMCAUST, FARIDABAD** and has not been presented elsewhere.

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ABSTRACT

The performance of an industrial system has great significance in recent years due to competitive environment and overall operating and production costs. The performance of an equipment or system depends on reliability and availability of the equipment used, operating environment, maintenance efficiency, operation process and technical expertise of operators, etc. When the performance of a large complex system or process plant such as chemical, paper, textile, thermal, paint, fertilizer, dairy, sugar etc. plant is low, efforts are needed to improve the performance by reducing the failure rate or increasing the repair rate for each component or subsystem of the system. The performance of an industrial system or process plant can be quantified in terms of the reliability or availability if the operating system is modeled mathematically and analyzed in real working conditions. It is necessary that these process plants should remain in upstate for a longer duration of time to have high reliability and availability by adopting some suitable maintenance strategies and find some important measures that show the criticality of the components or subsystems. These failed systems can be brought back to their upstate after repair or replacement in minimum possible down time. The reliability and availability analysis has helped to identify the critical subsystems or components of the system that need more attention for improvement. In this research work, decision matrices are developed to identify critical subsystems for improving the reliability and availability of repairable systems of the dairy and sugar plants. The availability of the systems is further optimized by means of some advanced optimization technique i.e. Genetic Algorithm (GA). Further, the concept of reliability, availability, maintainability and dependability (RAMD) analysis and fuzzy-reliability analysis are also used to identify the critical subsystem of the systems of the dairy and sugar plants. The results shows that availability and reliability measures can be used as a guideline for managing the efforts for performance improvement of the system.

Keywords: Reliability, Availability, Maintainability, Dependability, Mean Time Between Failures (MTBF), Imperfect fault coverage, Markov birth-death process, Kolmogorov Differential Equations, Decision Support System (DSS), RAMD analysis, Fuzzy-reliability, Genetic Algorithm (GA).

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LIST OF ABBREVIATIONS

R	Reliability
A	Availability
M	Maintainability
D	Dependability
S	Subsystem
DSS	Decision Support System
c	Imperfect fault coverage

$\lambda, \beta, \theta, \phi, \varepsilon, \sigma, \eta, \psi, \delta$: Failure rate of Skim milk powder production system, Butter oil production system, Steam generation system, Refrigeration system, Feeding system, Crushing system, Refining system, Evaporation system and Crystallization system resp..

$\mu, \alpha, \omega, \tau, \Delta, \rho, \xi, \gamma$, ø:Repair rate of Skim milk powder production system, Butter oil production system, Steam generation system, Refrigeration system, Feeding system, Crushing system, Refining system, Evaporation system and Crystallization system resp..

Av_1	Steady state availability of the Skim milk powder production system
Av_2	Steady state availability of the Butter oil production system
Av_3	Steady state availability of the Steam generation system
Av_4	Steady state availability of the Refrigeration system
Av_5	Steady state availability of the Feeding system
Av_6	Steady state availability of the Crushing system
Av_7	Steady state availability of the Refining system
Av_8	Steady state availability of the Evaporation system
Av_9	Steady state availability of the Crystallization system
R_1	Reliability of the Skim milk powder production system
R_2	Reliability of the Butter oil production system
R_3	Reliability of the Steam generation system
R_4	Reliability of the Refrigeration system

R_5	Reliability of the Feeding system
R_6	Reliability of the Crushing system
R_7	Reliability of the Refining system
R_8	Reliability of the Evaporation system
R_9	Reliability of the Crystallization system
$R_{F!}$	Fuzzy-reliability of the Skim milk powder production system
R_{F2}	Fuzzy-reliability of the Butter oil production system
R_{F3}	Fuzzy-reliability of the Steam generation system
R_{F4}	Fuzzy-reliability of the Refrigeration system
R_{F5}	Fuzzy-reliability of the Feeding system
R_{F6}	Fuzzy-reliability of the Crushing system
R_{F7}	Fuzzy-reliability of the Refining system
R_{F8}	Fuzzy-reliability of the Evaporation system
R_{F9}	Fuzzy-reliability of the Crystallization system
$P_i(t)$	Probability that the system is in i^{th} state at time, *t*
P_i	Probability that the system is in i^{th} state
R_{Fi}	Fuzzy-reliability of the system in i^{th} state
$P'(t)$	Derivative of P w.r.t. time ‘t’
P_c	Crossover Probability
P_m	Mutation Probability
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
MTBM	Mean Time Between Maintenance
GA	Genetic Algorithm

CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

Reliability engineering deals with the longevity and dependability of parts, products and systems. More poignantly, it is about controlling risk. Reliability engineering incorporates a wide variety of analytical techniques designed to help engineers to understand the failure modes and patterns of these parts, products and systems. Traditionally, the reliability engineering field has focused upon product reliability and dependability assurance. In recent years, organizations that deploy machines and other physical assets in production settings have begun to deploy various reliability engineering principles for the purpose of production reliability and dependability assurance. However, suitability counts on good performance of system under given operating conditions for a given period of time but, failure of the systems cannot be predicted every time, because failure is inevitable due to various causes such as change in operating conditions/ temp., voltage fluctuation, presence of vibrations etc. A system can be made reliable by providing proper repair facilities, replacement of unit within time, introduction of redundancy, proper selection of components and parts with minimum failure rates etc. as these precautions maximize the reliability of every system (Dayal and Singh, 1992). Reliability is the probability of a device or equipment performing its purpose adequately for the period intended under the given operating condition. This definition brings into focus four important factors as:

- Reliability means that there is always some chance of failure.
- Reliability is predicated on ‘intended function’. Generally, this is taken to mean operation without failure. However, even if no individual part of the system fails, but the system as a whole does not do what was intended, then it is a still charged against the system reliability. The system requirement is the criterion against which reliability is measured (Ebling, 2001).
- Reliability applies to a specified period of time (Shooman, 1968). It means that a system has a specified chance that it will operate without failure before time, *t*. Reliability ensures that components and materials will meet the requirements during the specified time. Units other than time may sometimes be used; Mechanical equipment may have a reliability rating value in terms of cycles of use. The

automotive industry might express reliability in terms of miles while, the military might express reliability of a gun for a certain number of rounds fired.

- Reliability is restricted to operation under stated conditions (Ebling, 2001). This constraint is necessary because it is impossible to design a system for unlimited conditions.

Reliability is not only a subject of study for academicians and scientists but also a serious concern to the plant engineers, manufacturer, economists etc. In the past, the reliability was recognized only in qualitative sense but during the past Second World War period, it revealed many surprising results and hence the attention was given by scientists and engineers for further serious investigation towards it due to technological advancement and increase in complexity in the system.

In recent years, research scholars and academicians are paying more attention to the real life problems of improving the performance of industrial systems such as textile industry, paper plants, fertilizer plants, dairy plants, sugar plants etc. (Kumar and Singh, 1989; Singh et al., 1990; Kumar and Tiwari, 2011) In these process plants, it is necessary that all the systems should remain update for a longer duration of time to achieve high availability and reliability. However, these systems are subjected to random failure due to various reasons like; poor product design, lack of operative skills, poor lighting and ventilation etc. These failed subsystems of the systems become operative after doing sufficient repair/replacement. This needs special considerations to the study of reliability engineering as the concept of reliability engineering plays a key role in the performance analysis of the system. When the performance of the system is low, efforts are made to improve it by reducing the failure rate or increasing the repair rate for each subsystem of the system. Suitable maintenance policies/strategies may be applied to improve the system availability and reliability. In order to plan a suitable maintenance policy/strategy, the detailed knowledge of failure rate pattern of the subsystems of the system is needed. Generally, system/reliability analysts model and analyze the system behaviour through various qualitative and quantitative techniques. These techniques require precise knowledge of numerical probabilities and functional dependencies of components of the system. Large quantity of data is needed to compute precise probabilities. Sometimes, it is very difficult to extract large quantity of data from industrial systems. In this situation, the data available either from historical data cards, logbooks or from experts are used. But, the data available may be imprecise and vague as it is collected under different operating and diverse environmental situations. Therefore, it is very hard to construct a precise and comprehensive mathematical model for industrial systems under real conditions.

In the present work such a mathematical interrelationship among all operating equipments (taking both operative as well as cold standby units) is developed for each subsystem and behavioural analysis for the systems of dairy and sugar plants are carried out. The interrelationship for various subsystems of each plant are developed using simple probabilistic approach and the mathematical formulation is done using Markov birth-death process. The performance is evaluated and utilized in predicting the future behaviour of each system of the plant.

The study is conducted in DOABA milk plant and sugar plant situated at district Palwal, Haryana. The Chapman-Kolmogorov differential equations associated with these real models with time dependent parameters are derived and solved with Runge-Kutta fourth order method. Since, in the process industries it is necessary that its various subsystems or systems should remain perpetually operative for an infinitely long duration, hence the steady state conditions is introduced and the differential equations are reduced to steady state equations which are solved recursively. The detailed study of these plants has been conducted with special reference to failure and repair time data and the existing maintenance policies being followed. In varying operating conditions, the reliability and steady state availability for each subsystem of the system are computed, tabulated and analyzed.

The objective of the present research work is to develop Decision Support Systems (DSS) for various systems of the selected plants. The mathematical modeling of each system of the plant is carried out to quantify its performance in terms of reliability and availability. However, the concept of reliability, availability, maintainability and dependability (RAMD) analysis (Adhikary et al. 2012) and fuzzy-reliability (Singh and Mahajan, 1999) are also used for performance analysis of the systems of the dairy and sugar plants. Finally, the performance (i.e. availability) of the systems is optimized with the help of some advanced optimization technique (Kumar and Tiwari, 2011) i.e. Genetic Algorithm (GA).

1.2 BASIC CONCEPTS

1.2.1 Failure rate and repair rate

The failure rate (λ) is expressed in terms of failures per unit time. It is computed as the ratio of number of failures of the items undergoing the test time (Shooman, 1968).

$$\lambda = \frac{N_f}{T}$$

where, λ =failure rate, N_f = No. of failures during test interval, T = Total test time.

The repair rate (μ) is expressed in terms of repairs per unit time. It is computed as the ratio of number of repairs (N) of the items undergoing the test time (Shoman, 1968).

$$\mu = \frac{N}{T}$$

1.2.2 Exponential distribution

The exponential distribution is most widely used distribution in reliability and risk assessment. It is the only distribution having constant hazard rate and is used to model the "useful life" of many engineering systems. The exponential distribution is closely related to the Poisson distribution, which is discrete. If the number of failures per unit time is a Poisson distribution then the time between failures follows an exponential distribution. The probability density function (PDF) of the exponential distribution is given by the equation as:

$$f(t) = \lambda e^{-\lambda t} \text{ for } 0 \le t \le \infty,$$

$$= 0 \text{ for } t < 0$$

The exponential CDF can be derived from its PDF as

$$F(t) = \int_0^t f(t)dt = \int_0^t \lambda e^{-\lambda t}\, dt = 1 - e^{-\lambda t}$$

The reliability function is the complement of the CDF

$$R(t) = 1 - F(t) = e^{-\lambda t}$$

The hazard function is the ratio of the PDF and its reliability function i.e.

$$h(t) = \frac{f(t)}{R(t)} = \frac{\lambda\, e^{-\lambda t}}{e^{-\lambda t}} = \lambda$$

The exponential hazard function is constant 'λ'. This is the reason for the *memoryless property* for the exponential distribution. The memoryless property means the probability of failure in a specific time interval is the same regardless of the starting point of that interval.

1.2.3 Mean Time Between Failures (MTBF)

It is a basic measure for the reliability of a system. It is typically represented in units of hours. The reliability of the system increases with the increase in number of MTBF. It is commonly used as a variable in reliability and maintainability analysis as

Reliability = $e^{\left[-\frac{Time}{MTBF}\right]}$

$$\text{MTBF} = \int_0^\infty R(t)dt = \int_0^\infty e^{-\lambda t}dt = \frac{1}{\lambda} \quad (1.1)$$

The constant failure rate model is widely used to reduce the computational burden of the resulting problem as the parameter MTBF obtained from equation (1.1) becomes time-independent in this case.

1.2.4 Reliability

Reliability can be defined as the probability that an item can perform a required function for a specific period of time under the specified operating conditions. Reliability of an individual component in terms of failure rate can be expressed as

$$R(t) = e^{-\int_0^t z(t)dt} \quad (1.2)$$

The reliability parameters are; mean time to failure, mean time between repairs, mean life of components and the maximum number of failures in a specific time interval. The equation (1.2) for a component with a constant failure rate get reduces as

$$R(t) = e^{-\lambda t} \quad (1.3)$$

The equation (1.3) is generally used for the calculation of reliability of a component of a given system. The reliability of the system decreases with the increase in number of components used in the system. There are two approaches used to increase the reliability of the system

(a) Increasing the reliability of the system components, and

(b) Use of redundant components in the system

Reliability is an important factor in equipment maintenance because lower equipment reliability means higher maintenance.

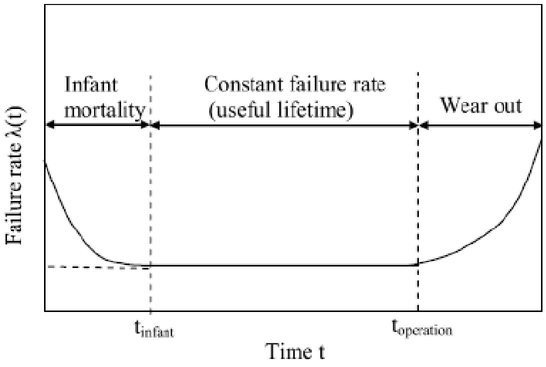


Fig1.1: Bath-Tub Curve

The basic requirement of a high plant performance is its equipment reliability because factors such as product quality, profitability and production capacity hinge on this crucial factor alone. In reliability analysis of an engineering system, it is often assumed that the hazard or time dependent failure rate of items follows the shape of a bathtub as shown in Fig. 1.1. The bathtub curve has three distinct regions: infant mortality, useful life time and wear out period. The infant mortality is also known as burn in period or debugging period. During this period the failure rate decreases and the failures occur due to design and manufacturing defects, cracks, incorrect installation or setup, mishandling, defective parts, contamination and poor workmanship etc. The burn in period failures can effectively be reduced by burn in testing, acceptance sampling and quality control techniques. In the useful life period, the failure rate is constant and the failures occur randomly or unpredictably. Some of the causes of failures in this region include insufficient design margins, incorrect use, undetectable defects, human errors and unavoidable failures i.e. ones that cannot be avoided by even the most effective preventive maintenance practices. The useful life period failures can be reduced by incorporating redundancy in the system. The wear out period begins when the item passes its useful life period. During the wear out period the hazard rate increases. Some causes for the occurrence of wear out region failures are aging, inadequate or improper preventive maintenance, limited life components, friction, misalignments, corrosion, creep and incorrect overhaul practices. Wear out period failures can be reduced significantly by executing effective replacement and preventive maintenance policies and procedures.

1.2.5 Availability

It is the measure for a unit or system to have up-time and it is basically a measure of how often the unit or system is alive and well. Generally, it is expressed in terms of up-time and down time with many variants as

(a) Instantaneous availability
(b) Average availability
(c) Steady state availability
(d) Inherent availability
(e) Achieved availability
(f) Operational availability

(a) **Instantaneous availability**

It is defined as the probability that a unit or system will be operational at any random time, t. Unlike reliability, its measure incorporates maintainability information.

(b) **Mean availability**

It is the proportion of time during a mission or time period that a unit or system is available for use. Basically, it represents the mean value of the instantaneous availability function over the period (0, t).

(c) **Steady state availability**

It is defined as the limit of the instantaneous availability function as the time approaches to infinity. The steady state availability can be considered as a stabilizing point where the availability of the system becomes a constant value.

(d) **Inherent availability**

It is the steady state availability in which corrective downtime of the unit or system is considered only. It is determined purely for the purpose of the design of equipment. It excludes logistic time, waiting time and preventive maintenance downtime.

(e) **Achieved availability**

It is the probability that a unit or system will operate satisfactorily at a given point of time under stated conditions. It includes active preventive and corrective maintenance downtime. It is very similar to inherent availability with the exception that preventive maintenance downtimes are also included.

(f) **Operational availability**

It is measure of the average availability over a period of time. It is the probability that an item will operate satisfactorily at a given point of time when used in real conditions. It includes ready time, logistics time, waiting time and both preventive and corrective maintenance downtime. It is the ratio of the system uptime and total time.

1.2.6 Maintainability

It refers to the ease with which hardware or software is restored to a functional state. A key maintainability figure of merit is the mean time to repair (MTTR) and a limit for maximum repair time. It can be expressed as

$$M(t) = 1 - \exp\left(\frac{-t}{\text{MTTR}}\right) = 1 - e^{-\mu t}$$

Where 'μ' is constant repair rate and MTTR is mean time to repair.

Ertas (1993) established a linear relation between mean time to failure (MTTF) and mean time to repair (MTTR) for a constant value of availability (A) when the reliability and maintainability are represented by exponential distributions.

$$\text{MTTR} = \left(\frac{1-A}{A}\right) \text{MTTF}$$

1.2.7 Dependability

Wohl (1996) stated that the dependability parameter provides a single measurement of the performance conditions by means of the combination of the failure and repair rates associated with reliability and maintainability respectively. It is defined as the probability that a component does not fail or does fail and can be repaired in an acceptable period of time. An important property of dependability is that it includes the simultaneous analysis of costs, reliability and maintainability. Its analysis is based on the assumption that failure and repair rates follow exponential distributions in both cases.

$$d = \frac{\mu}{\lambda} = \frac{\text{MTTF}}{\text{MTTR}}$$

$$A = \frac{\mu}{\lambda + \mu} = A = \frac{\mu/\lambda}{1 + \mu/\lambda} = \frac{d}{1 + d}$$

Ertas (1993) stated that there is significant increase in the dependability ratio (d) if the availability value is above 0.9 and there is corresponding decrease if the availability value is less than 0.1 (Fig. 1.2). The minimum value of dependability ($D_{min.}$) is given by

$$D_{min} = 1-\left(\frac{1}{d-1}\right).(e^{-\ln d/d-1} - e^{-d.\ln d/d-1}) \qquad (1.4)$$

where, d is dependability ratio.

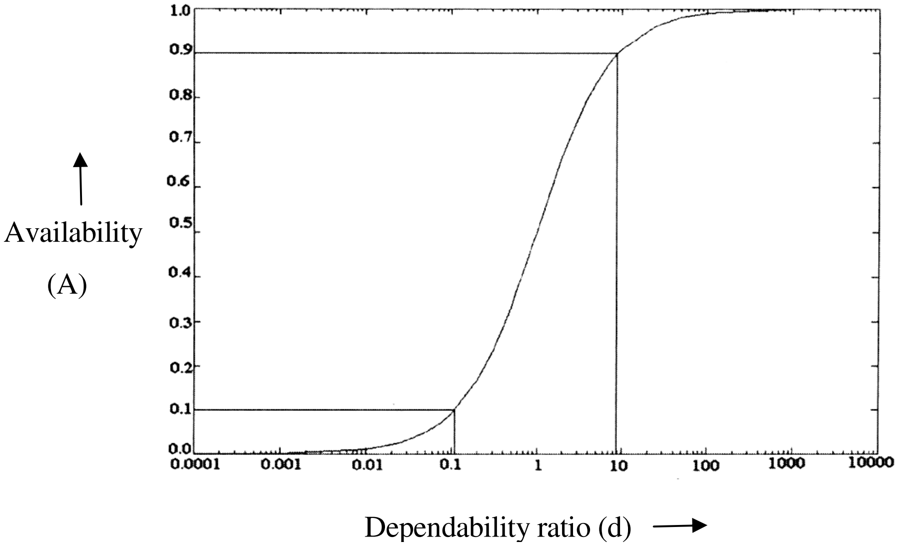


Fig. 1.2 Relation between availability and dependability ratio

1.2.8 Decision making process

The decision making is the process of identifying and choosing alternatives based on the values and preferences of the decision maker. In Decision making, the objective is to identify and choose best one among the alternative choices that has the highest probability of success or effectiveness and best fits with our goals.Therefore, the decision making is the process of sufficiently reducing uncertainties and doubts about alternatives to allow a reasonable choice to be made from among them. It should be noted here that uncertainty is reduced rather than eliminated. Very few decisions are made with absolute certainty because complete knowledge about all the alternatives is seldom possible. Thus, every decision involves a certain amount of risk. There are five elements concern with decision making;

(i) **The decision:** “The act of choosing” within the control of the decision maker. He decides the course of action to be followed.

(ii) **The alternatives:** Number of available possibilities to the decision maker for achieving his goal.

(iii) **The criteria:** The end results to be achieved by the decision maker (maximize/minimize). These are the characteristics or requirements that each alternative must possess to a greater or lesser extent.

(iv) **The constraints:** The limitations which are not to be violated e.g. manpower and capital requirements.

(v) **The events:** These are the factors beyond the control of decision maker. These are due to outside influences e.g. lack of preventive maintenance, excessive usage, fluctuations in operating parameters.

1.2.9 Decision Making Environments

Every decision is made under a certain decision environment, which is defined as the collection of information, alternatives and preferences available at the time of the decision. There are three types of decision-making environments as:

(a) **Decision making under certainty**: When decision maker has complete knowledge, information with certainty about the consequences of every course of action.

(b) **Decision making under risk**: When, the decision maker has less information than complete i.e. less certain for the complete information of the consequence of every course of action. Thus, there is more than one future events and the decision maker know the probability of occurring each future event. It implies that there are more than one states of nature (future events) and for which we make an assumption that the decision maker knows the probability with which each state of nature will occur.

(c) **Decision making under uncertainty:** When probability of occurrence of any future event is not known the decision is based upon the value of actual conditional performance along with the attitude of workers. So, decision making is not only a matter of gaining the right data but also to recognize the range of groups and industrial activities, which are involved in the process of decision-making especially for process industries like dairy, sugar, chemical, paper plants etc.

The process plants like dairy, Paper, sugar, fertilizer are complex engineering systems and their complexities are reflected in the maintenance problems. Many times, it is difficult even under the best capabilities of any decision maker to obtain all the information he would like to assure that the alternative he has chosen is the best.

1.2.10 Decision Support System

Khanduja (2008a) stated that the DSS is a well defined and documented system for applying the maintenance procedures and strategies as defined by the plant management. This system includes the availability model, the solution procedure and operating procedures for the implementation of maintenance programmes. It is generally a computer based system which can provide a data base for the purpose of maintenance planning and control. In a process industry, such data base provides up to date input for the model at any time of use. A solution procedure i.e. a program is applied to the particular model then additional computer programs may trigger the implementation of results automatically.

Generally an interactive computer based system called a decision Support helps the maintenance managers to plan maintenance strategies by using failure and or repair data. Thus, a Decision Support System generates a database information system which provides the primary data i.e. failure and repair times which are generally based upon past experience of the maintenance personnel.

The Decision Support System deals with the quantitative analysis of the factors; maintenance policies/strategies and nature of the components or subsystem of the system which influence the quality and production of the product. It is helpful to identify the subsystem or component which influences more the performance of the system. It helps to prepare a plan in advance for schedule maintenance or preventive maintenance of the system.

1.2.11 Markov birth-death process

Mahmood and Lu (2011) stated that the behaviour of many systems can be described by the set of states the system may occupy and the transition relations among all the states of the system. The probability distributions may also be associated with each system transition so that the model defines a stochastic process. As a result of such probability associations, the model allows the stochastic nature of the system and its environment to be analyzed. Queuing theory and Markov process are examples of stochastic modeling tools used to analyze steady state or transient behaviour of the system. The advantage of Markov process is that it neatly describes both the failure of a component and its subsequent repair.

A Markov process can be characterized as a process, consisting of a countable sequence of stages that can be judged at each stage to fall in to one of a countable number of states. In a Markov process, as the process moves from one stage to the next, the probability of its moving from a particular state, *i* to another state, *j* is independent of how the process arrived at state, *i* in the first place. This latter property is known as the memoryless property of Markov process and to use Markov process, it is not necessary for all elements of the system to exhibit the memoryless property; rather, the system as a whole must exhibit this property. The properties of Markov process are

(a) The process consists of a countable number of stages

(b) At each stage, the process can be in a countable number of possible states

(c) The probability of moving from state, *i* at stage *k* to state *j* at stage *k*+1 is independent of how the process actually arrived at state *i*.

Markov process of continuous-time discrete-state type is used to represent population growth, queuing models, reliability of mechanical systems etc. The Markov birth-death process is characterized by the birth rate (μ) and death rate (β) with the assumption that the birth and death events do not depends on each other. The Markov process goes from *i* to *i*+1 when birth occurs. Similarly, it goes from *i* to *i*-1 when death occurs. Dhillon and Singh (1981), Shooman (1968), Barlow and Proschan (1965), Sandler (1963), Balaguruswamy (1984) and used by Arora and Kumar (1997), Kumar et al. (1988, 1989 and 2007) stated that the behaviour of repairable systems can be described by continuous-time Markov process. Markov stated that

$$P_o\,(t+\Delta t) = (1-\delta t)\,P_o\,(t) \tag{1.4}$$

And

$$P_1\,(t+\Delta t) = \mu\Delta t\,P_o\,(t) + (1-\delta\Delta t)\,P_1\,(t) \tag{1.5}$$

Where, $P_o\,(t)$ = Probability of zero occurrences in time, *t*.

The probability of zero occurrence in time (t+Δt) is given by the equation (1.5). The equation (1.5) shows that the probability of one occurrence in time $(t+\Delta t)$ is composed of the following

(i) Multiplication of the probability of zero occurrence in time, *t* and probability of one occurrence in time interval, Δ*t* and

(ii) Multiplication of the probability of one occurrence in time, *t* and probability of no occurrence in time interval, Δ*t*.

The birth-death process is a special case of continuous time Markov process, where the states represent a current size of a population and the transitions are limited to birth and death. When a birth occurs, the process goes from state *i* to state *i*+1. Similarly, when death occurs, the process goes from state i to state *i*–1. It is assumed that the birth and death events are independent of each other. The birth-and-death process is characterized by the birth rate $\{\lambda_i\}_{i=0,\dots,\infty}$ and death rate $\{\mu_i\}_{i=0,\dots,\infty}$, which vary according to state *i* of the system. We can define a pure birth process as a birth-death process with $\mu_i = 0$ for all *i*. Similarly, a pure death process corresponds to a birth-death process with $\lambda_i = 0$ for all *i*.

1.2.12 Redundant system

To increase reliability of the system, improving the reliability of individual parts or subsystem is certainly one effective approach. However, another way to achieve this goal is to provide a redundancy in the system. In redundancy engineering; active redundancy, parallel redundancy, series redundancy and standby redundancy systems are available.

1.2.13 Fault tolerant system

It is the property of a system due to which it operates even in the presence of one or more faults. Fault tolerance has been an essential architectural attributes for achieving high reliability in many critical applications of the systems. The fault tolerant systems do not get stopped completely due to these faults (i.e. problems in hardware or software). The concept of automatic recovery and reconfiguration mechanism is used in fault tolerant systems.

1.2.14 Imperfect fault coverage

It is also known as coverage factor and it is defined as the probability of successfully covering a fault i.e. avoiding fault propagation given that the fault has occurred and it is denoted by c and its value lies between 0 and 1. If any subsystem fails, then the system immediately take reconfiguration operation within no time and reconfiguration operation will detect and remove the failed subsystem from the system. Ram et al. (2012) defined the imperfect fault coverage as the conditional probability of recovery, given that a fault has occurred i.e.

Coverage factor (c) = probability (fault detected system recovers/fault occurs)

It is one of the most important aspects to take in to account in design and evaluation of fault-tolerant systems. A system is known as fault-tolerant, if it can tolerate some faults and function successfully even in the presence of these faults. Hence, a system subjected to imperfect fault coverage may fail prior to the exhaustion of redundancy due to uncovered component failures.

1.2.15 Fuzzy-reliability model

Fuzzy-reliability of a component or system is the ability with fuzzy linguistic value to perform a required function under stated conditions within a stated period of time. The fuzzy approach is a superset of the classical Markov model. In order to simplify the presentation of fuzzy-reliability model, a non-redundant system with only one module with coverage factor (*c*) considered as shown in Fig. 1.3. The system begins in state 1_0, without faulty modules. Upon a module failure with coverage, the system transits to state 0_o and a repair may lead it again to the fault free state; otherwise, if the failure is without coverage, the transition to state 0_l takes place and only a repair can make the system return to state 1_o.

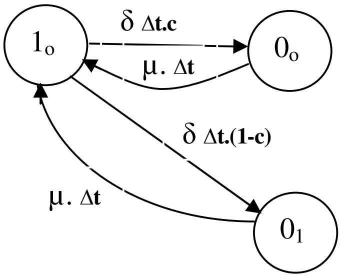


Fig. 1.3 State transition diagram with imperfect fault coverage and repair

If the system state at time, *t* is 1_0 and for the next time (t+Δt) changes to state 0_0.

If the failure is detected

$P_{10} = \delta\ \Delta t.c$

If the failure is not detected

$P_{10} = \delta\ \Delta t.\ (1\text{-}c)$

After failure detection and after repair, the system will return to the previous state as

$P_{10} = \mu\ \Delta t$

Fuzzy-reliability of a system

Suppose a system with 'n' non-fuzzy states is S_1, S_2 ….S_n. Let U= {S_1, S_2,……,S_n} denotes the universe of discourse.

The fuzzy success state is given by

S; S = {(S_i, μ_s (S_i); i=1, 2, 3... n} and Fuzzy failure state is given by

F; F= {(Si, μ_F (S_i); i=1, 2, 3... n}

Where, μ_s (S_i) and μ_F (S_i) are the corresponding membership functions respectively

The fuzzy-reliability of the system with 'n' number of states is defined as

$$R(t) = \sum_{1}^{n} \mu s(Si)Pi(t)$$

1.2.16 Genetic Algorithm

An abundance of optimization methods have been used to solve various reliability optimization problems. The algorithms applied are either heuristics or exact procedures based mainly on modifications of dynamic programming and nonlinear programming.

Most of these methods are strongly problem oriented i.e. they are designed for solving certain optimization problems i.e. they cannot be easily adapted for solving other problems.

In recent years, many studies on reliability optimization use a universal optimization approach based on metaheuristics. These metaheuristics hardly depend on the specific nature of the problem that is solved and, therefore, can be easily applied to solve a wide range of optimization problems. The metaheuristics are based on artificial reasoning rather than on classical mathematical programming. Their important advantage is that they do not require any information about the objective function besides its values corresponding to the points visited in the solution space. All metaheuristics use the idea of randomness when performing a search, but they also use past knowledge in order to direct the search. Such search algorithms are known as randomized search techniques. Genetic algorithms (GAs) are one of the most widely used metaheuristics. They were inspired by the optimization procedure that exists in nature, the biological phenomenon of evolution. A GA maintains a population of different solutions allowing them to mate, produces offspring, mutate, and fight for survival. The principle of survival of the fittest ensures the population's drive towards optimization. The most basic concept is that the strong tend to adapt and survive while the weak tend to die out i.e. optimization is based on evolution, and the "Survival of the fittest" concept. GAs has the ability to create an initial population of feasible solutions, and then recombine them in a way to guide their search to only the most promising areas of the state space. Each feasible solution is encoded as a chromosome (string) also called a genotype, and each chromosome is given a measure of fitness via a fitness (evaluation or objective) function. GA uses probabilistic rules to evolve a population from one generation to the next. GA has following parameters

(a) **Population**: To solve an optimization problem, GAs start with the string (structural) representation of a parameter set, chosen randomly. A set of such chromosomes in a generation is called a population. The size of a population may vary from one generation to another or it may be constant.

(b) **Chromosome selection**: The chromosomes are selected from the current population for reproduction. Let, there is population of size 2N; the selection procedure picks out two parent chromosomes, based on their fitness values, which are then used by the crossover and mutation operators to produce two offspring for the new population. This selection/crossover/mutation cycle is repeated until the new population contains 2N chromosomes i.e. after cycles. The higher the fitness value the higher the probability of that chromosome being selected for reproduction.

(c) **Crossover technique and mutation**: Once a pair of chromosomes has been selected, crossover can take place to produce offspring. A crossover probability of 1.0 indicates that all the selected chromosomes are used in reproduction i.e. there are no survivors. However, empirical studies have shown that better results are achieved by a crossover probability of between 0.65 and 0.85, which implies that the probability of a selected chromosome surviving to the next generation unchanged (apart from any changes arising from mutation) ranges from 0.35 to 0.15. If the crossover operator is used only to produce offspring, one potential problem that may arise is that if all the chromosomes in the initial population have the same value at a particular position then all future offspring will have this same value at this position.

The methodology for performance optimization is presented in Fig. 1.4 and stated as:

(i) Initialize the parameters of the GA
(ii) Randomly generate the initial population and prepare the coded strings
(iii) Compute the fitness of each individual in the old population
(iv) Form the mating pool from the old population
(v) Select two parents from the mating pool randomly
(vi) Perform the crossover of the parents to produce two off springs
(vii) Mutate if required
(viii) Place the child strings to new population
(ix) Compute the fitness of each individual in new population
(x) Create best-fit population from the previous and new population
(xi) Repeat the steps (iv) to (x) until the best individuals in new population represent the optimum value of the performance function i.e. availability of the system

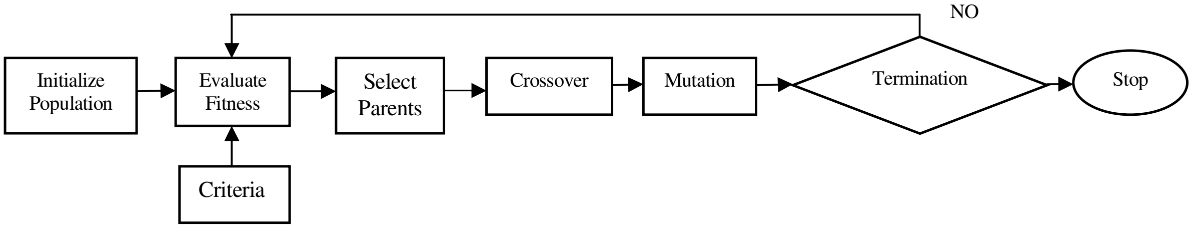


Fig. 1.4 Genetic Algorithm flow chart

1.3 PRESENT RESEARCH WORK: SIGNIFICANCE

Reliability and availability analysis of the systems has a wide scope in various process industries. A lot of research has taken place in this field in many industries like; chemical industries, fertilizer industries, soap industries, foundry units, paper mills, rice mills, pharmaceutical industries, thermal power plants etc. but the quality research is lacking in dairy and sugar plants. Therefore, the dairy and sugar plants are selected for the performance analysis and optimization of various operating systems of these plants.

1.4 RESEARCH OBJECTIVES

The research work is undertaken with the following scope of work;

(a) To understand the functioning of various subsystems of dairy and sugar plants.

(b) Mathematica lformulation of each subsystem of the plants.

(c) Development of reliability and availability models for eah subsystem of the plants.

(d) Development of Decision Support System (DSS) with the help of decision matrices.

(e) Performance optimization of each subsystem by using Genetic Algorithm (GA) technique.

(f) To identify the reasons for poor availability, poor reliability and the critical equipment.

(g) To reduce downtime and hence to improve the up-time and finally the availability and reliability of the system.

1.5 METHODOLOGY

Two process plants i.e. dairy and sugar plants are identified for this purpose and the required data for different subsystems/systems of the plants were collected by discussion with the personnel of maintenance department of the plant, log books or history sheets of the maintenance department.

Systems of the dairy plant are identified as:

(i) Skim milk powder production system
(ii) Butter oil production system
(iii) Steam generation system
(iv) Refrigeration system

Systems of the sugar plant are identified as:

(i) Feeding system
(ii) Crushing system
(iii) Refining system
(iv) Evaporation system
(v) Crystallization system

For achieving the objectives of the present research work, the following steps have been followed

(a) Development of decision support system (DSS) for reliability and availability of each system of the plant.
(b) The availability of each system is optimized by using Genetic Algorithm (GA) for improving the overall performance of the system and to plan the maintenance strategies accordingly.
(c) The reasons for the poor availability and poor reliability of the system are identified.
(d) Some maintenance management practices are suggested for reduction of downtimes, improvement of uptime, availability and reliability of the systems.

In addition to the above mentioned in research objectives, the performance of the systems is also analyzed by using the following approaches

(i) Reliability, Availability, Dependability and Maintainability (RAMD) analysis
(ii) Fuzzy-reliability analysis

1.5.1 Development of Decision Support System (DSS) for the reliability and availability of the systems of dairy and sugar plants

(a) Study the nature of various systems, subsystems of the concerned plant alongwith their failure characteristics/repair facilities/redundancy and prepare schematic process flow diagram for each system of the plant.

(b) Collection of required data/information for each subsystem of the system from maintenance history sheet/ log books or by discussion with maintenance personnel of the plant.

(c) Preparation of state transition diagram for each system of the plant.

(d) Mathematical modelling for each system of the plant is carried out to develop Chapman-Kolmogorov differential equations based on Markov birth-death process.

(e) The model for computing reliability for each subsystem of the system is developed by solving these differential equations by Runge-Kutta fourth order method.

(f) The model for computing steady state availability for each subsystem of the system is developed by solving these differential equations by recursive method.

(g) Feed the collected data (i.e. failure and repair rates) available for each subsystem in the reliability model to develop decision support system (DSS) for the reliability of the system. The DSS for reliability of the system is computed for one year under different combinations of failure and repair rates of the system.

(h) Feed the collected data (i.e. failure and repair rates) available for each subsystem in the availability model to develop decision support system for the availability of the system. The DSS for the availability of the system is computed under different combinations of failure and repair rates of the system.

(i) Based on decision support matrices, the subsystems with poor availability i.e. critical subsystems are identified.

1.5.2 Performance optimization of the systems by Genetic Algorithm (GA)

The authors involve complex computations and little work is done concerned with the systems of sugar plant (Kumar et al., 1992; Sharma and Khanduja, 2013; Sharma and Vishwakarma, 2014). Hence, the present research work is concerned with the reliability analysis of industrial systems (as mentioned above) using advance numerical method known as Runge-Kutta method and performance i.e. availability of the system is optimized with the use of genetic algorithm (GA) which gives the optimum values of process parameters i.e. failure and repair rates of each subsystem of the systems.

1.5.3 Reliability, Availability, Maintainability and Dependability (RAMD) analysis of the systems of dairy and sugar plants

Many of the authors presented models concerned with the availability analysis, while some of the authors concerned with reliability and maintainability analysis (Sharma and Kumar, 2008) for performance measurement of some industrial systems based on theoretical concept only. There is need to evaluate the performance of the industrial systems under real working conditions. In the present research work, the dependability, dependability ratio, MTBF and MTTR parameters are analyzed simultaneously in addition to Reliability, Availability and Maintainability i.e. RAM parameters (Adhikary et al., 2012) to analyze the performance of the systems in real conditions.

1.5.4 Fuzzy-reliability analysis of the systems

Conventional reliability analysis relies on the probability theory and the binary states i.e. success or failed state of a component or system only. This type of reliability analysis amplifies the uncertainty in computation of system reliability (Zadeh, 1965). To overcome this problem, the concept of fuzzy reliability (Verma et al., 2003) has been used in the evaluation of reliability of the system and the binary states i.e. success and failure of a component or system is viewed in a fuzzy way.

CHAPTER 2: LITERATURE REVIEW

A comprehensive literature review related to the reliability, availability, maintainability, dependability, Genetic Algorithm (GA) and fuzzy-reliability issues concerned with the process industries is presented in this chapter. The review of literature is sub-divided into; review of literature on reliability and availability analysis using conventional and stochastic methods, review of literature on system performance optimization using GA, review of literature on reliability, availability, maintainability and dependability analysis and performance analysis using fuzzy approach.

2.1 REVIEW OF LITERATURE ON RELIABILITY AND AVAILABILITY ANALYSIS USING CONVENTIONAL AND STOCHASTIC METHODS

Dhillon and Singh (1981), Adamyan and Dravid (2002) and Bhamare et al. (2008) used Markovian approach for the availability analysis using exponential distribution for failure and repair times. Bradley and Dawson (1998), Kumar et al. (1988, 1989, 1991 and 2007), Sharma and Garg (2011) used Markov modeling for analysis and evaluation of the performances of paper and urea fertilizer plants. Gupta and Agarwal (1984), Gupta and Sharma (1993) considered the reliability and mean time to failure (MTTF) of a complex system with different types of failures and one type of repair. Kumar et al. (1988) presented the reliability, availability and operational behaviour analysis for different systems in the paper plant. Kumar et al. (1993) dealt with maintenance planning for the systems in fertilizer and thermal plants. Michelson (1998) discussed the use of reliability technology in process industry. Singh et al. (1990) discussed the reliability and availability analysis for fertilizer industry. Somani and Ritcey (1992) presented reliability analysis for systems with variable configuration. Kumar et al. (1992) discussed the availability analysis for the Crystallization system of a sugar industry. Dayal and Singh (1992) studied reliability analysis of a system in a fluctuating environment. Singer (1990) and Arora and Kumar (1997) discussed the availability analysis of steam and powder generation systems of a thermal power plant. Singh and Jain (2000) computed the reliability of repairable multi-component redundant system. Singh and Mahajan (1999) computed the reliability and long-run availability of a utensils manufacturing plant using Laplace transformation method. Kumar et al. (1999) discussed the availability model for ammonia synthesis system of a fertilizer plant. Singh and Jain (2000) evaluated the reliability of repairable multi-component redundant system. Arora and Kumar (2000) analyzed the availability for coal handling system of a paper plant. Blischke and Murthy (2003) stated that there are many factors like; engineering design, material, manufacturing, operation, maintenance etc. which affects reliability and availability of the system. Castro and Cavalca (2003) stated that there are two ways to increase the availability of an engineering system i.e. by increasing availability of each component or by using redundant components. Gupta et al. (2005) studied the steady state behaviour of a cement manufacturing plant. Gupta et al. (2005 and 2007) discussed the long-run availability and reliability analysis for butter oil processing plant and plastic-pipe manufacturing plant respectively. Singh et al. (2005) developed a model for an ash handling system to analyze a three-unit standby system of water pumps. Tewari et al. (2000 and 2005) dealt with the determination of availability for the systems with elements exhibiting independent failures and repairs for a sugar industry. Ameri and Teri (2007) developed a method for transient analysis of availability and survivability of a system with identical components and identical repairman. Gupta et al. (2008) developed the performance model and decision support system for feed water unit of a thermal power plant. Khanduja et al. (2008a, 2008b) developed decision support system for the performance evaluation of some complex systems. Barabady and Kumar (2008) concluded that the high reliability is desirable to reduce the maintenance costs of the systems. Kumar et al. (2008 and 2009) presented a simulation model for evaluating the performance of CO-shift conversion system and urea decomposition system of a fertilizer plant. Rajiv et al. (2008) have developed performance evaluation system for the screening unit of a paper plant. Sanjeev et al. (2008, 2009 and 2010) dealt with simulation model for evaluating the performance of urea decomposition system of a fertilizer plant. Gupta et al. (2009) discussed the reliability and availability analysis of the ash handling unit of a steam thermal power plant. Kumar et al. (2009) performed the performance evaluation and availability analysis for ammonia synthesis unit of a fertilizer plant. Garg et al. (2010) analyzed the availability of crank-case manufacturing system in an automobile industry. Rigdon et al. (2000), Gertsbakh (2000) and Lim et al. (2000) described the various methods for the reliability analysis of repairable systems. 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, Lisnianski (2007) performed reliability assessment for a multistate system with repair facility using extended block diagram method. 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. 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. Sharma et al. (2008, 2009) proposed the performance modeling for different process industries using reliability and availability analysis. 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 for a pipe manufacturing industry by using supplementary variable technique. 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) provided a risk-based stochastic modeling approach using a Markov decision process to assess availability of a processing unit, which was referred as the risk-based availability Markov model (RBAMM). 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. Kiilumen and Frisk (2014) proposed a method to examine the long-term reliability of an anisotropic conductive adhesive (ACA) attached polyethylene terephthalate (PET) flex-on-board (FOB) assembly for industrial application used in harsh environment and the possibility of reducing reliability testing time was also studied. 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.

2.2 REVIEW OF LITERATURE ON SYSTEM PERFORMANCE OPTIMIZATION USING GENETIC ALGORITHM (GA)

Yokota et al. (1995) utilized GA to solve successfully the reliability optimization problem of series-parallel system with parallel components and several failure modes. Deb (1995) explained the use of optimization techniques for performance optimization of engineering problems. Painton and Campbell (1995) solved the reliability optimization problem related to personal computer design. A personal computer was considered as a series-parallel system of twelve components, each of which has three optional packages. Hsieh et al. (1998) utilized genetic algorithms and solved various reliability design problems, such as reliability optimization of series systems, series parallel systems and complex systems. Goldberg (2001) made a systematic study on GA mechanism and identified three basic operators; reproduction, crossover and mutation so that the GA has higher opportunity for obtaining near optimal solutions. Chales and Kondo (2003) tackled a multi objective combinatorial optimization problem by using genetic algorithm to optimize the availability and cost of a series and parallel repairable system. Tewari et al. (2003) dealt with the determination of availability for the systems with elements exhibiting independent failures and repairs or the operation with standby elements for sugar industry. They also dealt with mathematical modeling and behavioural analysis for a Refining system of a sugar industry using Genetic Algorithm. Nourelfath (2007), Marquez et al. (2007) and Zhao et al. (2007) studied the latest concepts in system reliability optimization. Juang et al. (2008) presented a new method to compute optimal values of MTBF and MTTR based on GA. Moghaddam et al. (2008) studied the reliability optimization of the complex systems. Taboada et al. (2008) and Khanduja et al. (2009) recently studied the reliability optimization of the complex systems. Kumar et al. (2010) discussed the availability optimization of CO shift conversion system of a fertilizer plant using Genetic Algorithm. Kumar and Tewari (2011) discussed the mathematical modeling and performance optimization of CO_2 cooling system of a fertilizer plant using genetic algorithm. Chatterjee and Bandopadhyay (2012) developed a neural network based model for forecasting reliability and genetic algorithm was applied for selecting neural network parameters. Kajal (2012) discussed the performance optimization for milk processing unit of a dairy plant. Okafor and Sun (2012) studied a series-parallel system with active redundancy and proposed genetic pareto set identification algorithm (GPSIA) for reliability-redundant multi-objective optimization problem. Safari (2012) developed a variant of the non-dominated sorting GA to solve a novel mathematical model for multi-objective redundancy allocation problems. Rathod et al. (2013) presented a comparative study of different formulation approaches of reliability based robust design optimization (RBRDO) and their performances. Kanagaraj et al. (2013) hybridized cuckoo search (CS) with genetic algorithm (GA) to solve the reliability and redundancy allocation problem. Katherasan et al. (2013) used genetic algorithm to optimize the welding parameters for the flux cored arc welding process. Marseguerra et al. (2006) explained the basics of genetic algorithm optimization for RAMS applications. Sahoo et al. (2014) used stochastic programming technique to convert the chance constraints in to deterministic form and the corresponding problem is transformed to mixed-integer constrained optimization problem with interval objective. Toledo et al. (2014) applied genetic algorithm embedded with mathematical programming techniques to solve a synchronized and integrated two-level lot sizing and scheduling problem for soft drink production.. Tsai and Fu (2014) considered the discrete optimization via simulation problem with single stochastic constraints and presented two genetic algorithm-based algorithms that adopt different sampling rules and searching mechanisms.

Many authors solved the problems concern with the redundancy allocation for different types of industrial systems by using genetic algorithm with the consideration of cost and weight as constraints (Colt and Smith, 1996a, b; Ramachandran et al., 1997).

Taguchi and Yokota (1999) formulated a NIP problem for the system reliability by using Genetic Algorithm.

Some of the academicians or researchers formulated to solve the problems of multi-objective optimization by using GA (Elegbede and Adjallah, 2003; Konak et al., 2006; Azaron et al. 2009). Martorell et al. (2004) developed two GA based methods to solve multi-objective optimization problems based on availability, reliability and maintainability. Minguez et al. (2005) developed a method for the sensitive analysis to calculate the rate of change of cost and reliability indices. Azaron et al. (2009) solved a multi-objective discrete reliability problems using GA approach. Shao et al. (2009) presented a model in which scheduling functions and process planning were carried out simultaneously.

2.3 REVIEW OF LITERATURE ON RELIABILITY, AVAILABILITY, MAINTAINABILITY AND DEPENDABILITY ANALYSIS

Jackson (1988) developed a RAMCAD methodology, which consists of interfacing reliability, maintainability and supportability (RMS) computerized analysis with computer-aided design. Jobe (1988) presented new R&M measures for the systems. The reliability and maintainability measure is referred to as MTUT. It is the mean time to restore equipment to its original working status; it is expressed as a proportion of the mean time to failure for any given equipment. DuJulio and Leet (1988) presented space station synergetic RAM-Logistics analysis, this study emphasizes to analyze the maintenance activities and processes that can be accomplished on-orbit within the known design and support constraints of the space station. Cockerill (1990) presented a Reliability, Availability and Maintainability (RAM) analysis for a turbine-generator system. Guthrie et al. (1990) developed RAM program guidelines to present a structured RAM process for integrating RAM considerations in each defined project phases. Hansen (1990) discussed the reliability and maintainability aspects of components in computer aided engineering. McFadden (1990) proposed the techniques for the development of reliability, availability and maintainability improvement program for an industrial plant. Sherrieb and Stracener (1991) presented R&M issue in conceptual aircraft design. Kumar et al. (1992) presented some results from an analytic study of reliability and availability of the Crystallization system of a sugar plant. Jokubaitis and Quinn (1992) discussed the new army methods for assessing the RAM requirements of a system. Hansen et al. (1992) developed a RAM expert system to conduct weapon system RAM performance analysis.

Born and Criscimagna (1995) developed a methodology to evaluate the need of reliability, maintainability and diagnostics for translation processes. Wohl (1966) defined the dependability concept as the probability that an entity does not fail, or does fail and can be repaired in an acceptable period of time. This definition is an important design parameter, because it provides a single measurement of the performance conditions by means of the combination of the failure and repair rates associated to reliability and maintainability respectively. Edson and Hansen (1996) developed a software RAM engineering system to aid in management and implementation of a post deployment support process for computer software. Carlier et al. (1996) evaluated the reliability, availability, maintainability and safety requirements for manned space vehicle with extended on-orbit stay time. Tatry et al. (1997) presented an advance study on RAMS (reliability, availability, maintainability and safety) for a reusable launch vehicle. Van Baaren and Smit (1998) presented a framework to develop and implement the RAMS in the design and development process of large complex system. Hajeeh and Chaudhuri (2000) worked on assessment of reliability and availability for reverse osmosis. Barabady (2005) presented the reliability and maintainability analysis of crushing plants. In this study crushing plants are divided into seven subsystems. Jackson et al. (2005) developed a guide for achieving and assessing RAM. Rajpal et al. (2006) used artificial neutral networks method to model the performance of a complex repairable system. Sunand et al. (2007) discussed the simulated availability of fertilizer plant. Sharma and Kumar (2008) used Markovian approach to model the system behaviour and presented the application of RAM analysis in a process industry. Markovian approach is used to model the system behaviour. Adhikary et al. (2012) investigated the reliability, availability and maintainability characteristics of a 210 MW coal-fired thermal power plant.

2.4 REVIEW OF LITERATURE ON PERFORMANCE ANALYSIS USING FUZZY APPROACH

Zadeh (1965) introduced the concept of fuzzy sets. Singh (1989) evaluated the reliability parameters for a biogas plant using Markov chains. Cai et al. (1991) discussed survivability index for CCNs; a measure of fuzzy-reliability. Cai et al. (1991) presented profust reliability theory based on the probability assumptions and the fuzzy-state assumptions. Pham (1992) analyzed a high voltage system with imperfect coverage in which the failure rate of the fault coverage was a constant. Akhtar (1994) analyzed the reliability of K-out-of-n: G system with imperfect fault coverage. Powel et al. (1965)

stated that the imperfect fault coverage is used to quantify the efficiency of fault-tolerant systems, since the validation of fault-tolerant systems is based on the efficiency of their fault tolerance mechanisms. Liang et al. (1993) presented fuzzy fault tree analysis incorporating the assumption of failure possibilities. Zaho (1994) developed an availability model for repairable component of series system including perfect and imperfect repair. Chen (1994) analyzed the system reliability by using fuzzy number arithmetic operations. Moustafa (1997) studied a K-out-of-N system with imperfect coverage. Wu (1997), Jiang and Chen (2003) studied the fuzzy system reliability. Vaurio (2002) dealt with a method for quantifying the uncertainties in common cause failures. Verma et al. (2003) represented two approaches to model fuzzy availability of deteriorating systems. Verma et al. (2004) proposed semi-Markovian approach for availability modeling of a deteriorating system under fuzziness. Klir and Yuan (2005) discussed some basic concepts of fuzzy set theory and their applications in detail. Kumar et al. (2005) described a methodology for fuzzy Markov model to determine the fuzzy state probabilities of generating units. Huang et al. (2006) did a fuzzy analysis for steady state availability. Levitin and Amari (2008) suggested a modified reliability block diagram method concerned with the multi-fault coverage for multi-state systems. Kumar et al. (2009) analyzed fuzzy-reliability and fuzzy availability for the butte-oil processing plant for various choices of failure and repair rates of its subsystem. Ke et al. (2008) analyzed a redundant repairable system with imperfect coverage and fuzzy parameter. Wang et al. (2009) performed the reliability optimization of a series parallel system with fuzzy approach. Komal et al. (2010) developed a hybridized technique based on Genetic Algorithm and Lambda-Tau to analyze the system's behaviour up to a desired degree of accuracy utilizing imprecise data. Garg and Sharma (2011) presented a technique for analyzing the behaviour of an industrial system with the use of vague, imprecise and uncertain data. Kumar and Kumar (2011) developed a method for analyzing the fuzzy system reliability of series and parallel systems using intuitionistic fuzzy set theory. Garg and Sharma (2012) presented a technique for analyzing the behaviour of an industrial system utilizing vague, imprecise, and uncertain data. Garg and Sharma (2011) presented the application of RAM analysis for urea decomposition system in a fertilizer plant by using Fuzzy Lambda–Tau methodology to model the system behaviour. Ram et al. (2012) discussed the effect of coverage factor on the reliability characteristics of a parallel redundant complex system. Garg et al. (2013) presented a technique for analyzing the behaviour of an industrial system stochastically by utilizing vague, imprecise, and uncertain data. This technique utilizes Petri nets and fuzzy Lambda-Tau method for analyzing the reliability indices of time varying failure rate instead of the constant failure rate. . Kumar et al. (2013) developed an approach for computing various performance measures such as reliability, availability, MTBF, ENOF etc. for an industrial system. Razak and Raj Kumar (2013) presented a new model for fuzzy system reliability analysis based on fuzzy semi-Markov model with fuzzy transitions. Verma et al. (2013) evaluated reliability parameters by presenting a new methodology, named vague Lambda-Tau used for reliability analysis of a combustion system. Chandna and Ram (2014) applied fuzzy time series to forecast the availability of a standby system incorporating waiting time to repair. Damcese et al. (2014) analyzed both series and parallel system composed of three identical or different elements using the fuzzy concepts. Jamkhaneh (2014) investigated the reliability characteristics under fuzzy environment by using fuzzy Weibull distribution. Patrai and Uprety (2014) analyzed the effect of repair and coverage factors for a four unit degradable system. Seth et al. (2014) proposed service oriented system reliability based on an adaptive neuro-fuzzy inference system approach. Sicre et al. (2014) proposed a method for the online recalculation of efficient driving is a genetic algorithm with fuzzy parameters based on an accurate simulation of the train motion. Garg et al. (2014) presented a novel technique named as an artificial bee colony (ABC) algorithm based Lambda–Tau (ABCBLT) technique for analyzing the behaviour of an industrial system by utilizing vague, imprecise, and uncertain data.

2.5 PRESENT STATUS

A review of the literature concludes that the authors used different methods to compute steady state availability for different systems and computation of steady state availability is extensively covered in the literature. The review of literature brings out the following gaps in the context of design and development of decision support systems as:

- Insufficient literature is available to develop the decision support system for the reliability and availability analysis of the industrial systems.
- Insufficient literature is available which explores fuzzy-reliability analysis for the process plants.
- Little literature is available which explores Reliability, Availability, and Maintainability (RAM) analysis for process plants.
- Literature is not available concerned with Reliability, Availability, Maintainability and dependability (RAMD) analysis of the industrial systems.

CHAPTER 3: SYSTEM DESCRIPTION

3.1 INTRODUCTION

The Skim milk powder production system, Butter oil production system, Steam generation system and Refrigeration system of the dairy plant and Feeding system, Crushing system, refined system, Evaporation system and Crystallization system of the sugar plant are analyzed for performance analysis.

3.2 ASSUMPTIONS

The assumptions used in development of the performance models for the systems of dairy and sugar plants are:

(a)Failure and repair rates are constant over time and they are statistically independent
(b)A repaired subsystem is as good as new, performance wise for a specified duration
(c)Sufficient repair facilities are available i.e. no waiting time to start the repairs
(d)Service includes repair and /or replacement
(e)Standby units (if any) are of the same nature and capacity as the active units
(f)Failure and repair rates follow exponential distribution
(g)There are no simultaneous failures among systems

3.3 NOTATIONS

⬭	Start: This symbol marks the starting point of the system
◇	Decision: A decision or branching point. Lines representing different decisions emerge from different points of the diamond.
▭	Action/Process: A box can represent a single step or entire sub-process within a larger process.

The various notations associated are given in Table 3.1. Based on assumptions and notations, state transition diagrams were drawn for different systems. These diagrams give the visual representation of the various states of the system at any instant of time.

Table 3.1 Notations used in the analysis of dairy and sugar plants

S. No.	State	Dairy plant				Sugar plant				
		Skim milk production system	**Butter oil production system**	**Steam generation system**	**Refrigeration system**	**Feeding system**	**Crushing system**	**Refining system**	**Evaporation system**	**Crystallization system**
1	Schematic process flow diagram	Fig. 3.1	Fig. 3.2	Fig. 3.3	Fig. 3.4	Fig. 3.5	Fig. 3.6	Fig. 3.7	Fig. 3.8	Fig. 3.9
2	State transition diagram	Fig. 4.1	Fig. 4.5	Fig. 4.9	Fig. 4.13	Fig. 4.17	Fig. 4.21	Fig. 4.25	Fig. 4.29	Fig. 4.33
3	Schematic representation	Fig. 4.2	Fig. 4.6	Fig. 4.10	Fig. 4.14	Fig. 4.18	Fig. 4.22	Fig. 4.26	Fig. 4.30	Fig. 4.34
4	State transition of subsystem	Fig. 4.3	Fig. 4.7	Fig. 4.11	Fig. 4.15	Fig. 4.19	Fig. 4.23	Fig. 4.27	Fig. 4.31	Fig. 4.35
5	State transition diagram with imperfect fault coverage	Fig. 4.4	Fig. 4.8	Fig. 4.12	Fig. 4.16	Fig. 4.20	Fig. 4.24	Fig. 4.28	Fig. 4.32	Fig. 4.36
6	Full capacity (without standby)	A1 to A5	B1 to B6	C1 to C5	D1 to D5	E1 to E4	F1 to F3	G1 to G4	H1 to H3	J1 to J3
7	Full capacity (with standby)	A4*, A5*	B4*	C3*, C5*	D1*, D2*	E1*, E3*, E4*	F3*	G1*,G1**, G3*	H1*, H3*	J1*, J2*, J2**
8	Failed states	a1 to a5	b1 to b6	c1 to c5	d1 to d5	e1 to e4	f1 to f3	g1 to g4	h1 to h3	j1 to j3
9	Failure rates	λ_1 to λ_7	β_1 to β_7	θ_1 to θ_7	ϕ_1 to ϕ_7	ε_1 to ε_7	σ_1 to σ_4	η_1 to η	ψ_1 to ψ_5	δ_1 to δ_6
10	Repair rates	μ_1 to μ_7	α_1 to α	ω_1 to ω_7	τ_1 to τ_7	Δ_1 to Δ_7	ρ_1 to ρ_4	ξ_1 to ξ_7	γ_1 to γ_5	$\emptyset_1$ to $\emptyset_6$
11	Prob. of full capacity (without standby)	P_o	P_1	P_o	P_1	P_1	P_1	P_1	P_1	P_1
12	Prob. of full capacity (with standby)	P_1 to P_3	P_2	P_1 to P_3	P_2 to P_4	P_2 to P_8	P_2	P_2 to P_6	P_2 to P_4	P_2 to P_6
13	Probability of failed states	P_4 to P_{19}	P_3 to P_{13}	P_4 to P_{19}	P_5 to P_{20}	P_9 to P_{28}	P_3 to P_7	P_7 to P_{25}	P_5 to P_{12}	P_7 to P_{17}

3.4 DAIRY PLANT

Milk production in India has developed significantly in the past few decades from a low volume of 17 million tons in 1951 to 110 million tonnes in 2009. Currently, the Indian dairy market is growing at an annual rate of 7%. Despite the increase in production, a demand supply gap has become imminent in the dairy industry due to the changing consumption habits, dynamic demographic patterns, rapid urbanization of rural India and lower productivity of the dairy plants. Hence, there is need to enhance the productivity by improving the reliability and availability of the systems of the plants. The dairy plant includes Skim milk powder production system, Butter oil production system, Steam generation system and Refrigeration system.

3.4.1 Skim milk powder production system

A sample of milk is tested and then it is filtered. The filtered milk is cooled to about 5^{o}C and then it is stored in silos for 12 to 24 hours. The fresh milk has a tendency to get separated into high-fat cream layers on the top of low-fat milk layer. The separation of cream from the milk is usually accomplished with Centrifugal cream separator in the plant. The skim milk has as much fat removed as much possible and it should not contain more than 0.5% milk fat by weight and usually contains less than 0.5 gm of fat per cup. The pasteurization of the milk is done to kill harmful microorganism by heating for a short time and then immediately cooling it. The skim milk gets concentrated due to evaporation of water when subjected to superheated steam in an Evaporator. The concentrated skim milk is injected through nozzles to convert in the form of fine mist or droplets in a Drying chamber. These droplets of milk get converted in to fine powder inside the Drying chamber. The skim milk in powder form is known as skim milk powder and it is collected at the bottom of the Drying chamber.

The skim milk powder production system comprises of the following six subsystems with series or parallel configurations as shown in Fig. 3.1.

(a) Subsystem A1 (Chiller): The filtered milk received after testing get chilled to about 5^{o}C and stored in silos. It is a single subsystem connected in series and failure of this subsystem causes the complete failure of the system. It is provided with Pump, Compressor etc. connected in series.

(b) Subsystem A2 (Cream separator): It is based on the principle of centrifugal force. The fat from the milk get separated in the form of cream and remaining skim milk is stored in skim milk silos. It is single unit connected in series and failure of this subsystem causes the complete failure of the system. It is provided with bearings, motor, gearbox connected in series.

(c) Subsystem A3 (Pasteurizer): Pasteurization is a process, in which every particle of the milk is heated to at least 72°C or below. During this process, the pathogenic and spoilage organisms get destroyed. The milk is immediately cooled to 4°C after pasteurization process. It is single subsystem connected in series and failure of this subsystem causes the complete failure of the system. It is provided with bearings, motor etc.

(d) Subsystem A4 (Evaporator): The skim milk is heated with saturated steam under low pressure in an Evaporator to increase its concentration. It consists of two subsystems connected in parallel; one operative and other in cold standby state with perfect switch over devices. The complete failure of the system will occur when both subsystems get failed at a time. It is provided with pump, motor, temperature and pressure measuring devices.

(e) Subsystem A5 (Drying chamber): The concentrated skim milk is converted in the form of fine mist or droplets by passing through nozzles. These droplets of skim milk get converted in to fine powder when subjected to superheated air inside the chamber. The skim milk in powder form is collected at the bottom of the Drying chamber. It consists of two subsystems connected in parallel; one operative and other in cold standby with perfect switch over devices. The complete failure of the system will occur when both subsystems get failed at a time. It is provided with mechanical vibrator, motor, atomizing devices connected in series.

(f) Packaging: The skim milk powder is normally packed and distributed in bulk containers or 25 kg packing. It is assumed that this subsystem never fails.

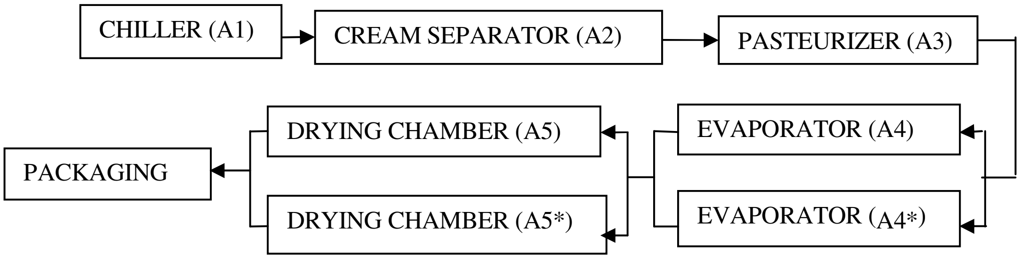


Fig. 3.1 Schematic Process flow diagram of Skim milk powder production system

3.4.2 Butter oil production system

Butter oil may be defined as fat concentrate obtained exclusively from butter or cream resulting from the removal of practically the entire water and solid-not-fat (SNF) content i.e. changing whole milk to butter oil is a process of transforming a fat-in-water emulsion (milk) to anhydrous milk fat. The Butter oil production system comprises of the following six subsystems with series or parallel configurations as shown in Fig. 3.2.

(a) Subsystem B1 (Chiller): The filtered milk is chilled to about 5^{o}C and stored in silos. It is a single subsystem connected in series and failure of this subsystem causes the complete failure of the system.

(b) Subsystem B2 (Cream separator): The fat from the milk get separated in the form of cream due to difference in density when acted upon by centrifugal force in the cream separator. It is a single unit connected in series and failure of this subsystem causes the complete failure of the system.

(c) Subsystem B3 (Pasteurizer): The cream containing 45% to 50% fat is subjected to pasteurization process. After pasteurization, the temp. of the cream is lowered to 5-6^{0}C. The cream is then allowed to stand for at least two hours, and then the temperature of cream is raised to about 18-21^{0}C. It is a single subsystem connected in series and failure of this subsystem causes the complete failure of the system.

(d) Subsystem B4 (Continuous butter making): The cream is pumped to the churner or continuous butter making (CBM) machine. In churning process, the cream is violently agitated until the fats separate from liquid (buttermilk) and the butter is in semi-solid state. Finally, the butter usually carries 80% to 85% fat, 15-16% water and 2% solid-not-fat (SNF). It is yellow or white in colour. It consists of two subsystems connected in parallel; one operative and other in cold standby condition. The complete failure of the system will occur when both subsystems get failed at a time.

(e) Subsystem B5 (Melting vats): It consists of a double jacket storage tank and hot water is circulated in the jacket. The butter is melted to get butter oil, it is a single subsystem connected in series and failure of this subsystem causes the complete failure of the system.

(f) Subsystem B6 (Butter oil clarifier): The Butter oil clarifier is also known as settling tanks in which the butter oil from melting vats is taken and kept for few hours to settle down fine and suspended particles. It is a single subsystem connected in series and failure of this subsystem causes the complete failure of the system.

(g) Packaging: The butter oil is normally cooled and packed in 25 kg paper packing. It is assumed that this subsystem never fails.

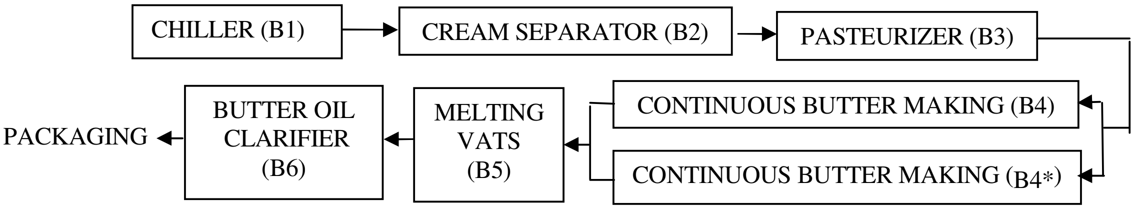


Fig. 3.2 Schematic Process flow diagram of Butter oil production system

3.4.3 Steam generation system

The dry saturated steam is produced in water-tube boilers and it is distributed in the dairy plant through pipes. The dry saturated steam is used in pasteurization process and for washing and sterilization of the process equipments. The Steam generation system consists of five subsystems namely; low pressure (L.P.) pump, Feed pump, high pressure (H.P.) pump, Economizer and Boiler drum connected in series or parallel as shown in Fig. 3.3. The Steam generation system comprises of the following five subsystems

(a) Subsystem C1 (L.P. Heater): Its function is to raise the temperature of condensate from Condensate pump discharge temperature to the de-aerator inlet temperature. It is a single subsystem connected in series and failure of this subsystem causes the complete failure of the system.

(b) Subsystem C2 (Feed Pump): This pump closes the boiler, steam and condensate loop by returning the condensate back into the system for re-use. It is a single unit connected in series and failure of this subsystem causes the complete failure of the system.

(c) Subsystem C3 (H.P. Heater): Its function is to raise the temperature of feed water from de-aerator outlet temperature to the required boiler economizer inlet. It consists of two subsystems connected in parallel; one operative and other in cold standby condition. Complete failure of the system will occur when both of its units get failed at a time.

(d) Subsystem C4 (Economizer): It is feed water heater, deriving heat from flue gases. It is a single subsystem connected in series and failure of this subsystem causes the complete failure of the system.

(e) Subsystem C5 (Boiler Drum): Water-tube type boiler drum is used due to its light weight and as it can respond quickly to the change in steam demand. It consists of two subsystems connected in parallel; one operative and other in cold standby condition. Complete failure of the system will occur when both of its units get failed at a time.

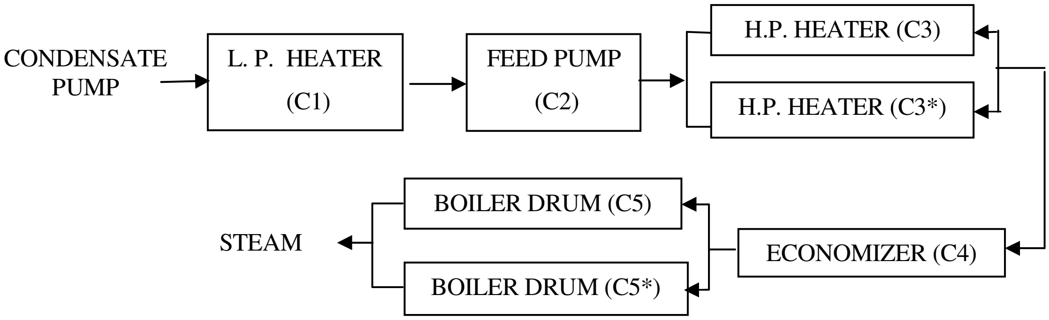


Fig. 3.3 Schematic Process flow diagram of Steam generation system

3.4.4 Refrigeration system

In the dairy plants, refrigeration is produced primarily for refrigeration of storage rooms and cooling of liquids. The refrigeration equipment most frequently used in the dairy plant is compression refrigeration machines with ammonia or compounds based on chlorofluorocarbons (CFCs) as refrigerant. The refrigerating agent can be used for cooling storage rooms directly or it can be used to cool a second fluid refrigerant usually brine or glycol water for indirect refrigeration. A Refrigeration system consists of number of subsystems namely; Compressor, Condenser, Ammonia storage and Evaporator connected to each other either in series or parallel. The Refrigeration system comprises of the following five subsystems as shown in Fig. 3.4.

(a) Subsystem D1 (Compressor): The refrigerant is pumped round the circuit by a compressor and the rate of circulation primarily determines the heat extraction capacity. It consists of two subsystems connected in parallel; one operative and other in cold standby with perfect switch over devices. Complete failure of the system will occur when both subsystems failed at a time.

(b) Subsystem D2 (Condenser): The refrigerant in the form of hot gas enters in shell and tube type condenser. It consists of two subsystems connected in parallel; one operative and other in cold standby with perfect switch over devices. Complete failure of the system will occur when both subsystems failed at a time.

(c) Subsystem D3 (Ammonia storage): It acts as reservoir of the refrigerant. It is a single subsystem connected in series and failure of this subsystem causes the complete failure of the system.

(d) Subsystem D4 (Expansion valve): The temperature of the liquid refrigerant gets reduced further by reducing its pressure. It is a single subsystem connected in series and failure of this subsystem causes the complete failure of the system.

(e) Subsystem D5 (Evaporator): The liquid refrigerant evaporates progressively as it passes through the evaporator. The evaporator is arranged for indirect cooling and it is situated in a brine tank. The brine or chilled water is circulated independently. The brine or chilled water acts as a buffer because of its great heat capacity. It is a single subsystem connected in series and failure of this subsystem causes the complete failure of the system.

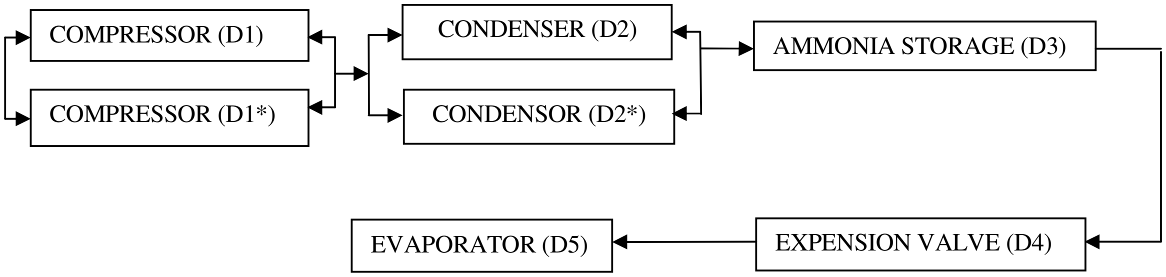


Fig. 3.4 Schematic Process flow diagram of Refrigeration system

3.5 SUGAR PLANT

India ranks first in sugar consumption and second in sugar production in the world. Globalization has brought a number of opportunities but at the same time posed certain challenges before sugar industry. Mounting losses and decreasing net worth of sugar factories have been responsible for sickness of sugar industry. India has to gear up to the new challenges of higher cane and sugar production to meet the future requirement. With the present trend of sugarcane and sugar production India will be hard, to sustain effort and is needed to increase the present trend of cane production to a level that India becomes a sugarcane surplus country. Sugar cane is a raw material that can be transformed in to many end products; sugar, alcohol for alcoholic beverages, ethanol for fuel, alcohol for industrial and antiseptic uses, paper pulp, solid pellet fuels for domestic stoves, organic fertiliser (compost) for agriculture, and thermal and electric energy for in-process use and grid supply. The sugar plant includes; Feeding system, Crushing system, Refining system, Evaporation system and Crystallization system. There are a number of steps in producing raw sugar from cane:

(i) Cane receiving and unloading i.e. receive the cane at the factory and unload it from the transport vehicles
(ii) Cane preparation
(iii) Juice extraction
(iv) Juice clarification
(v) Juice evaporation
(vi) Crystallisation
(vii) Separation of the sugar crystals from the mother liquor, most done by centrifugal machines
(viii) Sugar drying
(ix) Packaging and delivery

These processing steps will produce a brown or raw sugar. Mill white sugar also known as plantation white sugar can be produced by introducing some form of colour removal process (i.e. sulphitation) between the juice clarification and the juice evaporation stages. The raw sugar produced is often refined to produce white sugar. This sugar refining can be done either at a completely separate factory or at a back-end refinery which is attached to the raw sugar factory.

3.5.1 Feeding system

After the truck is weighed and the testing concluded, processing begins. The cargo is transferred to conveyor belts that carry the cane to the Crushing system. Cane that was cut manually is first washed to remove impurities. The water is treated and re-utilized. The cane is then chopped up and readied for crushing. The Feeding system comprises of the following four subsystems with series or parallel configurations as shown in Fig. 3.5.

(a) Subsystem E1 (cutting system): It has conveyor with cutters to cut sugar cane in to small pieces. It has two subsystems with parallel configuration; one is operative while other remains in cold standby state. The complete failure of the system takes place when both subsystems get failed at a time.

(b) Subsystem E2 (Crushing system): It consists of conveyor and a crusher. It is used to extract raw juice by crushing the small pieces of sugar cane. It is a single subsystem connected in series and failure of this subsystem causes the complete failure of the system.

(c) Subsystem E3 (Bagasse carrying system): Its function is to move the crushed sugar cane pieces to the Heat generating system. The crushed cane pieces are used as fuel for boilers. The use of bagasse is to increase the efficiency of Heat generating system. It has two subsystems with parallel configuration; one is operative while other remains in cold standby state. The complete failure of the system takes place when both subsystems get failed at a time.

(d) Subsystem E4 (heat generating system): The coal, wood or bagasse i.e. crushed cane is used to generate the heat required in sugar plant. It has two subsystems with parallel configuration; one is operative while other remains in cold standby state. The complete failure of the system takes place when both subsystems get failed at a time.

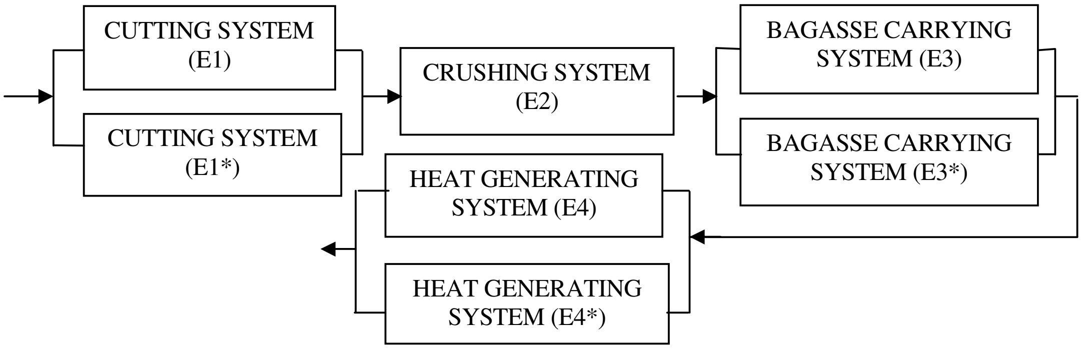


Fig.3.5 Schematic Process flow diagram of Feeding system

3.5.2 Crushing system

Juice extraction by crushing is the process of squeezing the juice from the cane under high pressure between heavy iron rollers. Imbibition water is used to improve the extraction efficiency of the crushing process: Hot water is poured over the cane just before it enters the last mill in the Milling train. The juice squeezed from this cane is low in sugar concentration and is pumped to the preceding mill and poured onto the can just before it enters the rollers, the juice from this mill is the same way pumped back up the Milling train. Mixed juice i.e. cane juice mixed with the water introduced at the last mill is withdrawn from the first and second mills and is sent for further processing. Milling trains typically have four, five or six mills in the tandem. Finally, the juice is collected, filtered and sometimes treated and then boiled to drive off the excess water. The dried cane residue i.e. bagasse is often used as fuel for this process. The remaining liquid is allowed to set into a solid mass known as Jiggery or Gur. Crushing system includes cane preparation, Pressure feeder and Milling trains. The Crushing system comprises of the following three subsystems as shown in Fig. 3.6.

(a) Subsystem F1 (Cane preparation): It is used to pulverize cane in to small pieces for feeding the mills and also to rupture the cells without extracting juice. It has three types; knives, shredders and fibrizers. The function of knives is to cut cane in to pieces, shredders are used to shred cut cane in to long fine pieces whereas, fibrizers works on the combination of knives and shredders. It is a single system and failure of this subsystem causes the complete failure of the system.

(b) Subsystem F2 (Pressure feeder): It consists of two rollers; top Pressure feeder and bottom Pressure feeder. It is a single system and failure of this subsystem causes the complete failure of the system.

(c) Subsystem F3 (Milling train): The milling process involves the removal of juice from sugarcane by squeezing the cane between pairs of large cylindrical rolls in a series of milling units collectively known as Milling train. Only the first milling unit in the Milling train processes prepared cane. The remaining milling units process bagasse. The milling unit consists of three rollers; top roller, feed roller and delivery roller. It has two subsystems with parallel configuration; one is operative while other remains in cold standby state. The complete failure of the system takes place when both subsystems get failed at a time.

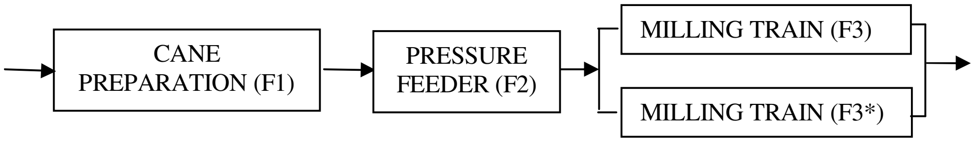


Fig. 3.6 Scheatic Process flow diagram of Crushing system

3.5.3 Refining system

Refining system ensures the complete cleaning of juice as raw juice available from a Crushing system contains fibres, refuse and mud. It is refined by using a number of filters in series to ensure the complete removal of bagasse from the juice. The bagasse free juice is diluted with water to increase its fluidity and is heated by steam in the heated unit. The juice boils in the heater for a definite period to achieve a desired pH value and sent to the sulphonation unit. Here sulphor dioxide is passed through the juice to remove the mud. The process is repeated to ensure complete removal of mud from the juice and thus to ensure proper cleaning of the juice. The Refining system comprises of the following four subsystems with series or parallel configurations as shown in Fig. 3.7.

(a) Subsystem G1 (Filter): It consists of three units of filters connected in parallel; one operative and others in cold standby state. The complete failure of the system will occur when three units get failed at a time.

(b) Subsystem G2 (Clarifier): It consists of single unit and failure of this unit causes complete failure of the system.

(c) Subsystem G3 (Sulphonation): It consists of two units of sulphonation connected in parallel; one operative and other in cold standby state. The complete failure of the system will occur when both units get failed at a time.

(d) Subsystem G4 (Heater): It consists of single unit of heater and failure of this unit causes complete failure of the system.

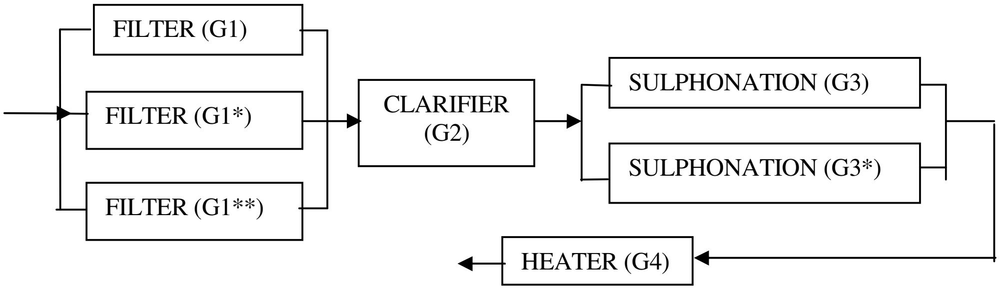


Fig. 3.7 Schematic Process flow diagram of Refining system

3.5.4 Evaporation system

The clarified juice is passed through heat exchangers to preheat the juice and then the same is passed to the evaporator station. Evaporation is performed in two stages; initially the juice is concentrated in an evaporator station and the sugar is crystallized in Vacuum pans. Evaporator station consists of two evaporators connected in parallel with each other. The steam from larger boilers is used to heat the juice in evaporator and the reduced pressure inside the evaporator allows the juice to boil at the lower temperature. Crystallization of the sugar starts in the Vacuum pans, whose function is to produce sugar crystals from the syrup. The Evaporation system comprises of the following three subsystems with series configurations as shown in Fig. 3.8.

(a) Subsystem H1 (Evaporator unit): It consists of two evaporators connected in parallel. The complete failure of the system occurs when both units fails at a time.

(b) Subsystem H2 (Pump): Its function is to increase the flow of concentrated juice. It has a single subsystem and failure of this subsystem causes complete failure of the system.

(c) Subsystem H3 (Vacuum pan unit): It consists of two Vacuum pans connected in parallel. The complete failures of the system occurs when both units fails at a time.

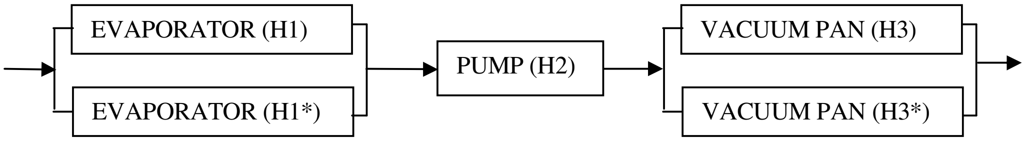


Fig. 3.8 Schematic Process flow diagram of Evaporation system

3.5.5 Crystallization system

Crystallization is not only a means to convert the sucrose to a more usable form, but also an important refining step, since pure sucrose tends to crystallize out of the solution, leaving most of the impurities in the associated syrup. This process is carried out under a reduced pressure of 75-90 KPa to allow a reduced boiling temp. (60-70^{o}C), so avoiding the further formation of colour compounds. The Crystallization system comprises of the following three subsystems with series or parallel configurations as shown in Fig. 3.9.

(a) Subsystem J1 (Crystallization): It has two subsystems with parallel configuration; one is operative while other remains in cold standby state. The complete failure of the system takes place when both subsystems get failed at a time.

(b) Subsystem J2 (Centrifugal pump): It has three subsystems with parallel configuration; one is operative while others remain in cold standby state. The complete failure of the system takes place when both subsystems get failed at a time.

(c) Subsystem J3 (Sugar grader unit): It has single unit connected in series. The complete failure of the system takes place when it gets failed at a time.

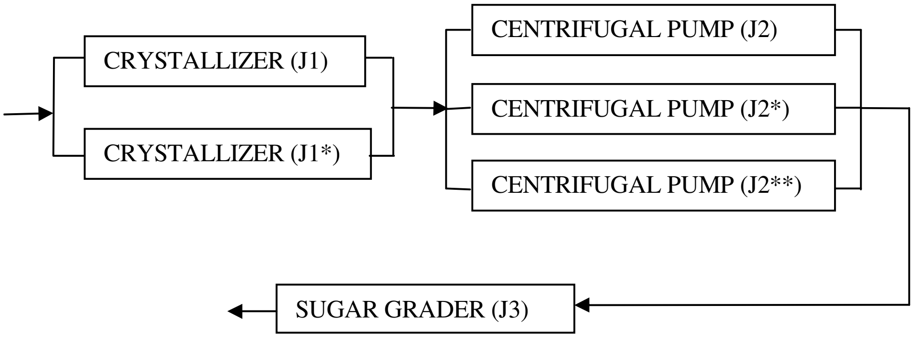


Fig. 3.9 Schematic Process flow diagram of Crystallization system

CHAPTER 4: PERFORMANCE MODELING OF THE SYSTEMS

The performance modeling of the systems of the dairy and sugar plants were carried out using simple probabilistic considerations and Chapman-Kolmogorov differential equations are developed based on Markov birth-death process as stated by Kumar et al. (1988, 1989 and 2007).

4.1 PERFORMANCE MODELING FOR THE SKIM MILK PRODUCTION SYSTEM OF THE DAIRY PLANT

Performance modeling for the Skim milk powder production system is carried out by deriving mathematical equations for the development of the decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

4.1.1 Performance modeling for the Decision Support Systems (DSS) of the Skim milk powder production system

The transition diagram (Fig. 4.1) depicts a simulation model showing all the possible states of the Skim milk powder production system.

State 0 : The system is working with full capacity (with no standby).
State 1 : The system is working with standby unit of Evaporator (A4*).
State 2 : The system is working with standby unit of Drying chamber (A5*).
State 3 : The system is working with standby unit of Evaporator (A4*) and Drying chamber (A5*).
State 4 to 19 : Failed states of the system due to complete failure of other subsystems i.e. A1, A2, A3, A4, A4*, A5 and A5* resp.
A1, A2, A3, A4 and A5: Indicates full working states of the subsystems
A4* and A5* : Indicates that the subsystem A4 and A5 are working under cold standby state
a1, a2, a3, a4 and a5 : Indicates the failed states of the subsystems A1, A2, A3, A4 and A5 resp.

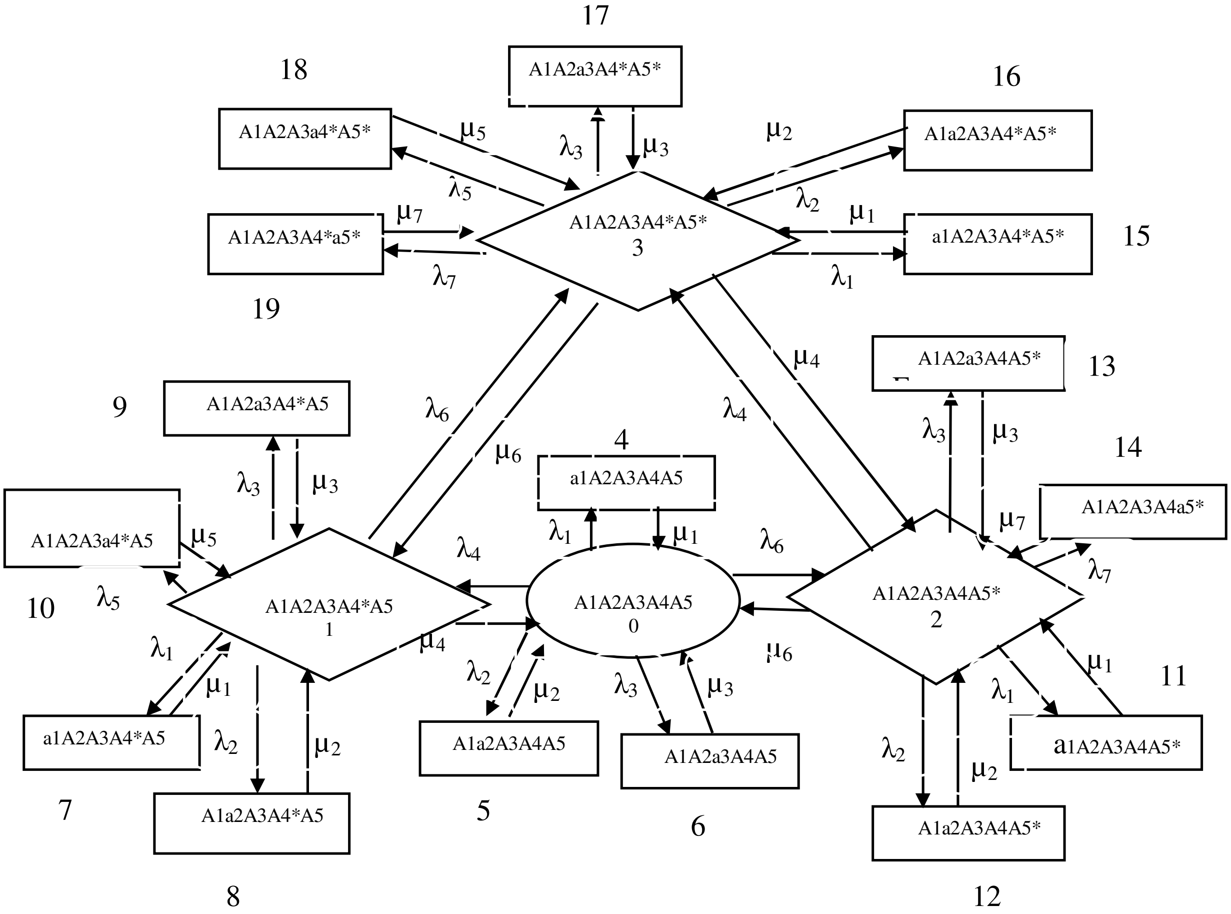


Fig. 4.1 State transition diagram of the Skim milk powder production system

P_o (t) : Probability of the system working with full capacity.

P_1 (t), P_2 (t) and P_3 (t): Probability of the system working under standby state.

λ_i , i =1, 2, 3….7 : The constant failure rates of the subsystems A1,A2, A3, A4, A4*,A5 and A5* resp..

μ_i , i =1, 2, 3….7 : The constant repair rates of the subsystems A1,A2,A3, A4, A4*,A5 and A5* resp..

P_j (t), j=1, 2, 3… 19 : The probability that the system is in j^{th} state at time, *t*

The mathematical equations (4.1.1)-(4.1.8) based on Markov-birth death process are developed for each state one by one out of 20 states of transition diagram (Fig. 4.1) as explained by Sharma and Garg (2011).

$$P'_o(t) = - X_oP_o(t) + \mu_1P_4(t) + \mu_2P_5(t) + \mu_3P_6(t) + \mu_4P_1(t) + \mu_6P_2(t) \qquad (4.1.1)$$

$$P'_1(t) = - X_1P_1(t) + \mu_1P_7(t) + \mu_2P_8(t) + \mu_3P_9(t) + \lambda_4P_o(t) + \mu_5P_{10}(t) + \mu_6P_3(t) \qquad (4.1.2)$$

$P'_2(t) = - X_2P_2(t) + \mu_1P_{11}(t) + \mu_2P_{12}(t) + \mu_3P_{13}(t) + \mu_4P_3(t) + \lambda_6P_0(t) + \mu_7P_{14}(t)$ (4.1.3)

$P'_3(t) = - X_3P_3(t) + \mu_1P_{15}(t) + \mu_2P_{16}(t) + \mu_3P_{17}(t) + \lambda_4P_2(t) + \mu_5P_{18}(t) + \lambda_6P_1(t)$ (4.1.4)

where

$X_o = (\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_6)$, $X_1 = (\lambda_1+\lambda_2+\lambda_3+ \mu_4+\lambda_5+\lambda_6)$, $X_2 = (\lambda_1+\lambda_2+\lambda_3+\lambda_4+ \mu_6+\lambda_7)$,

$X_3 = (\lambda_1+\lambda_2+\lambda_3+ \mu_4+ \lambda_5 + \mu_6+\lambda_7)$

$P'_i(t) + \mu_j P_i(t) = \lambda_j P_o(t)$ (4.1.5), where i=4, 5, 6 and j=1, 2, 3

$P'_i(t) + \mu_j P_i(t) = \lambda_j P_1(t)$ (4.1.6), where i=7, 8, 9, 10 and j=1, 2, 3, 5

$P'_i(t) + \mu_j P_i(t) = \lambda_j P_2(t)$ (4.1.7), where i=11, 12, 13, 14 and j=1, 2, 3, 7

$P'_i(t) + \mu_j P_i(t) = \lambda_j P_3(t)$ (4.1.8), where i=15, 16, 17, 18, 19 and j=1, 2,3,5,7

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } \ j = 1 \\ 0, \text{if } \ j \neq 1 \end{cases} \tag{4.1.9}$$

The system of differential equations (4.1.1) - (4.1.8) with initial conditions given by Eq. (4.1.9) was solved by Runge-Kutta fourth order method. The numerical computations were carried out by taking that

(i) The failure and repair rates of the Evaporator subsystem (λ_4, μ_4) and its standby unit (λ_5, μ_5) are the same.

(ii) The failure and repair rates of the Drying chamber subsystem (λ_6, μ_6) and its standby unit (λ_7, μ_7) are the same.

The numerical computations were carried out for one year (i.e. time, t=30-360 days) for different choices of failure and repair rates of the subsystems. The data regarding failure and repair rates of all the subsystems were taken from the plant personnel.

The reliability of the system, $R_1(t)$ is composed of the sum of the reliability of the system working with full capacity and its standby states i.e.

$R_1(t) = P_o (t) + P_1 (t) + P_2 (t) + P_3 (t)$ (4.1.10)

The reliability of the skim milk powder system is computed by Eq. (4.1.10)

Khanduja et al. (2012) stated that in process plant or industries, the management is interested to get the steady state availability of the system. The steady state probabilities of the system are obtained by imposing the following restrictions; d/dt→0, as t→∞. The equations (4.1.1)- (4.1.8) get reduced to the following system of Eqs.

$X_0P_0 = \mu_1P_4 + \mu_2P_5 + \mu_2P_5 + \mu_3P_6 + \mu_4P_1 + \mu_6P_2$ (4.1.11)

$X_1P_1 = \mu_1P_7 + \mu_2P_8 + \mu_2P_5 + \mu_3P_9 + \lambda_4P_0 + \mu_5P_{10} + \mu_6P_3$ (4.1.12)

$X_2P_2 = \mu_1P_{11} + \mu_2P_{12} + \mu_3P_{13} + \mu_4P_3 + \lambda_6P_0 + \mu_7P_{14}$ (4.1.13)

$X_3P_3 = \mu_1P_{15} + \mu_2P_{16} + \mu_3P_{17} + \lambda_4P_2 + \mu_5P_{18} + \lambda_6P_1$ (4.1.14)

$\mu_j P_i = \lambda_j P_0$ (4.1.15)

where, i=4, 5, 6 and j=1, 2, 3

$\mu_j P_i = \lambda_j P_1$ (4.1.16)

where, i=7, 8, 9, 10 and j=1, 2, 3, 5

$\mu_j P_i = \lambda_j P_2$ (4.1.17)

where, i=11, 12, 13, 14 and j=1, 2, 3, 7

$\mu_j P_i = \lambda_j P_3$ (4.1.18)

where, i=15, 16, 17, 18, 19 and j=1, 2, 3, 5, 7

The values of P_1, P_2 and P_3 are obtained by solving Eqs. (4.1.11) - (4.1.18) by recursive method

$P_1= P_0 A$ (4.1.19)

$P_2= P_0 B$ (4.1.20)

$P_3= P_0 C$ (4.1.21)

where

$A= (K_1 K_4- \lambda_6 \mu_6+ \lambda_4\mu_4)/ (\mu_4 K_4-\mu_4K_3)$, $B= (K_1 K_3+ \lambda_6 \mu_6- \lambda_4\mu_4)/ (\mu_6 K_4+ \mu_6K_3)$,

$C= (K_4 \lambda_6 \lambda_4+ \lambda_6 \lambda_4 K_3)/ (K_2K_3 K_4- K_4 \lambda_6 \mu_6 - \mu_4 \lambda_4K_3)$,

$K_1= (\lambda_4+\lambda_6)$, $K_2= (\mu_4+ \mu_6)$, $K_3= (\lambda_6+ \mu_4)$, $K_4= (\lambda_4+ \mu_6)$

Under normalized conditions i.e. sum of all the probabilities is equal to one

$$\therefore \quad \sum_{i=0}^{19} P_i = 1 \quad \text{i.e. } P_o+P_1+P_2+\ldots\ldots\ldots\ldots+P_{19}=1$$

$$P_o\left[1+\frac{P_1}{P_o}+\frac{P_2}{P_o}+\frac{P_3}{P_o}+\frac{P_4}{P_o}+\ldots\ldots\ldots\ldots+\frac{P_{19}}{P_o}\right]=1$$

$$P_o [1+A +B +C+4(\lambda_1 / \mu_1 + \lambda_2 / \mu_2 + \lambda_3 / \mu_3) +2(\lambda_5 / \mu_5 + \lambda_7 / \mu_7)] =1$$

$$P_o=\frac{1}{[1+A\ +B\ +C+4\left(\lambda_1/\mu_1+\lambda_2/\mu_2+\lambda_3/\mu_3\right)+2\left(\lambda_5/\mu_5+\lambda_7/\mu_7\right)]} \qquad (4.1.22)$$

The steady state availability of the Skim milk powder production system (A_{v1}) is the summation of its working and standby states i.e.

$A_{v1} = P_o (1+ A + B + C)$ (4.1.23)

The Eq. (4.1.23) gives the steady state availability of the Skim milk powder production system

4.1.2 Performance modeling for RAMD analysis of the Skim milk powder production system

The Skim milk powder production system is transformed in to four subsystems (S1-S4) as shown in Fig. 4.2. The transition diagrams associated with the subsystems (S1-S4) are shown in Fig. 4.3((a)-(d)). The data regarding failure and repair rates of the subsystems is presented in table 4.1.

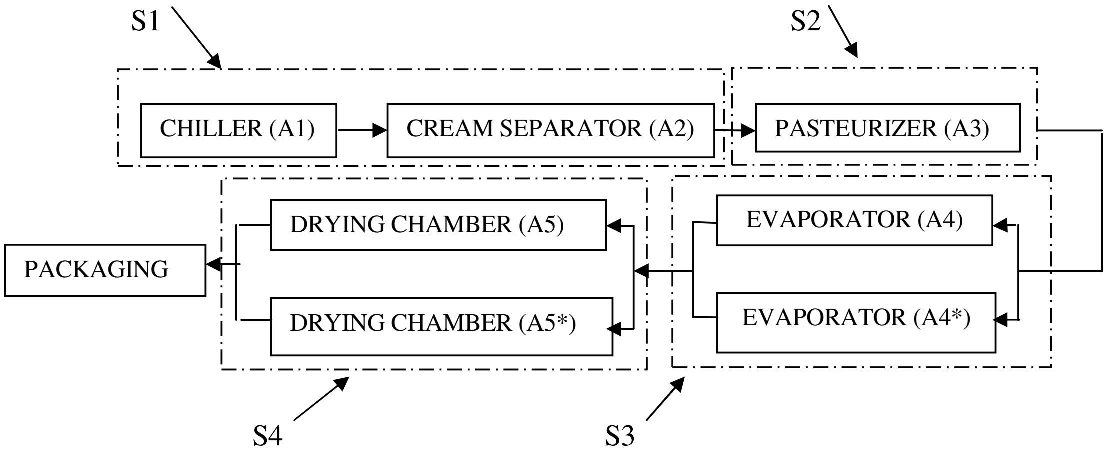
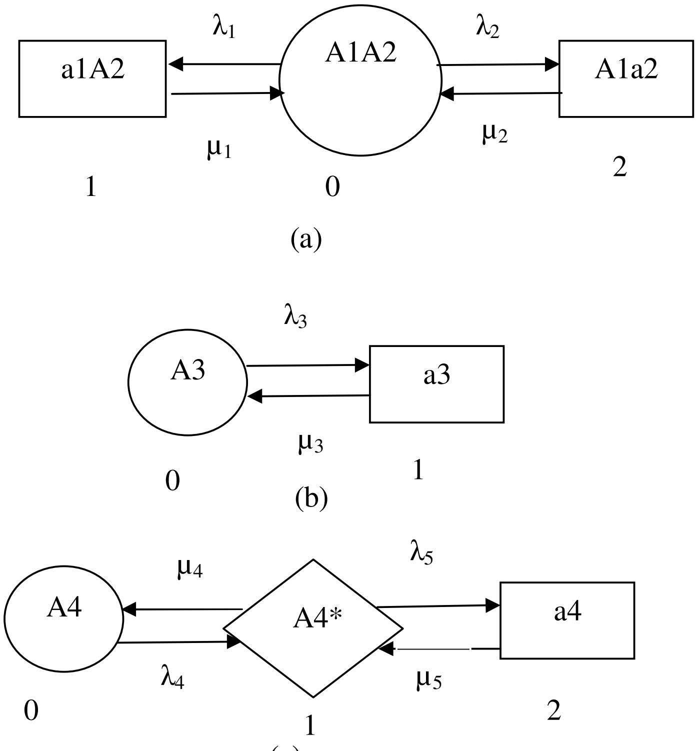


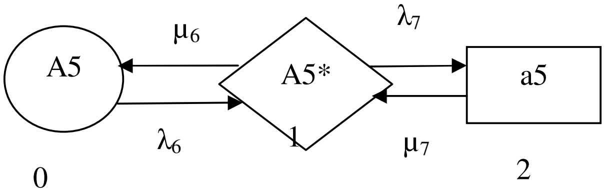
Fig. 4.2 Schematic representation of the Skim milk powder production system



(a)

(b)

(c)



(d)

Fig. 4.3 State transition diagram of the subsystems of the Skim milk powder production system: (a) subsystem S1, (b) subsystem S2, (c) subsystem S3, (d) subsystem S4

RAMD indices for Subsystem S1

The subsystem S1 consists of two units; A1 (Chiller) and A2 (Cream separator) connected in series. Failure of unit A1 or unit A2 causes complete failure of this subsystem. The differential equations associated with Fig. 4.3(a) are:

$P'_o(t) = - (\lambda_1 + \lambda_2)P_o(t) + \mu_1P_1(t) + \mu_2P_2(t)$ (4.1.24)

$P'_1(t) = - \mu_1P_1(t) + \lambda_1P_0(t)$ (4.1.25)

$P'_2(t) = - \mu_2P_2(t) + \lambda_2P_0(t)$ (4.1.26)

Under steady state conditions, the Eqs. (4.1.24) - (4.1.26) get reduced as

$(\lambda_1 + \lambda_2)P_o = \mu_1P_1 + \mu_2P_2$ (4.1.27)

$\mu_1P_1= \lambda_1P_0$ (4.1.28)

$\mu_2P_2= \lambda_2P_0$ (4.1.29)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 =1$ (4.1.30)

Putting the values of P_1 and P_2 from Eqs. (4.1.28) and (4.1.29) in Eq. (4.1.30)

$P_0 (1+ \lambda_1 / \mu_1 + \lambda_2 / \mu_2) =1$ (4.1.31)

The availability for the subsystem S1 is given by Eq. (4.1.31)

$R_{S1\ (t)} = e^{-0.0095t}$ (4.1.32)

The reliability Eq. for the subsystem S1 is given by Eq. (4.1.32)

$M_{S1}\ (t) = 1\text{-}e^{-0.10565t.}$ (4.1.33)

The maintainability Eq. for the subsystem S1is given by Eq. (4.1.23)

The others parameters for the subsystem S1 are computed as:

$D_{min.(S1)} = 0.9376508$

MTBF= 105.26315 hr.

MTTR= 9.465284 hr. and

d= 11.120972.

RAMD indices for Subsystem S2

This subsystem has one unit A3 (Pasteurizer) only and failure of this unit causes the failure of the complete system. The differential equations associated with Fig. 4.3(b) are:

$P'_0(t) = - \lambda_3 P_0(t) + \mu_3 P_1(t)$ (4.1.34)

$P'_1(t) = - \mu_3 P_1(t) + \lambda_3 P_0(t)$ (4.1.35)

Under steady state conditions, the Eqs. (4.1.1.34) and (4.1.1.35) get reduced as:

$\mu_3 P_1 = \lambda_3 P_0$ (4.1.36)

$\mu_3 P_1 = \lambda_3 P_0$ (4.1.37)

Now, using the normalizing conditions

$P_0 + P_1 = 1$ (4.1.38)

Put the value of P_1 from Eq. (4.1.36) and (4.1.37) in Eq. (4.1.38)

$P_0 (1 + \lambda_3 / \mu_3) = 1$ (4.1.39)

The availability for the subsystem S2 is given by Eq. (4.1.39)

$R_{S2\ (t)} = e^{-0.0073t}$ (4.1.40)

Reliability Eq. for the subsystem S2 is given by Eq. (4.1.40)

$M_{S2}\ (t) = 1 - e^{-0.281t}$ (4.1.41)

The maintainability Eq. for the subsystem S2 is given by Eq. (4.1.41)

The other parameters for the subsystem S2 are computed as:

$D_{min.(S2)} = 0.981519$

MTBF=136.9863 hr.

MTTR=3.558719 hr. and

d=38.49315

RAMD indices for Subsystem S3

This subsystem has one unit A4 (Evaporator) only but it has standby unit and failure of both units will cause the system to fail. The differential equations associated with Fig. 4.3(c) are:

$P'_0(t) = - \lambda_4 P_0(t) + \mu_4 P_1(t)$ (4.1.42)

$P'_1(t) = - (\mu_4 + \lambda_5) P_1(t) + \lambda_4 P_0(t) + \mu_5 P_2(t)$ (4.1.43)

$P'_2(t) = - \mu_5 P_2(t) + \lambda_5 P_1(t)$ (4.1.44)

Under steady state conditions, the Eqs. (4.1.42), (4.1.43) and (4.1.44) get reduced as:

$(\mu_4 + \lambda_5) P_1 = \lambda_4 P_0 + \mu_5 P_2$ (4.1.45)

$\mu_5 P_2 = \lambda_5 P_1$ (4.1.46)

$\mu_4 P_1 = \lambda_4 P_0$ (4.1.47)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.1.48)

Put the values of P_1 and P_2 by solving Eqs. (4.1.45) and (4.1.46) in Eq. (4.1.48)

$P_0 (1 + \lambda_4 / \mu_4 + \lambda_5 \lambda_4 / \mu_5 \mu_4) = 1$ (4.1.49)

The availability for the subsystem S3 is given by Eq. (4.1.49)

$R_{S3\ (t)} = e^{-0.0048t}$ (4.1.50)

Reliability Eq. for the subsystem S3 is given by Eq. (4.1.50)

$M_{S3}(t) = 1 - e^{-3.710667t}$ (4.1.51)

The maintainability Eq. for the subsystem S3 is given by Eq. (4.1.51)

The other parameters for the subsystem S3 are computed as:

$D_{min.\ (S3)} = 0.99810862$

MTBF=104.1667 hr.

MTTR=0.2694933 hr. and

d= 386.528

RAMD indices for Subsystem S4

This subsystem has one unit A5 (Drying chamber) only but it has standby unit and failure of both units will cause the system to fail. The differential equations associated with Fig. 4.3 (d) are:

$P'_0(t) = -\lambda_6 P_0(t) + \mu_6 P_1(t)$ (4.1.52)

$P'_1(t) = -(\mu_6 + \lambda_7) P_1(t) + \lambda_6 P_0(t) + \mu_7 P_2(t)$ (4.1.53)

$P'_2(t) = -\mu_7 P_2(t) + \lambda_7 P_1(t)$ (4.1.54)

Under steady state conditions, the Eqs. (4.1.52)- (4.1.54) get reduced as

$(\mu_6 + \lambda_7) P_1 = \lambda_6 P_0 + \mu_7 P_2$ (4.1.55)

$\mu_6 P_1 = \lambda_6 P_0$ (4.1.56)

$\mu_7 P_2 = \lambda_7 P_1$ (4.1.57)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.1.58)

Put the values of P_1 and P_2 by solving Eqs. (4.1.56) and (4.1.57) in Eq. (4.1.58)

$P_0 (1 + \lambda_6 / \mu_6 + \lambda_6 \lambda_7 / \mu_6 \mu_7) = 1$ (4.1.59)

The availability for the subsystem S4 is given by Eq. (4.1.59)

$R_{S4}(t) = e^{-0.00451t}$ (4.1.60)

Reliability Eq. for the subsystem S4 is given by Eq. (4.1.60)

$M_{S4}(t) = 1 - e^{-3.690t}$ (4.1.61)

The maintainability Eq. for the subsystem S4 is given by Eq. (4.1.60)

The other parameters for the subsystem S4 are computed as:

$D_{min.(S4)} = 0.998212738$

MTBF=110.864745 hr.

MTTR= 0.2709558 hr. and

d= 409.16

System Reliability

The overall system reliability of the Skim milk powder production system, $R_{sys}(t)$

$R_{sys}(t) = R_{S1}(t) \times R_{S2}(t) \times R_{S3}(t) \times R_{S4}(t)$

$R_{sys}(t) = e^{-0.0095t} \times e^{-0.0073t} \times e^{-0.0048t} \times e^{-0.00451t} = e^{-0.02611t}$

$R_{sys}(t) = e^{-0.02611t}$

System Availability

The overall system availability of the Skim milk powder production system, A_{sys}

$A_{sys} = A_{S1} \times A_{S2} \times A_{S3} \times A_{S4}$

$A_{sys} = 0.917498 \times 0.974679 \times 0.997419 \times 0.997562 = 0.8897833$

System Maintainability

The overall system maintainability of the Skim milk powder production system, $M_{sys}(t)$

$M_{sys}(t) = M_{S1}(t) \times M_{S2}(t) \times M_{S3}(t) \times M_{S4}(t)$

$M_{sys}(t) = 1 - e^{-0.0737221t}$

System Dependability

The overall system dependability of the Skim milk powder production system, $D_{min.(sys)}$

$D_{min.(sys)} = D_{min.(S1)} \times D_{min.(S2)} \times D_{min.(S3)} \times D_{min.(S4)}$

$D_{sys} = 0.937650 \times 0.981519 \times 0.998109 \times 0.998213 = 0.916940$

Table 4.1 Failure and repair rates of the subsystems of the Skim milk powder production system

Subsystem	Failure Rate (λ)	Repair Rate (μ)
S1	Chiller (λ_1)=0.0038/hour (hr.), Cream separator (λ_2)=0.0057/hr.	Chiller (μ_1)=0.321/hr., Cream separator (μ_2)=0.073/hr.
S2	Pasteurizer (λ_3)=0.0073/hr.	Pasteurizer (μ_3)=0.281/hr.
S3	Evaporators (λ_4, λ_5); $\lambda_4 = \lambda_5$ =0.0048/hr.	Evaporators (μ_4, μ_5); $\mu_4 = \mu_5$=0.092/hr.
S4	Drying chambers (λ_6, λ_7); $\lambda_6 = \lambda_7$=0.00451/hr.	Drying chambers(μ_6, μ_7); $\mu_6 = \mu_7$=0.089/hr.

4.1.3 Performance modeling for the fuzzy-reliability analysis of the Skim milk powder production system

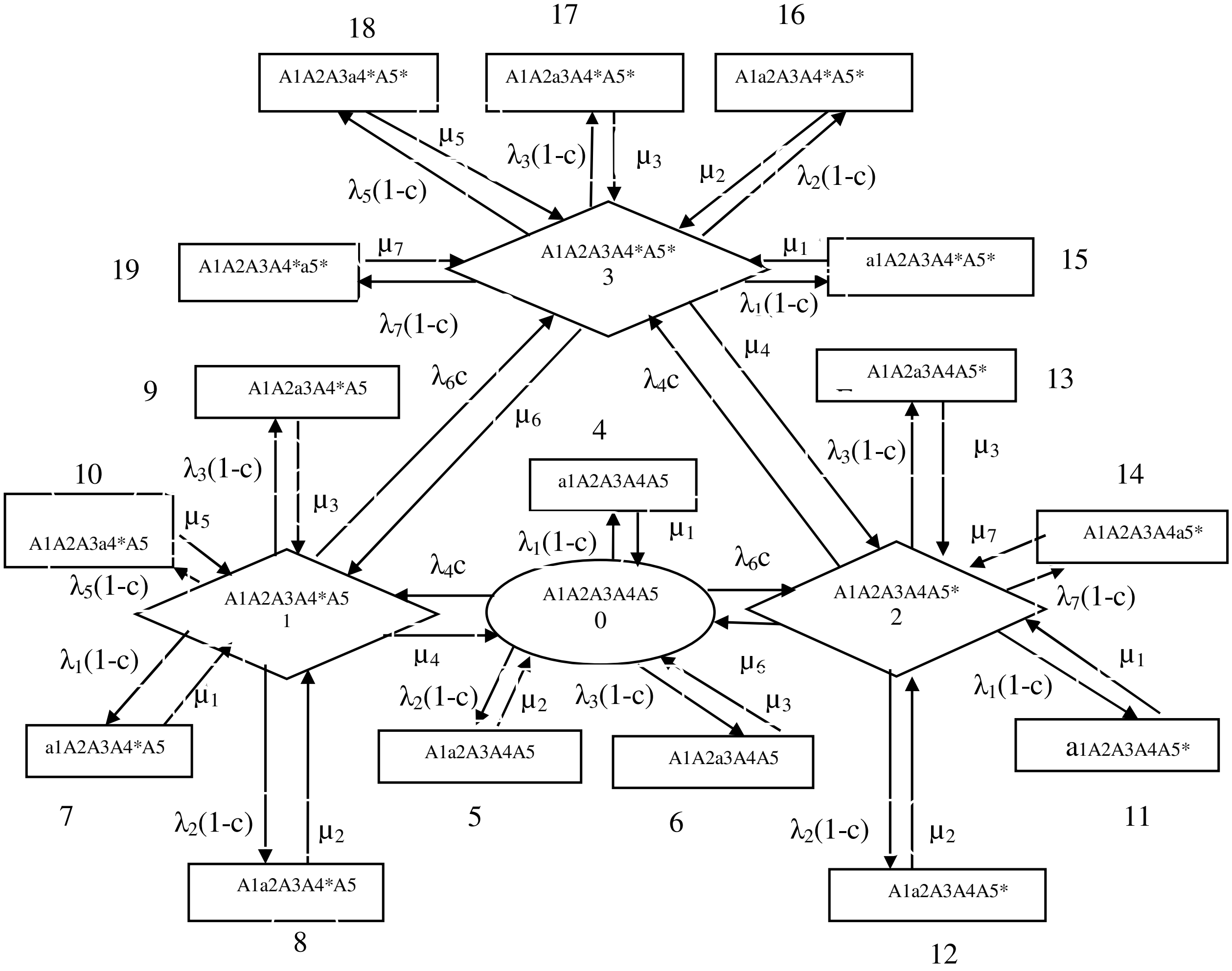


Fig. 4.4 State transition diagram of the Skim milk powder production system with imperfect fault coverage

$P'_1(t) + X_1P_1(t) = \mu_1P_5(t) + \mu_2P_6(t) + \mu_3P_7(t) + \mu_4P_2(t) + \mu_6P_3(t)$ (4.1.62)

$P'_2(t) + X_2P_2(t) = \mu_1P_8(t) + \mu_2P_9(t) + \mu_3P_{10}(t) + \lambda_4 cP_1(t) + \mu_5P_{11}(t) + \mu_6P_4(t)$ (4.1.63)

$P'_3(t) + X_3P_3(t) = \mu_1P_{12}(t) + \mu_2P_{13}(t) + \mu_3P_{14}(t) + \mu_4P_4(t) + \lambda_6 cP_1(t) + \mu_7P_{15}(t)$ (4.1.64)

$P'_4(t)+X_4P_4(t) =\mu_1P_{16}(t) + \mu_2P_{17}(t)+\mu_3P_{18}(t)+\lambda_4 cP_3(t)+\mu_5P_{19}(t)+\lambda_6 cP_2(t)+\mu_7P_{20}(t)$.(4.1.65)

where

$X_1= \lambda_1 (1-c) +\lambda_2 (1-c)+\lambda_3 (1-c)+\lambda_4 c+\lambda_6 c$, $X_2=\lambda_1 (1-c) +\lambda_2 (1-c)+\lambda_3(1-c)+ \mu_4+\lambda_5(1-c)+\lambda_6c$,

$X_3= \lambda_1 (1-c) +\lambda_2 (1-c)+\lambda_3(1-c)+\lambda_4c+ \mu_6+\lambda_7(1-c)$,

$X_4= \lambda_1 (1-c) +\lambda_2 (1-c)+\lambda_3(1-c)+ \mu_4+ \lambda_5 (1-c)+ \mu_6+\lambda_7 (1-c)$

$P'_i(t) + \mu_j P_i(t) = \lambda_j (1\text{-}c)P_1(t)$ (4.1.66)

where i= 5, 6, 7 and j=1, 2, 3

$P'_i(t) + \mu_j P_i(t) = \lambda_j (1\text{-}c)P_2(t)$ (4.1.67)

where i= 8, 9, 10, 11 and j=1, 2, 3, 5

$P'_I(t) + \mu_j P_i(t) = \lambda_j (1\text{-}c)P_3(t)$ (4.1.68)

where i=12, 13, 14, 15 and j=1, 2, 3, 7

$P'_i(t) + \mu_j P_i(t) = \lambda_j (1\text{-}c)P_4(t)$ (4.1.69)

where i=16, 17, 18, 19, 20 and j=1, 2,3,5,7

With initial conditions

$$P_j(0) = \begin{cases} 1,\text{if } j = 1 \\ 0,\text{if } j \neq 1 \end{cases}$$

(4.1.70)

The system of differential equations (4.1.62)-(4.1.69) with initial conditions given by Eq. (4.1.70) was solved with Runge-Kutta fourth order method. The numerical computations were carried out by taking that

(i) The failure and repair rates of the evaporator (λ_4, μ_4) subsystem and its standby unit (λ_5, μ_5) are same.

(ii) The failure and repair rates of the Drying chamber (λ_6, μ_6) subsystem and its standby unit (λ_7, μ_7) are same.

The fuzzy-reliability of the Skim milk powder production system was computed for one year (i.e. time, t=30-360 days) for different choices of failure rates of the subsystems. The fuzzy-reliability (R_{F1}) of the Skim milk powder production system is composed of the fuzzy-reliability of the system working with full capacity and its standby states i.e.

$R_{F1}(t) = P_1 (t) + ½P_2 (t) + ½P_3 (t) + ¼P_4(t)$ (4.1.71)

The fuzzy-reliability of the Skim milk powder production system is computed by the Eq. (4.1.71)

4.2 PERFORMANCE MODELING FOR THE BUTTER OIL PRODUCTION SYSTEM OF THE DAIRY PLANT

Performance modeling for the Butter oil production system is carried out by deriving mathematical equations for the development of the decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

4.2.1 Performance modeling for Decision Support Systems (DSS) of the Butter oil production system.

The transition diagram (Fig. 4.5) depicts a simulation model showing all the possible states of the Butter oil production system.

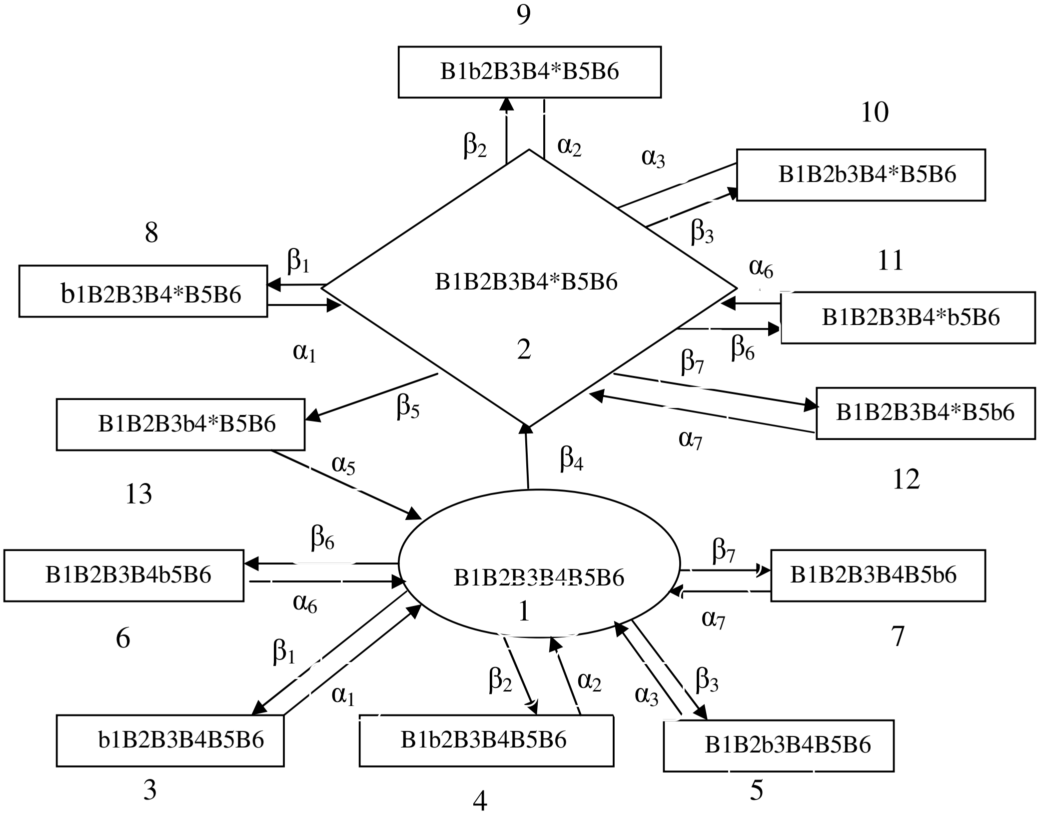


Fig. 4.5 State transition diagram of the Butter oil production system

State 1: The system is working with full capacity (with no standby).

State 2: The system is working with standby unit of continuous butter making (B4*)

B1, B2, B3, B4, B5 and B6: Indicates full working states of the subsystems

B4* : Indicates that the subsystem B4 is working under cold standby state

b1, b2, b3, b4, b5 and b6 : Indicates the failed states of the subsystems

$P_1(t)$: Probability of the system working with full capacity

$P_2(t)$: Probability of the system working under cold standby state

β_i, $i=1,2,3\ldots\ldots7$: The constant failures rates of the subsystems B1, B2, B3, B4, B4*, B5 and B6 resp.

α_i, $i=1,2,3\ldots\ldots..7$: The constant repair rates of the subsystems B1, B2, B3, B4, B4*, B5 and B6 resp.

$P_j(t)$, $j=1,2,3,\ldots..13$: Probability that the system is in j^{th} state at time t.

The mathematical equations (4.2.1)-(4.2.5) based on Markov birth-death process are developed for each state one by one out of 13 states of transition diagram (Fig. 4.6).

$$P'_1(t)=-X_1P_1(t)+\alpha_1P_3(t)+\alpha_2P_4(t)+\alpha_3P_5(t)+\alpha_5P_{13}(t)+\alpha_6P_6(t)+\alpha_7P_7(t) \qquad (4.2.1)$$

$$P'_2(t)=-X_2P_2(t)+\alpha_1P_8(t)+\alpha_2P_9(t)+\alpha_3P_{10}(t)+\beta_4P_1(t)+\alpha_6P_{11}(t)+\alpha_7P_{12}(t) \qquad (4.2.2)$$

where

$X_1=(\beta_1+\beta_2+\beta_3+\beta_4+\beta_6+\beta_7)$, $X_2=(\beta_1+\beta_2+\beta_3+\beta_5+\beta_6+\beta_7)$

$$P'_i(t)+\alpha_j P_i(t)=\beta_j P_1(t) \qquad (4.2.3)$$

where $i=3, 4, 5, 6, 7$ and $j=1, 2, 3, 6, 7$

$$P'_i(t)+\alpha_j P_i(t)=\beta_j P_2(t) \qquad (4.2.4)$$

where $i=8, 9, 10, 11, 12$ and $j=1, 2, 3, 6, 7$

$$P'_{13}(t)+\alpha_5 P_{13}(t)=\beta_5 P_2(t) \qquad (4.2.5)$$

With initial conditions

$$P_j(0)=\begin{cases}1,\text{if } j=1\\0,\text{if } j\neq 1\end{cases} \qquad (4.2.6)$$

The system of differential equations (4.2.1) - (4.2.5) with initial conditions given by Eq. (4.2.6) was solved by Runge-Kutta fourth order method. The numerical computations were carried out by taking that the failure and repair rates of the continuous butter making machine (β_4, α_4) subsystem and its standby unit (β_5, α_5) are same. The numerical computations were carried out for one year (i.e. time, t=30-360 days) for different choices of failure and repair rates of the subsystems.

The reliability, $R_2(t)$ of the system is composed of the sum of the reliability of the system working with full capacity and its standby states i.e.

$$R_2(t)=P_1(t)+P_2(t) \qquad (4.2.7)$$

The reliability of the Butter oil production system is computed by Eq. (4.2.7)

The management of the plant is interested to get the long-run or steady state availability of the system. The steady state probabilities of the system are obtained by imposing the steady state condition i.e. P′ i.e. d/dt→0, as t→∞. The equations (4.2.1) to (4.2.5) get reduced to the following system of Eqs.

$$X_1P_1= \alpha_1P_3 + \alpha_2P_4 + \alpha_3P_5 + \alpha_5P_{13}+ \alpha_6P_6 + \alpha_7P_7 \tag{4.2.8}$$

$$X_2P_2= \alpha_1P_8 + \alpha_2P_9 + \alpha_3P_{10} + \beta_4P_1+ \alpha_6P_{11}+\alpha_7P_{12} \tag{4.2.9}$$

$$\alpha_j\, P_i(t) = \beta_j\, P_1(t) \tag{4.2.10}$$

where i=3, 4, 5, 6,7 and j=1,2,3,6,7

$$\alpha_j\, P_i(t) = \beta_j\, P_2(t) \tag{4.2.11}$$

where i=8, 9, 10, 11, 12, 13 and j=1, 2, 3, 6, 7, 5

The values of P_1 and P_2 are obtained by solving Eqs. (4.2.8)-(4.2.11) by recursive method

$$P_2=\left(\frac{\beta_4}{\beta_5}\right)P_1 \tag{4.2.12}$$

Under normalized conditions i.e. sum of all the probabilities is equal to one

$$\therefore \sum_{i=1}^{13} P_i = 1 \text{ i.e. } P_1+P_2+\ldots\ldots\ldots\ldots\ldots\ldots\ldots+P_{13}=1 \Rightarrow P_1\left[1+\frac{P_2}{P_1}+\frac{P_3}{P_1}+\frac{P_4}{P_1}+\frac{P_5}{P_1}+\ldots\ldots\ldots\ldots+\frac{P_{13}}{P_1}\right]=1$$

$$P_1=\frac{1}{[(1+\beta_1/\alpha_1++\beta_2/\alpha_2+\beta_3/\alpha_3+\beta_6/\alpha_6+\beta_7/\alpha_7)*(1+\beta_4/\alpha_5)+\beta_4/\alpha_5]}. \tag{4.2.13}$$

The steady state availability i.e. A_{v2} of the Butter oil production system is the summation of working and standby states:

$$A_{v2}= P_1 + P_2 \tag{4.2.14}$$

$$A_{v2}= \left[\frac{1}{\{(1+\beta_1/\alpha_1++\beta_2/\alpha_2+\beta_3/\alpha_3+\beta_6/\alpha_6+\beta_7/\alpha_7)*(1+\beta_4/\alpha_5)+\beta_4/\alpha_5\}}\right][1+\left(\frac{\beta_4}{\beta_5}\right)] \tag{4.2.15}$$

The Eq. (4.2.15) gives the steady state availability of the Butter oil production system.

4.2.2 Performance modeling for RAMD analysis of the Butter oil production system

The Butter oil production system is transformed in to four subsystems (S1-S4) as shown in Fig. 4.6. The transition diagrams associated with the subsystems (S1- S4) are shown in Fig. 4.6((a)-(d)). The data regarding failure and repair rates of the subsystems is presented in table 4.2.

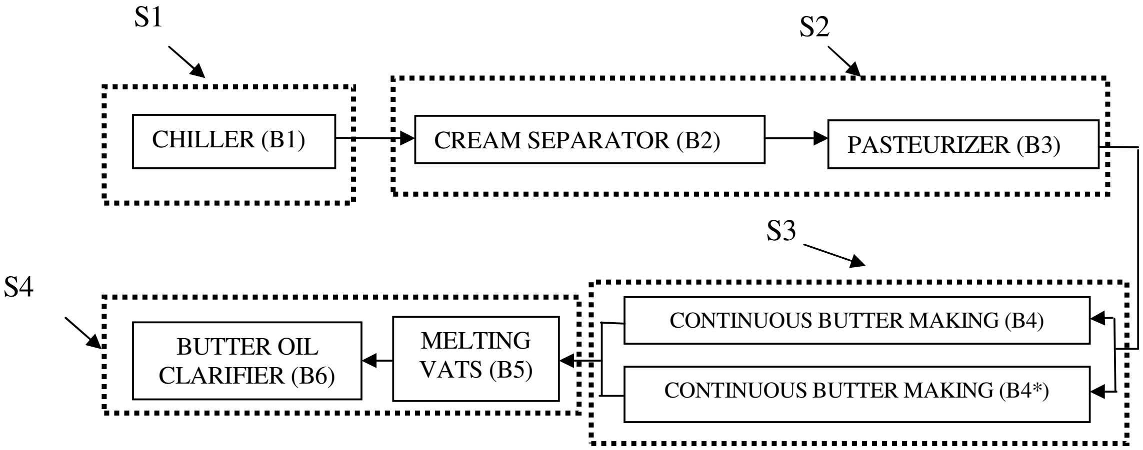
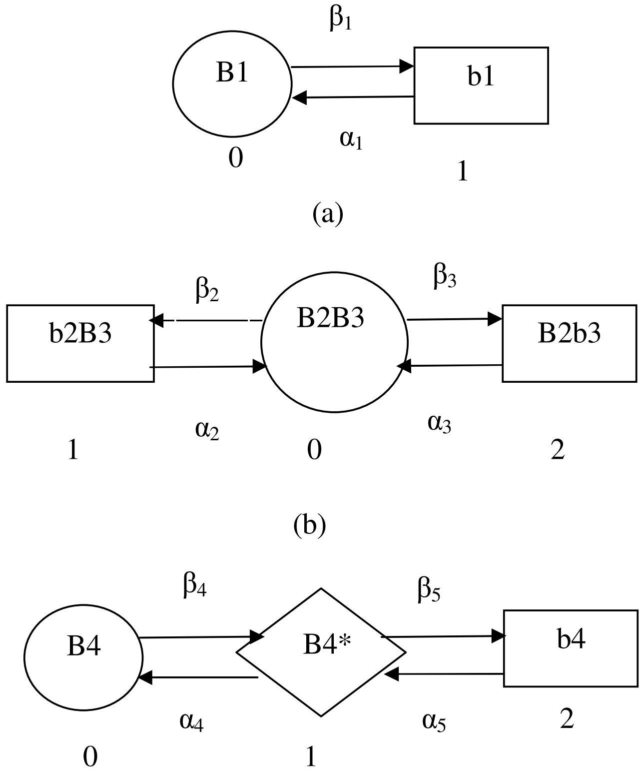


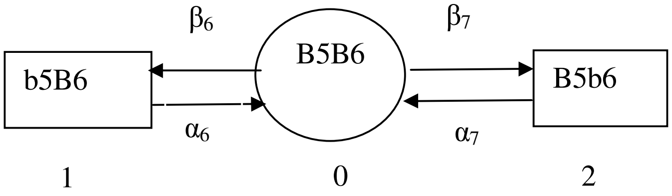
Fig. 4.6 Schematic representation of the Butter oil production system



(a)

(b)

(c)



(d)

Fig. 4.7 State transition diagram of the subsystems of the Butter oil production system: (a) subsystem S1, (b) subsystem S2, (c) subsystem S3, (d) subsystem S4

RAMD indices for subsystem S1

This subsystem has single unit B1 (Chiller) only and failure of this unit causes complete failure of the system. The differential equations associated with Fig. 4.7(a) are:

$P'_o(t) = -\beta_1 P_o(t) + \alpha_1 P_1(t)$ (4.2.16)

$P'_1(t) = -\alpha_1 P_1(t) + \beta_1 P_0(t)$ (4.2.17)

Under steady state conditions, the Eqs. (4.2.16) - (4.2.17) get reduced as:

$\beta_1 P_o = \alpha_1 P_1$ (4.2.18)

$\alpha_1 P_1 = \beta_1 P_0$ (4.2.19)

Now, using the normalizing conditions

$P_0 + P_1 = 1$ (4.2.20)

Eqs. (4.2.19) and (4.2.10) are solved to get the values of P_0 i.e.

$P_0 (1+\beta_1 /\alpha_1] = 1$ (4.2.11)

The availability of the subsystem S1 is given by Eq. (4.2.11)

$R_{S1\ (t)} = e^{-0.0038t}$ (4.2.12)

The reliability Eq. for the subsystem S1is given by Eq. (4.2.12)

$M_{s1}\ (t) = 1\text{-}e^{-0.321t}$ (4.2.13)

The maintainability Eq. for the subsystem S1is given by Eq. (4.2.13)

The other parameters for the subsystem S1 are computed as:

$D_{min.(s1)} = 0.9915$

MTBF= 263.158 hr.

MTTR= 3.1153 hr. and

d =84.4737

RAMD indices for subsystem S2

This subsystem S2 consists of two units B2 (cream separator) and B3 (pasteurizer) connected in series. Failure of unit B2 or B3 causes complete failure of the system. The differential equations associated with Fig. 4.7(b) are:

$P'_o(t) = -(\beta_2 + \beta_3)P_o(t) + \alpha_2 P_1(t) + \alpha_3 P_2(t)$ (4.2.14)

$P'_1(t) = -\alpha_2 P_1(t) + \beta_2 P_0(t)$ (4.2.15)

$P'_2(t) = -\alpha_3 P_2(t) + \beta_3 P_0(t)$ (4.2.16)

Under steady state conditions, the Eqs. (4.2.15)- (4.2.16) get reduced as:

$(\beta_2 + \beta_3)P_o = \alpha_2 P_1 + \alpha_3 P_2$ (4.2.17)

$\alpha_2 P_1 = \beta_2 P_0$ (4.2.18)

$\alpha_3 P_2 = \beta_3 P_0$ (4.2.19)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.2.20)

Putting the values of P_1 and P_2 from Eqs. (4.2.18) and (4.2.19) in Eq. (4.2.20)

$P_0 (1 + \beta_2 / \alpha_2 + \beta_3 / \alpha_3) = 1$ (4.2.21)

The availability of the subsystem S2 is given by Eq. (4.2.21)

$R_{S2\ (t)} = e^{-0.013t.}$ (4.2.22)

The reliability Eq. for the subsystem S2 is given by Eq. (4.2.22)

$M_{s2}\ (t) = 1 - e^{-0.321t}$ (4.2.23)

The maintainability Eq. for the subsystem S2is given Eq. (4.2.23)

The other parameters for the subsystem S2 are computed as:

$D_{min.(s2)} = 0.9280$

MTBF= 76.923 hr.

MTTR= 8.0047 hr. and

d= 9.6098.

RAMD indices for subsystem S3

This subsystem has single unit B4 (Continuous butter making) only but it has its cold standby unit. Failure of both units causes complete failure of the system. The differential equations associated with Fig. 4.7(c) are:

$P'_0(t) = -\beta_4 P_0(t) + \alpha_4 P_1(t)$ (4.2.24)

$P'_1(t) = -(\alpha_4 + \beta_5)P_1(t) + \beta_4 P_0(t) + \alpha_5 P_2(t)$ (4.2.25)

$P'_2(t) = -\alpha_5 P_2(t) + \beta_5 P_1(t)$ (4.2.26)

Under steady state conditions, the Eqs. (4.2.24)- (4.2.26) get reduced as:

$(\alpha_4 + \beta_5)P_1 = \beta_4 P_0 + \alpha_5 P_2$ (4.2.27)

$\alpha_5P_2=\beta_5P_1$ (4.2.28)

$\alpha_4P_1=\beta_4P_0$ (4.2.29)

Now, using the normalizing conditions

$P_0+P_1+P_2=1$ (4.2.30)

Put the values of P_1 and P_2 by solving Eqs. (2.27)-(2.29) in Eq. (4.2.30)

$P_0\,(1+\beta_4/\alpha_4+\beta_5\,\beta_4/\alpha_5\alpha_4)=1$ (4.2.31)

The availability of the subsystem S3 is given by Eq. (4.2.31)

$R_{S3\,(t)}=e^{-0.0045t}$ (4.2.32)

Reliability Eq. for the subsystem S3 is given by Eq. (4.2.32)

$M_{s3}\,(t)=1-e^{-4.3764t}$ (4.2.33)

The maintainability Eq. for the subsystem S3 is given by Eq. (4.2.33)

The other parameters for the subsystem S3 are computed as:

$D_{min.\,(s3)}=0.9985$

MTBF= 111.111 hr.

MTTR=0.2285 hr. and

d= 486.1975.

RAMD indices for subsystem S4

This subsystem S4 consists of two units B5 (Melting vats) and B6 (Butter oil clarifier) connected in series. Failure of unit B5 or B6 causes complete failure of the system. The differential equations associated with Fig. 4.7(d) are:

$P'_o(t)=-(\beta_6+\beta_7)P_o(t)+\alpha_6P_2(t)+\alpha_7P_2(t)$ (4.2.34)

$P'_1(t)=-\alpha_6P_1(t)+\beta_6P_0(t)$ (4.2.35)

$P'_2(t)=-\alpha_7P_2(t)+\beta_7P_0(t)$ (4.2.36)

Under steady state conditions, the Eqs. (4.2.34)- (4.2.35) get reduced as:

$(\beta_6+\beta_7)P_o=\alpha_6P_1+\alpha_7P_2$ (4.2.37)

$\alpha_6P_1=\beta_6P_0$ (4.2.38)

$\alpha_7P_2=\beta_7P_0$ (4.2.39)

Now, using the normalizing conditions

$P_0+P_1+P_2=1$ (4.2.40)

Putting the values of P_1 and P_2 by solving Eqs. (2.37)- (2.39) and put in Eq. (2.40)

$P_0\,(1+\beta_6/\alpha_6+\beta_7/\alpha_7)=1$ (4.2.41)

The availability of the subsystem S4 is given by Eq. (4.2.41)

$R_{S4\,(t)}=e^{-0.00759t}$ (4.2.42)

The reliability Eq. for the subsystem S4 is given by Eq. (4.2.42)

$M_{s4}(t) = 1 - e^{-0.0632t}$ (4.2.43)

The maintainability Eq. for the subsystem S4 is given by Eq. (4.2.43)

The other parameters for the subsystem S4 are computed as:

$D_{min.(S4)} = 0.9169$

MTBF=131.7523 hr.

MTTR=15.8278 hr. and

d= 8.3241.

System Reliability

The overall system reliability of Butter oil production system, $R_{sys}(t)$

$R_{sys}(t) = R_{s1}(t) \times R_{s2}(t) \times R_{s3}(t) \times R_{s4}(t)$

$R_{sys}(t) = e^{-0.0038t} \times e^{-0.013t} \times e^{-0.0045t} \times e^{-0.00759t} = e^{-0.02889t}$

$R_{sys}(t) = e^{-0.02889t}$

System Availability

The overall system availability of the Butter oil production system, (A_{sys}) is computed as

$A_{sys} = A_{s1} \times A_{s2} \times A_{s3} \times A_{s4}$

$A_{sys} = 0.9883 \times 0.9057 \times 0.9979 \times 0.8928 = 0.79747$

System Maintainability

The overall system maintainability of the Butter oil production system, $M_{sys}(t)$ is computed as

$M_{sys}(t) = M_{s1}(t) \times M_{s2}(t) \times M_{s3}(t) \times M_{s4}(t)$

$M_{sys}(t) = 1 - e^{-4.8856t}$

System Dependability

The overall system dependability of the Butter oil production system, $D_{min.\ (sys)}$ is computed as

$D_{min.\ (sys)} = D_{min.\ (s1)} \times D_{min.\ (s2)} \times D\ min_{.\ (s3)} \times D_{min.\ (s4)}$

$D_{sys} = 0.9915 \times 0.9280 \times 0.9985 \times 0.9169 = 0.882385$

Table 4.2 Failure and repair rates of the subsystems of the Butter oil production system

Subsystem	**Failure Rate (β)**	**Repair Rate (α)**
S1	Chiller (β_1)=0.0038/hr.	Chiller (α_1)=0.321/hr.
S2	Cream separator (β_2)=0.0057/hr. Pasteurizer (β_3)=0.0073/hr.	Cream separator (α_2)=0.073/hr. Pasteurizer (α_3)=0.281/hr.
S3	Continuous butter making ($\beta_4 = \beta_5$)=0.0045/hr.	Continuous butter making ($\alpha_4 = \alpha_5$)=0.097/hr.
S4	Melting vats (β_6)=0.00431/hr. Butter oil clarifier (β_7)=0.00328/hr.	Melting vats (α_6)=0.086/hr. Butter oil clarifier (α_7)=0.026/hr.

4.2.3 Performance modeling for the fuzzy-reliability analysis of Butter oil production system

$$P'_1(t) = -X_1P_1(t)+\alpha_1P_3(t)+\alpha_2P_4(t)+\alpha_3P_5(t) +\alpha_5P_{13}(t)+\alpha_6P_6(t)+\alpha_7P_7(t) \tag{4.2.44}$$

$$P'_2(t) = -X_2P_2(t)+\alpha_1P_8(t)+\alpha_2P_9(t)+\alpha_3P_{10}(t)+ \beta_4P_1(t)+\alpha_6P_{11}(t)+\alpha_7P_{12}(t) \tag{4.2.45}$$

where

$X_1= \beta_1(1-c)+\beta_2(1-c)+\beta_3(1-c)+\beta_4c+\beta_6(1-c)+\beta_7(1-c)$,

$X_2=\beta_1(1-c)+\beta_2(1-c)+\beta_3(1-c)+\beta_5(1-c)+ \beta_6(1-c)+\beta_7(1-c)$

$$P'_i(t)+\alpha_j P_i(t) = \beta_j(1-c) P_1(t) \tag{4.2.46}$$

where i=3, 4, 5, 6, 7 and j=1, 2, 3, 6, 7

$$P'_i(t)+\alpha_j P_i(t) = \beta_j(1-c) P_2(t) \tag{4.2.47}$$

where i=8, 9, 10, 11, 12 and j=1, 2, 3, 6, 7

$$P'_{13}(t)+\alpha_5 P_{13}(t)=\beta_5(1-c) P_2(t) \tag{4.2.48}$$

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j=1 \\ 0, \text{if } j \neq 1 \end{cases} \tag{4.2.49}$$

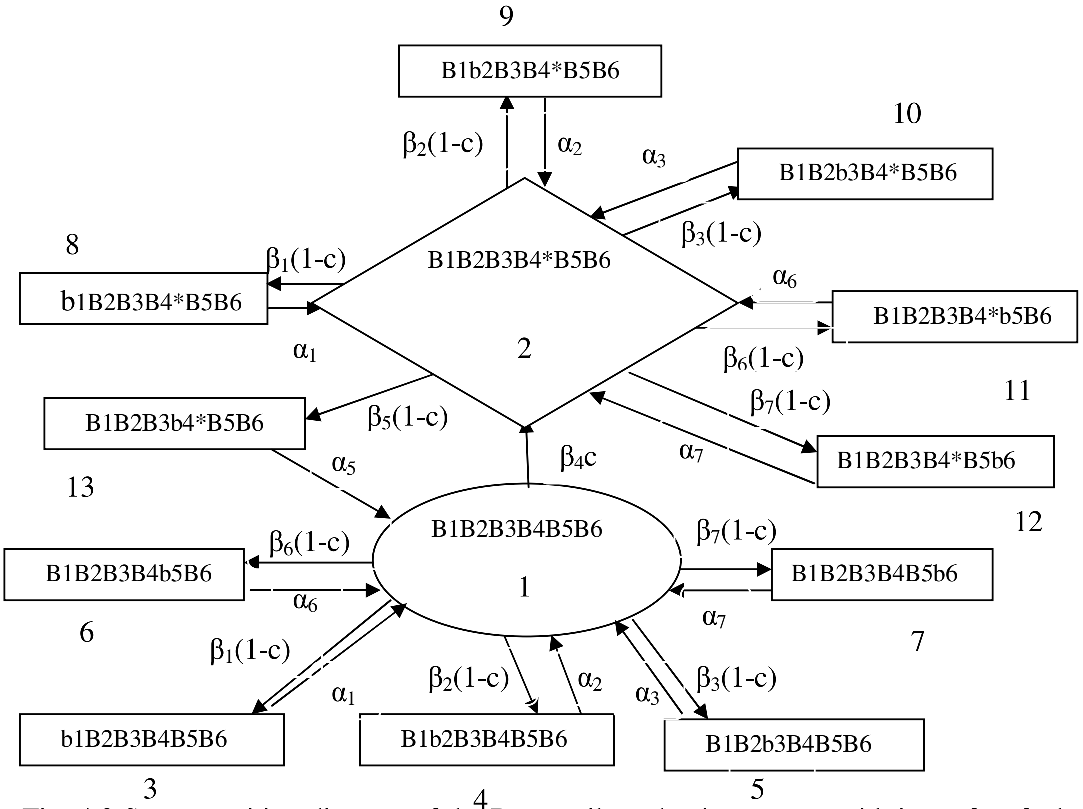


Fig. 4.8 State transition diagram of the Butter oil production system with imperfect fault coverage

The system of differential equations (4.2.44) - (4.2.48) with initial conditions given by Eq. (4.2.49) were solved with Runge-Kutta (4th order) method. The numerical computations were carried out by taking that the failure and repair rates of continuous butter making machine (β_4, α_4) and its standby unit (β_5, α_5) are same.

The fuzzy-reliability of the Butter oil production system was computed for one year (i.e. time, *t*=30-360 days) for different choices of failure rates of the subsystems. The fuzzy-reliability, $R_{F2}(t)$ of the Butter oil production system is composed of the fuzzy-reliability of the system working with full capacity and its standby states i.e.

$$R_{F2}(t) = P_1(t) + \tfrac{1}{2}P_2(t) \tag{4.2.50}$$

The fuzzy-reliability of the Butter oil production system is computed by the Eq. (4.2.50)

4.3 PERFORMANCE MODELING FOR THE STEAM GENERATION SYSTEM OF THE DAIRY PLANT

Performance modeling for the Steam generation system is carried out by deriving mathematical equations for the development of the decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

4.3.1 Performance modeling for the Decision Support Systems (DSS) for the Steam generation system

The transition diagram (Fig. 4.9) depicts a simulation model showing all the possible states of the Steam generation system.

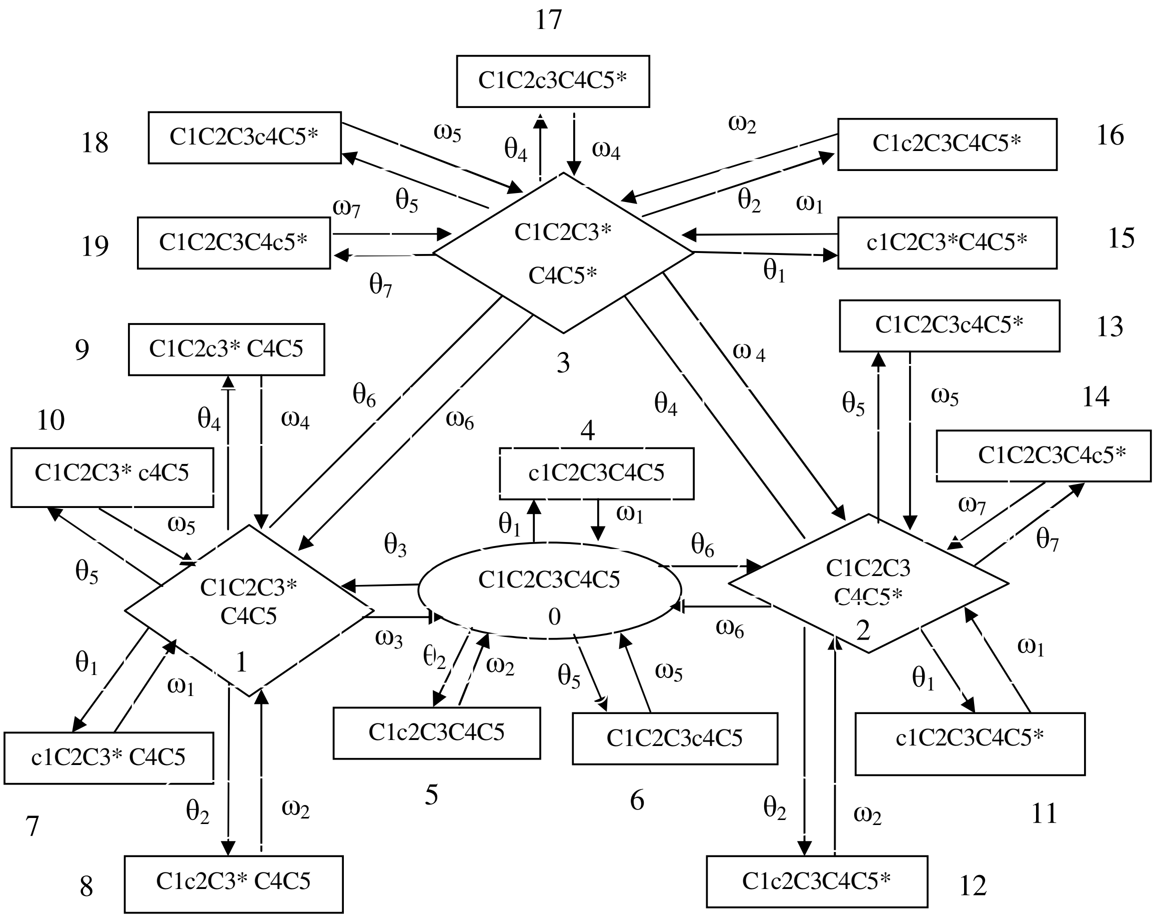


Fig. 4.9 State transition diagram of the Steam generation system

State 0: The system is working with full capacity (with no standby)

State 1: The system is working with standby unit of H.P. heater (C3*)

State 2: The system is working with standby unit of Boiler drum (C5*)

State 3: The system is working with standby units of H.P. heater (C3*) and Boiler drum (C5*)

State 4 to 19: Failed states of the system due to complete failure of other subsystems i.e. C1, C2, C3*, C4 and C5*.

C1, C2, C3, C4 and C5: Indicates full working states of the subsystems

C3* and C5* : Indicates that the subsystem C3 and C5 are working under reduced state

c1, c2, c3, c4 and c5: Indicates the failed states of the subsystems

$P_o(t)$: Probability of the system working with full capacity

P_1 (t), P_2 (t), P_3 (t): Probability of the system working under standby state

θ_i , i=1,2,3…7: The constant failures rates of the subsystems C1, C2, C3, C3*, C4, C5 and C5* resp.

ω_i , i=1,2,3…7 : The constant repair rates of the subsystems C1, C2, C3, C3*, C4, C5 and C5* resp.

$P_j(t)$, j=0,1,2,3,…..19 : The probability that the system is in j^{th} state at time, *t*.

The Mathematical equations (4.3.1)-(4.3.8) based on Markov-birth death process are developed for each state one by one out of 20 states of transition diagram (Fig. 4.9).

$$P'_o(t) = -X_oP_o(t)+\omega_1P_4(t)+\omega_2P_5(t)+\omega_5P_6(t)+\omega_3P_1(t)+\omega_6P_2(t) \qquad (4.3.1)$$

$$P'_1(t) = -X_1P_1(t)+\omega_1P_7(t)+\omega_2P_8(t)+\omega_4P_9(t)+\theta_3P_o(t)+\omega_5P_{10}(t)+\omega_6P_3(t) \qquad (4.3.2)$$

$$P'_2(t) = -X_2P_2(t)+\omega_1P_{11}(t)+\omega_2P_{12}(t)+\omega_5P_{13}(t)+\omega_4P_3(t)+\theta_6P_0(t)+\omega_7P_{14}(t) \qquad (4.3.3)$$

$$P'_3(t) = -X_3P_3(t)+\omega_1P_{15}(t)+\omega_2P_{16}(t)+\omega_4P_{17}(t)+\theta_4P_2(t)+\omega_5P_{18}(t)+\theta_6P_1(t)+\omega_7P_{19}(t) \qquad (4.3.4)$$

where

$X_o= (\theta_1+\theta_2+\theta_3+\theta_5+\theta_6)$; $X_1= (\theta_1+\theta_2+\omega_3+\theta_4+\theta_5+\theta_6)$,

$X_2= (\theta_1+\theta_2+\theta_5+\theta_4+\omega_6+\theta_7)$; $X_3= (\theta_1+\theta_2+\theta_4+\omega_4+\theta_5+\omega_6+\theta_7)$

$$P'_i(t) + \omega_j P_i(t) = \theta_j P_o(t) \qquad (4.3.5)$$

where *i*=4, 5, 6 and *j*=1,2,5

$$P'_i(t) + \omega_j P_i(t) = \theta_j P_1(t) \qquad (4.3.6)$$

where *i*=7, 8, 9, 10 and *j*=1,2,4,5

$$P'_i(t) + \omega_j P_i(t) = \theta_j P_1(t) \qquad (4.3.7)$$

where *i*=11,12,13,14 and *j*=1,2,5,7

$$P'_i(t) + \omega_j P_i(t) = \theta_j P_1(t) \qquad (4.3.8)$$

where *i*=15,16,17,18, 19 *j*=1,2,4,5,7

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j = 1 \\ 0, \text{if } j \neq 1 \end{cases} \tag{4.3.9}$$

The system of differential equations (4.3.1) - (4.3.8) with initial conditions given by Eq. (4.3.9) was solved by gives the reliability of the Steam generation system. The numerical computations have been carried out by taking Runge-Kutta fourth order method. The numerical computations were carried out by taking that

(i) The failure and repair rates of H.P. heater (θ_3, ω_3) and its standby unit (θ_4, ω_4) are same.

(ii) The failure and repair rates of Boiler drum (θ_6, ω_6) and its standby unit (θ_7, ω_7) are same.

The numerical computations were carried out for one year (i.e. time, *t*=30-360 days) for different choices of failure and repair rates of the subsystems. The reliability of the system, $R_3(t)$ is composed of the sum of the reliability of the system working with full capacity and its standby states i.e.

$$R_3(t) = P_o(t) + P_1(t) + P_2(t) + P_3(t) \tag{4.3.10}$$

The reliability of the Steam generation system is computed by Eq. (4.3.10)

The steady state probabilities of the system are obtained by imposing the following restrictions; d/dt→0, as t→∞. The equations (4.3.1) to (4.3.8) get reduced to the following system of Eqs.

$$X_oP_o = \omega_1P_4 + \omega_2P_5 + \omega_5P_6 + \omega_3P_1 + \omega_6P_2 \tag{4.3.11}$$

$$X_1P_1 = \omega_1P_7 + \omega_2P_8 + \omega_4P_9 + \theta_3P_o + \omega_5P_{10} + \omega_6P_3 \tag{4.3.12}$$

$$X_2P_2 = \omega_1P_{11} + \omega_2P_{12} + \omega_5P_{13} + \omega_4P_3 + \theta_6P_0 + \omega_7P_{14} \tag{4.3.13}$$

$$X_3P_3 = \omega_1P_{15} + \omega_2P_{16} + \omega_4P_{17} + \theta_4P_2 + \omega_5P_{18} + \theta_6P_1 + \omega_7P_{19} \tag{4.3.14}$$

$$P_i + \omega_j P_i = \theta_j P_o \tag{4.3.15}$$

where *i*=4, 5, 6 and *j*=1, 2, 5

$$P_i + \omega_j P_i = \theta_j P_1 \tag{4.3.16}$$

where i=7, 8, 9, 10 and *j*=1, 2, 4, 5

$$P_i + \omega_j P_i = \theta_j P_1 \tag{4.3.17}$$

where i=11, 12, 13, 14 *j*=1, 2, 5, 7

$$P_i + \omega_j P_i = \theta_j P_1 \tag{4.3.18}$$

where *i*=15, 16, 17, 18, 19 and *j*=1, 2, 4, 5, 7

Under normalized conditions i.e. sum of all the probabilities is equal to one

$$\therefore \quad \sum_{i=0}^{19} P_i = 1 \quad \text{i.e. } P_o+P_1+P_2+ \ldots\ldots\ldots\ldots +P_{19}=1$$

The value of P_o, $P_{1,}$ P_2 and P_3 are obtained by solving Eqs. (4.3.15)-(4.3.18) by recursive method.

$$P_0= \frac{1}{\begin{array}{c}[1+A+B+C+(\theta_1/\omega_1+\theta_2/\omega_2+\theta_3/\omega_3)+A(\theta_1/\omega_1+\theta_2/\omega_2+\theta_3/\omega_3+\theta_5/\omega_5)+\\ B(\theta_1/\omega_1+\theta_2/\omega_2+\theta_3/\omega_3+\theta_7/\omega_7)+C(\theta_1/\omega_1+\theta_2/\omega_2+\theta_3/\omega_3+\theta_5/\omega_5+\theta_7/\omega_7)]\end{array}} \tag{4.3.19}$$

$$P_1=\frac{P_0}{\theta_4/k_3} \tag{4.3.20}$$

$$P_2=\frac{P_0}{k_1/k_4} \tag{4.3.21}$$

$$P_3= P_0\frac{\theta_4\, k_1}{k_3\, k_4} \tag{4.3.22}$$

where, $A=\frac{\theta_4}{k_3}$, $B=\frac{k_1}{k_4}$, $C=\frac{\theta_4\, k_1}{k_3\, k_4}$, $k_1= \theta_4+\theta_6$, $k_2= \omega_4+\omega_6$, $k_3= \theta_6+\omega_4$, $k_4=\theta_4+\omega_6$

The steady state availability of the Steam generation system (A_{v3}) is the summation of its working and standby states i.e.

$$A_{v3}= P_0+ P_1+ P_2+ P_3 \tag{4.3.23}$$

The Eq. (4.3.23) gives the steady availability of the Steam generation system

4.3.2 Performance modeling for RAMD analysis of the Steam generation system

The Steam generation system is transformed in to four subsystems (S1-S4) as shown in Fig. 4.10. The transition diagrams associated with the subsystems (S1- S4) are shown in Fig. 4.11((a)-(d)). The data regarding failure and repair rates of the subsystems is presented in table 4.3.

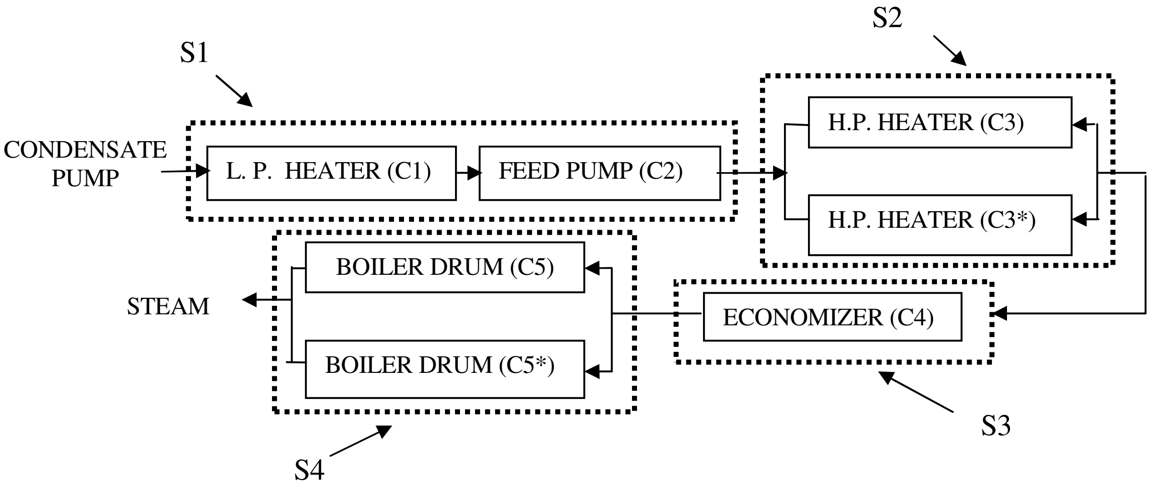


Fig. 4.10 Schematic representation of the Steam generation system

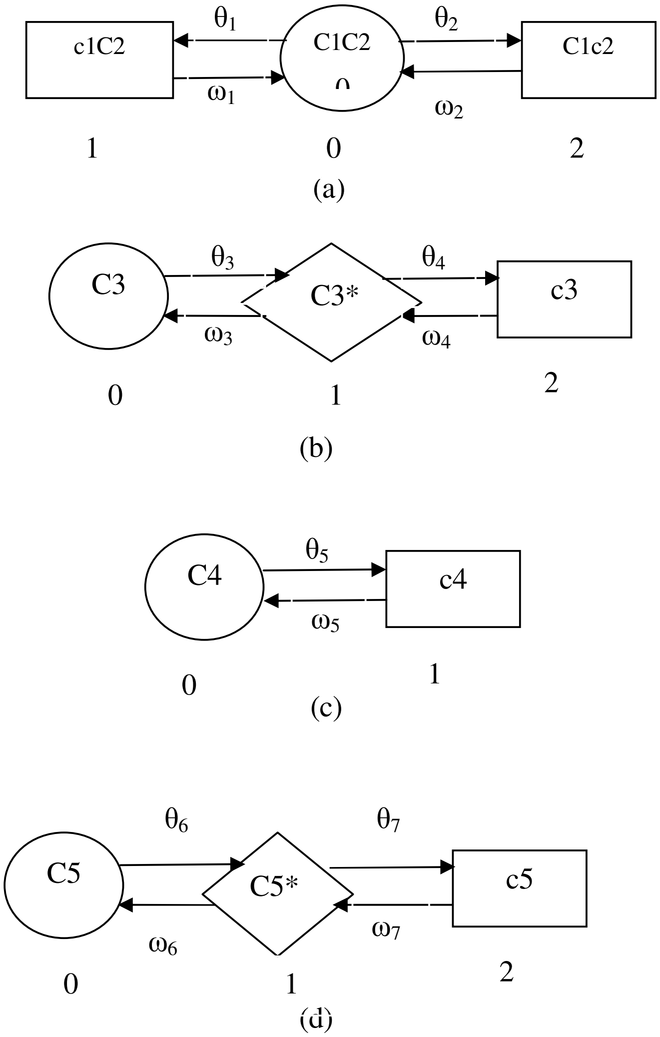


Fig. 4.11 State transition diagram of the subsystems of the Steam generation system

(a) subsystem S1, (b) subsystem S2, (c) subsystem S3, (d) subsystem S4

RAMD indices for subsystem S1

This subsystem S1 consists of two units C1 (L.P. heater) and C2 (Feed pump) connected in series. Failure of unit C1 or C2 causes complete failure of the system. The differential equations associated with Fig. 4.11(a) are:

$P'_o(t) = -(\theta_1 + \theta_2)P_o(t) + \omega_1 P_1(t) + \omega_2 P_2(t)$ (4.3.24)

$P'_1(t) = -\omega_1 P_1(t) + \theta_1 P_0(t)$ (4.3.25)

$P'_2(t) = -\omega_2 P_2(t) + \theta_2 P_0(t)$ (4.3.26)

Under steady state conditions, the Eqs. (3.24)-(3.26) get reduced as:

$(\theta_1 + \theta_2)P_o = \omega_1 P_1 + \omega_2 P_2$ (4.3.27)

$\omega_1 P_1 = \theta_1 P_0$ (4.3.28)

$\omega_2 P_2 = \theta_2 P_0$ (4.3.29)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.3.30)

Putting the values of P_1 and P_2 from Eqs. (3.28) and (3.29) in Eq. (4.3.30)

$P_0 (1 + \theta_1 / \omega_1 + \theta_2 / \omega_2) = 1$ (4.3.31)

The availability of the subsystem S1 is given by Eq. (4.3.31)

$R_{S1\,(t)} = e^{-0.0345t.}$ (4.3.32)

The reliability Eq. for the subsystem S1 is given by Eq. (4.3.32)

$M_{S1}(t) = 1 - e^{-0.192t}$ (4.3.33)

The maintainability Eq. for the subsystem S1is given by Eq. (4.3.33)

The other parameters for the subsystem S1 are computed as:

$D_{min.(S1)} = 0.8747$

MTBF= 28.9855 hr.

MTTR= 5.2067 hr. and

d= 5.567.

RAMD indices for subsystem S2

This subsystem has single unit C3 (H.P. Heater) only but it has its cold standby unit (C3*). Failure of both units causes complete failure of the system. The differential equations associated with Fig. 4.11 (b) are:

$P'_0(t) = -\theta_3 P_0(t) + \omega_3 P_1(t)$ (4.3.34)

$P'_1(t) = -(\omega_3 + \theta_4)P_1(t) + \theta_3 P_0(t) + \omega_4 P_2(t)$ (4.3.35)

$P'_2(t) = -\omega_4 P_2(t) + \theta_4 P_1(t)$ (4.3.36)

Under steady state conditions, the Eqs. (4.3.34)- (4.3.36) get reduced as:

$(\omega_3 + \theta_4)P_1 = \theta_3 P_0 + \omega_4 P_2$ (4.3.37)

$\omega_4 P_2 = \theta_4 P_1$ (4.3.38)

$\omega_3 P_1 = \theta_3 P_0$ (4.3.39)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.3.40)

Put the values of P_1 and P_2 by solving Eqs. (4.3.37) to (4.3.39) in eqn. (4.3.40)

$P_0 (1 + \theta_3 / \omega_3 + \theta_4 \theta_3 / \omega_4 \omega_3) = 1$ (4.3.41)

The availability of the subsystem S2 is given by Eq. (4.3.41)

$R_{S2\,(t)} = e^{-0.009t}$ (4.3.42)

Reliability Eq. for the subsystem S2 is given by Eq. (4.3.42)

$M_{S2}(t) = 1 - e^{-2.582t}$ (4.3.43)

The maintainability Eq. for the subsystem S2 is given Eq. (4.3.43)

The other parameters for the subsystem S2 are computed as:

$D_{min.\,(S2)} = 0.9975$

MTBF= 111.11 hr.

MTTR= 0.3873 hr. and

d= 286.8642

RAMD indices for subsystem S3

This subsystem has single unit C4 (Economizer) only and failure of this unit causes complete failure of the system. The differential equations associated with Fig. 4.11 (c) are:

$P'_o(t) = -\theta_5 P_o(t) + \omega_5 P_1(t)$ (4.3.44)

$P'_1(t) = -\omega_5 P_1(t) + \theta_5 P_0(t)$ (4.3.45)

Under steady state conditions, the Eqs. (4.3.44)- (4.3.45) get reduced as:

$\theta_5 P_o = \omega_5 P_1$ (4.3.46)

$\omega_5 P_1 = \theta_5 P_0$ (4.3.47)

Now, using the normalizing conditions

$P_0 + P_1 = 1$ (4.3.48)

The Eqs. (4.3.46) and (4.3.47) are solved to get the values of P_0 i.e.

$P_0 (1 + \theta_5 / \omega_5] = 1$ (4.3.49)

The availability of the subsystem S3 is given by Eq. (4.3.49)

$R_{S3\,(t)} = e^{-0.0054t}$ (4.3.50)

The reliability Eq. for the subsystem S3 is given by Eq. (4.3.50)

$M_{S3}(t) = 1 - e^{-0.38t}$ (4.3.51)

The maintainability Eq. for the subsystem S3 is given by Eq. (4.3.51)

The other parameters for the subsystem S4 are computed as:

$D_{min.(S3)} = 0.9898$

MTBF= 185.1852 hr.

MTTR= 2.6316 hr. and

d =70.3704.

RAMD indices for subsystem S4

This subsystem has single unit C5 (Boiler drum) only but it has its cold standby unit C5*. Failure of both units causes complete failure of the system. The differential equations associated with Fig. 4.11 (d) are:

$P'_0(t) = -\theta_6 P_0(t) + \omega_6 P_1(t)$ (4.3.52)

$P'_1(t) = -(\omega_6 + \theta_7)P_1(t) + \theta_6 P_0(t) + \omega_7 P_2(t)$ (4.3.53)

$P'_2(t) = -\omega_7 P_2(t) + \theta_7 P_1(t)$ (4.3.54)

Under steady state conditions, the Eqs. (4.3.52)- (4.3.54) get reduced as:

$(\omega_6 + \theta_7)P_1 = \theta_6 P_0 + \omega_7 P_2$ (4.3.55)

$\omega_7 P_2 = \theta_7 P_1$ (4.3.56)

$\omega_6 P_1 = \theta_6 P_0$ (4.3.57)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.3.58)

Put the values of P_1 and P_2 by solving Eqs. (4.3.55)- (4.3.57) in Eq. (4.3.58)

$P_0 (1 + \theta_6 / \omega_6 + \theta_7 \theta_6 / \omega_7 \omega_6) = 1$ (4.3.59)

The availability of the subsystem S4 is given by Eq. (4.3.59)

$R_{S4\ (t)} = e^{-0.0124t}$ (4.3.60)

Reliability Eq. for the subsystem S4 is given by Eq. (4.3.60)

$M_{S4}(t) = 1 - e^{-33.67t}$ (4.3.61)

The maintainability Eq. for the subsystem S4 is given by Eq. (4.3.61)

The other parameters for the subsystem S4 are computed as:

$D_{min.\ (S4)} = 0.9997$

MTBF= 80.6452 hr.

MTTR= 0.0297 hr. and

d= 0.002715

System Reliability

The overall system reliability of Steam generation system, $R_{sys}(t)$

$R_{sys}(t) = R_{s1}(t) \times R_{s2}(t) \times R_{s3}(t) \times R_{s4}(t)$

$R_{sys}(t) = e^{-0.0345t} \text{ x } e^{-0.009t} \text{ x } e^{-0.0054t} \text{ x } e^{-0.0124t} = e^{-0.02889t}$

$R_{sys}(t) = e^{-0.002456t}$

System Availability

The overall system availability of the Steam generation system (A_{sys}) is computed as:

$A_{sys} = A_{s1} \text{ x } A_{s2} \text{ x } A_{s3} \text{ x } A_{s4}$

$A_{sys} = 0.8477 \text{ x } 0.9965 \text{ x } 0.9860 \text{ x } 0.9996 = 0.8326$

System Maintainability

The overall system maintainability of Steam generation system, $M_{sys}(t)$ is computed as:

$M_{sys}(t) = M_{s1}(t) \text{ x } M_{s2}(t) \text{ x } M_{s3}(t) \text{ x } M_{s4}(t)$

$M_{sys}(t) = 1-e^{-8.2553t}$

System Dependability

The overall system dependability of the Steam generation system, $D_{min.\,(sys)}$ is computed as: $D_{min.\,(sys)} = D_{min.\,(S1)} \text{ x } D_{min.\,(S2)} \text{ x } D\ min_{.\,(s3)} \text{ x } D_{min.\,(S4)}$

$D_{sys} = 0.8747 \text{ x } 0.9975 \text{ x } 0.9898 \text{ x } 0.9997 = 0.86335$

Table 4.3 Failure and repair rates of the subsystems of the Steam generation system

Subsystem	Failure Rate (θ)	Repair Rate (ω)
S1	L.P. Heater (θ_1)=0.0065/hr. Feed Pump (θ_2)=0.028/hr.	L.P. Heater (ω_1)=0.27/hr. Feed Pump (ω_2)=0.18/hr.
S2	H.P. Heater ($\theta_3 = \theta_4$)=0.0045/hr.	H.P. Heater ($\omega_3 = \omega_4$)=0.074/hr.
S3	Economizer (θ_5)=0.0054/hr.	Economizer (ω_5)=0.38/hr.
S4	Boiler Drum ($\theta_6 = \theta_7$)=0.0062/hr.	Boiler Drum ($\omega_6 = \omega_7$)=0.32/hr.

4.3.3 Performance modeling for the fuzzy-reliability analysis of the Steam generation system

$$P'_o(t) = -X_oP_o(t)+\omega_1P_4(t)+\omega_2P_5(t)+\omega_5P_6(t) +\omega_3P_1(t)+\omega_6P_2(t) \qquad (4.3.62)$$

$$P'_1(t) = -X_1P_1(t)+\omega_1P_7(t)+\omega_2P_8(t)+\omega_4P_9(t) + \theta_3cP_o(t)+\omega_5P_{10}(t)+\omega_6P_3(t) \qquad (4.3.63)$$

$$P'_2(t) = -X_2P_2(t)+\omega_1P_{11}(t)+\omega_2P_{12}(t)+\omega_5P_{13}(t) +\omega_4P_3(t)+\theta_6cP_0(t)+\omega_7P_{14}(t) \qquad (4.3.64)$$

$$P'_3(t) = -X_3P_3(t)+\omega_1P_{15}(t)+\omega_2P_{16}(t)+\omega_4P_{17}(t) +\theta_4cP_2(t)+\omega_5P_{18}(t)+\theta_6cP_1(t) + \omega_7P_{19}(t) \qquad 4.3.65)$$

where

$X_o= \theta_1(1-c)+\theta_2(1-c)+\theta_3c+\theta_5(1-c)+\theta_6c$, $X_1= \theta_1(1-c)+\theta_2(1-c)+\omega_3+\theta_4(1-c) +\theta_5(1-c)+\theta_6c$,

$X_2=\theta_1(1-c)+\theta_2(1-c)+\theta_5(1-c)+\theta_4c+\omega_6+\theta_7(1-c)$,

$X_3=\theta_1(1-c)+\theta_2(1-c)+\theta_4(1-c)+\omega_4+\theta_5(1-c)+\omega_6+\theta_7(1-c)$

$$P'_i(t) + \omega_j P_i(t) = \theta_j(1-c)P_o(t) \qquad (4.3.66)$$

where i=4, 5, 6 and j=1,2,5

$$P'_i(t) + \omega_j P_i(t) = \theta_j(1\text{-}c)\, P_1(t) \qquad (4.3.67)$$

where i=7, 8, 9, 10 and j=1,2,4,5

$$P'_i(t) + \omega_j P_i(t) = \theta_j(1\text{-}c)\, P_1(t) \qquad (4.3.68)$$

where i=11,12, 13, 14 and j=1,2,5,7

$$P'_i(t) + \omega_j P_i(t) = \theta_j(1\text{-}c)\, P_1(t) \qquad (4.3.69)$$

where i=15,16,17,18, 19 and j=1,2,4,5,7

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j = 1 \\ 0, \text{if } j \neq 1 \end{cases} \qquad (4.3.70)$$

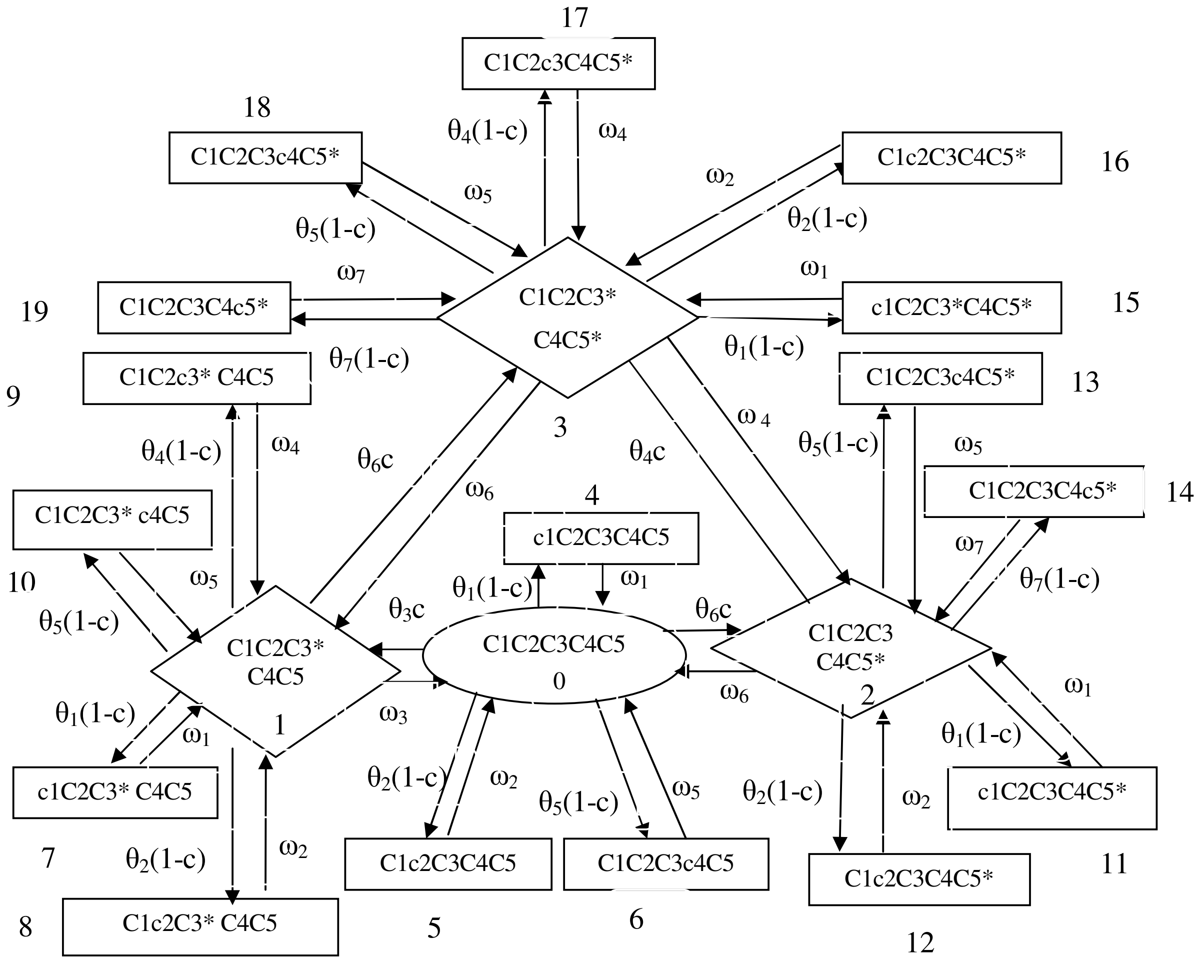


Fig. 4.12 State transition diagram of the Steam generation system with imperfect fault coverage

The system of differential equations (4.3.62) - (4.3.69) with initial conditions given by Eq. (4.3.70) was solved with Runge-Kutta fourth order method. The numerical computations were carried out by taking that

(i) The failure and repair rates of H.P. heater (θ_3, ω_3) and its standby unit (θ_4, ω_4) are same.

(ii) The failure and repair rates of boiler drum (θ_6, ω_6) and its standby unit (θ_7, ω_7) are same.

The fuzzy-reliability of the Steam generation system was computed for one year (i.e. time, *t*=30-360 days) for different choices of failure rates of the subsystems. The fuzzy-reliability (R_{F3}) of the Steam generation system is composed of the fuzzy-reliability of the system working with full capacity and its standby states i.e.

$$R_{F3}\,(t) = P_1+\frac{1}{2}P_2+\frac{1}{2}P_3+\frac{1}{4}P_4 \qquad (4.3.71)$$

The fuzzy-reliability of the Steam generation system is computed by the Eq. (4.3.71)

4.4 PERFORMANCE MODELING FOR THE REFRIGERATION SYSTEM OF THE DAIRY PLANT

Performance modeling for the Refrigeration system is carried out by deriving mathematical equations for the development of the decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

4.4.1 Performance modeling for the Decision Support Systems (DSS) for the Refrigeration system

The transition diagram (Fig. 4.13) depicts a simulation model showing all the possible states of the Refrigeration system.

State 1: The system is working with full capacity (with no standby)

State 2: The system is working with first standby unit of Compressor (D1*)

State 3: The system is working with standby unit of Condenser (D2*)

State 4: The system is working with standby units of Compressor (D1*) and Condenser (D2*).

State 5 to 20: Failed states of the system due to complete failure of its subsystems i.e. D1, D2, D3, D4 and D5.

D1, D2, D3, D4 and D5: Indicates full working states of the subsystems

D1* and D2* : Indicates that the subsystem D1 and D2 are working under standby state d1, d2, d3, d4 and d5: Indicates the failed states of the subsystems

P_1 (t) : Probability of the system working with full capacity

P_2 (t), P_3 (t), P_4 (t): Probability of the system working under standby state

$\phi_i = 1, 2, 3 ...7$: The constant failures rates of the subsystems D1, D1*, D2, D2*, D3, D4 and D5 resp.

$\tau_i = 1,2,3,.......7$: The constant repair rates of the subsystems D1, D1*, D2, D2*, D3, D4 and D5 resp.

$P_j(t)$, j= 1,2,3,…..20: The probability that the system is in j^{th} state at time , *t*

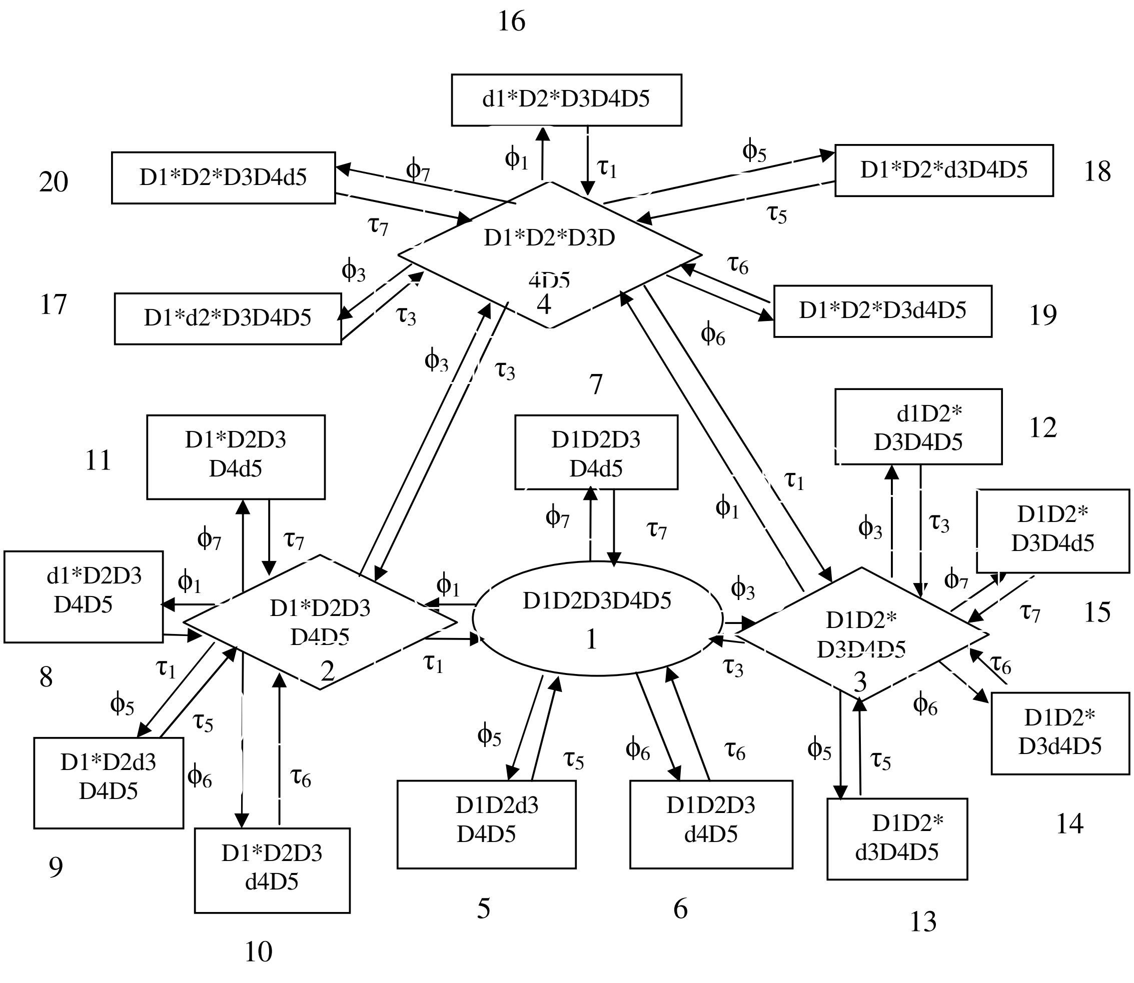


Fig. 4.13 State transition diagram of the Refrigeration system

The Mathematical equations (4.4.1)-(4.1.8) based on Markov-birth death process is developed for each state one by one out of 20 states of transition diagram (Fig. 4.13).

$$P'_1(t) = - X_1P_1(t) + \tau_5P_5(t) + \tau_6P_6(t) + \tau_7P_7(t)+\tau_1P_2(t)+\tau_3P_3(t) \quad (4.4.1)$$

$$P'_2(t) = - X_2P_2(t) + \tau_1P_8(t) + \tau_5P_9(t) + \tau_6P_{10}(t)+ \tau_7P_{11}(t) + \tau_2P_4(t) + \phi_1P_1(t) \quad (4.4.2)$$

$P'_3(t) = - X_3P_3(t) + \tau_3P_{12}(t) + \tau_5P_{13}(t) + \tau_6P_{14}(t) + \tau_7P_{15}(t) + \tau_1P_4(t) + \phi_3P_1(t)$ (4.4.3)

$P'_4(t) = - X_4P_4(t)+\tau_1P_{16}(t)+\tau_3P_{17}(t) + \tau_5P_{18}(t)+ \tau_6P_{19}(t) +\tau_7P_{20}(t) + \phi_2P_2(t)+ \phi_1P_3(t)$ (4.4.4)

where

$X_1= (\phi_5+\phi_6+\phi_7+\phi_1+\phi_3)$; $X_2 = (\phi_1+\phi_5+\phi_6 +\phi_7+ \tau_1+\phi_2)$,

$X_3= (\phi_3+\phi_5+\phi_6+\phi_7+ \tau_3+\phi_1)$, $X_4= (\phi_1+\phi_3+\phi_5+ \tau_2 + \tau_1+ \phi_6 +\phi_7)$

$P'_i(t) + \tau_jP_i(t) = \phi_jP_1(t)$ (4.4.5), where i= 5, 6, 7 and j=5, 6, 7

$P'_i(t) + \tau_jP_i(t) = \phi_jP_2(t)$ (4.4.6), where i= 8, 9, 10, 11 and j=1, 5, 6, 7

$P'_i(t) + \tau_jP_i(t) = \phi_jP_3(t)$ (4.4.7), where i= 12, 13, 14, 15 and j=3, 5, 6, 7

$P'_i(t) + \tau_jP_i(t) = \phi_jP_4(t)$ (4.4.8), where i= 16, 17, 18, 19, 20 and j=1, 3, 5, 6, 7

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j = 1 \\ 0, \text{if } j \neq 1 \end{cases} \quad (4.4.9)$$

The system of differential equations (4.4.1)-(4.4.8) with initial conditions given by Eq. (4.4.9) was solved with Runge-Kutta fourth order method. The numerical computations were carried out by taking that

(i)The failure and repair rates of compressor (ϕ_1, τ_1) and its standby unit (ϕ_2, τ_2) are same.

(ii)The failure and repair rates of condenser (ϕ_3, τ_3) and its standby unit (ϕ_4, τ_4) are same.

The numerical computations were carried out for one year (i.e. time, t=30-360 days) for different choices of failure and repair rates of the subsystems. The reliability of the system, $R_3(t)$ is composed of the sum of the reliability of the system working with full capacity and its standby states i.e.

$R_4(t) = R_1(t)+R_2(t)+ R_3(t)+R_4(t)$ (4.4.10)

The reliability of the Refrigeration system is computed by Eq. (4.4.10)

The management of the plant is interested to get the steady state availability of the system. The steady state probabilities of the system are obtained by imposing the following restrictions; d/dt→0, as t→∞. The equations (4.4.1) to (4.4.8) get reduced to the following system of Eqs.

$X_1P_1 =\tau_5P_5 +\tau_6P_6 + \tau_7P_7 +\tau_1P_2+\tau_3P_3$ (4.4.11)

$X_2P_2 =\tau_1P_8+\tau_5P_9+\tau_6P_{10}+\tau_7P_{11}+\tau_2P_4 +\phi_1P_1$ (4.4.12)

$X_3P_3=\tau_3P_{12}+\tau_5P_{13}+\tau_6P_{14}+\tau_7P_{15}+\tau_1P_4 +\phi_3P_1$ (4.4.13)

$X_4P_4=\tau_1P_{16} +\tau_3P_{17}+\tau_5P_{18}+\tau_6P_{19} +\tau_7P_{20}+\phi_2P_2 + \phi_1P_3$ (4.4.14)

where

$X_1= (\phi_5+\phi_6+\phi_7+\phi_1+\phi_3)$, $X_2 = (\phi_1+\phi_5+\phi_6 +\phi_7+ \tau_1+\phi_2)$,

$X_3= (\phi_3+\phi_5+\phi_6+\phi_7+ \tau_3+\phi_1)$, X4= $(\phi_1+\phi_3+\phi_5+ \tau_2 + \tau_1+ \phi_6 +\phi_7)$

$\tau_j P_i = \phi_j P_1$ (4.4.15), where i= 5, 6, 7 and j=5, 6, 7

$\tau_j P_i = \phi_j P_2$ (4.4.16), where i= 8, 9, 10, 11 and j=1, 5, 6, 7

$\tau_j P_i = \phi_j P_3$ (4.4.17), where i= 12, 13, 14, 15 and j=3, 5, 6, 7

$\tau_j P_i = \phi_j P_4$ (4.4.18), where i= 16, 17, 18, 19 and j=1, 3, 5, 6, 7

$P_1 = (L+M+N+O+P)^{-1}$, $P_2 = P_1 A$, $P_3 = P_1 B$, $P_4 = P_1 C$

where

$L = 1+A+B+C$, $M = \phi_5/\tau_5+\phi_6/\tau_6+\phi_7/\tau_7$, $N = A(\phi_1/\tau_1+\phi_5/\tau_5+\phi_6/\tau_6+\phi_7/\tau_7)$,

$O = B(\phi_3/\tau_3+\phi_5/\tau_5+\phi_6/\tau_6+\phi_7/\tau_7)$, $P = C(\phi_1/\tau_1+\phi_3/\tau_3+\phi_5/\tau_5+\phi_6/\tau_6+\phi_7/\tau_7)$,

$A = (\phi_1\tau_2 k1+\tau_3 k4\phi_1)/(\phi_1\tau_2\tau_1+\tau_3 k_4 k2-\tau_3\phi_2\tau_2)$, $B = (k1k2+\tau_2\phi_3-\phi_1\tau_1)/(\tau_2 k3+\tau_3 k2)$,

$C = (k1\ k2\ k3-\tau_1\phi_1\ k3-\tau_3\phi_3\ k2)/(\tau_1\tau_2\ k_3+\tau_3\ \tau_1\ k2)$, $k1=\phi_1+\phi_3$, $k2=\tau_1+\phi_3$, $k3=\tau_3+\phi_1$, $k4=\tau_3+\tau_1$

Under normalized conditions i.e. sum of all the probabilities is equal to one.

$$\therefore \quad \sum_{i=0}^{19} P_i = 1 \quad \text{i.e. } P_o+P_1+P_2+\ldots\ldots\ldots\ldots\ldots\ldots\ldots+P_{19}=1$$

$$P_o\left[1+\frac{P_1}{P_o}+\frac{P_2}{P_o}+\frac{P_3}{P_o}+\frac{P_4}{P_o}+\ldots\ldots\ldots\ldots+\frac{P_{19}}{P_o}\right]=1 \tag{4.4.19}$$

The steady state availability of the Refrigeration system (A_{v4}) is the summation of its working and standby states i.e.

$A_{v4} = P_1+ P_2+ P_3+ P_4$ (4.4.20)

The Eq. (4.4.20) gives the steady state availability of the Refrigeration system.

4.4.2 Performance modeling for RAMD analysis of the Refrigeration system

The Refrigeration system is transformed in to four subsystems (S1-S4) as shown in Fig. 4.14. The transition diagrams associated with the subsystems (S1- S4) are shown in Fig. 4.15((a)-(d)). The data regarding failure and repair rates of the subsystems is presented in table 4.4.

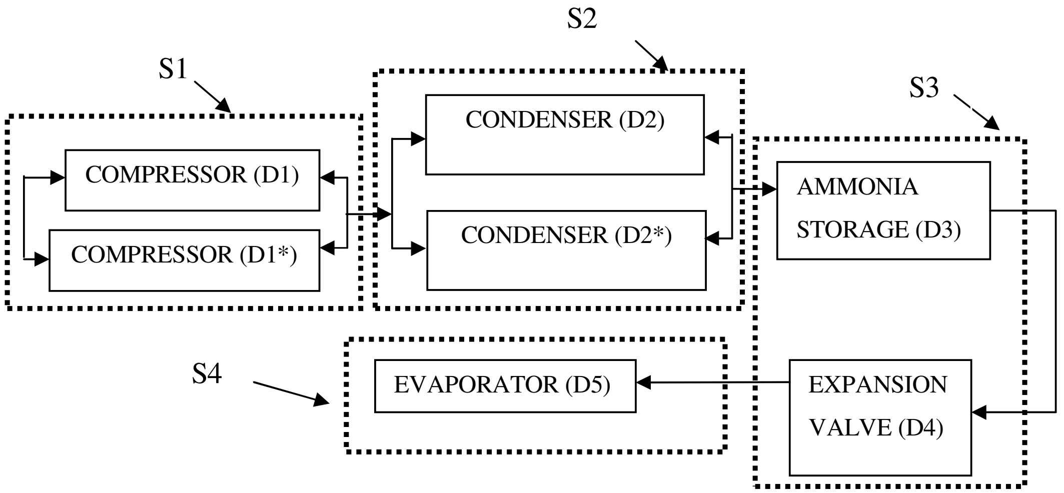
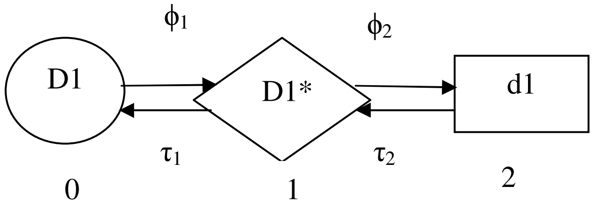
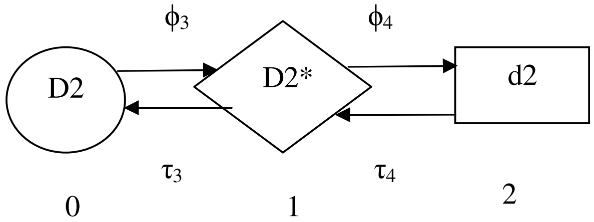


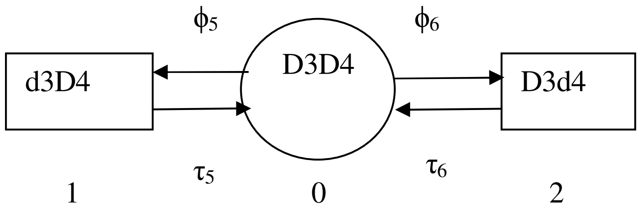
Fig. 4.14 Schematic representation of the Refrigeration system



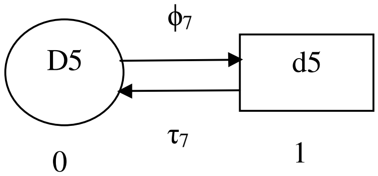
(a)



(b)



(c)



(d)

Fig. 4.15 State transition diagram of the subsystems of the Refrigeration system (a) subsystem S1, (b) subsystem S2, (c) subsystem S3, (d) subsystem S4

RAMD indices for subsystem S1

This subsystem has single unit (D1 (Compressor only but it has its cold standby unit (D1*). Failure of both units causes complete failure of the system. The differential equations associated with Fig. 4.15 (a) are:

$P'_0(t) = - \phi_1 P_0(t) + \tau_1 P_1(t)$ (4.4.21)

$P'_1(t) = - (\tau_1 + \phi_2)P_1(t) + \phi_1 P_0(t) + \tau_4 P_2(t)$ (4.4.22)

$P'_2(t) = - \tau_2 P_2(t) + \phi_2 P_1(t)$ (4.4.23)

Under steady state conditions, the Eqs. (4.4.21)-(4.4.23) get reduced as:

$(\tau_1 + \phi_2)P_1 = \phi_1 P_0 + \tau_2 P_2$ (4.4.24)

$\tau_2 P_2= \phi_2 P_1$ (4.4.25)

$\tau_1 P_1= \phi_1 P_0$ (4.4.26)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 =1$ (4.4.27)

Put the values of P_1 and P_2 by solving Eqs. (4.4.24) -(4.4.26) in Eq. (4.4.27)

$P_0 (1+ \phi_1 / \tau_1 + \phi_2 \phi_1 / \tau_2 \tau_1) =1$ (4.4.28)

The availability for the subsystem S1 is given by Eq. (4.4.28)

$R_{S1} (t) = e^{-0.132t}$ (4.4.29)

Reliability Eq. for the subsystem S1 is given by Eq. (4.4.29)

$M_{S1} (t) = 1-e^{-3.5323t}$ (4.4.30)

The maintainability Eq. for the subsystem S1 is given by Eq. (4.4.30)

The others parameters for the subsystem S1 are computed as:

$D_{min. (S1)}= 0.9736$

MTBF= 7.5758 hr.

MTTR= 0.2831 hr. and

d= 26.7585.

RAMD indices for subsystem S2

This subsystem has single unit D2 (Condenser) only but it has its cold standby unit (D2*). Failure of both units causes complete failure of the system. The differential equations associated with Fig. 4.15(b) are:

$P'_0(t) = - \phi_3 P_0(t) + \tau_3 P_1(t)$ (4.4.31)

$P'_1(t) = - (\tau_3 + \phi_4) P_1(t) + \phi_3 P_0(t) + \tau_4 P_2(t)$ (4.4.32)

$P'_2(t) = - \tau_4 P_2(t) + \phi_4 P_1(t)$ (4.4.33)

Under steady state conditions, the Eqs. (4.4.31)-(4.4.33) get reduced as:

$(\tau_3 + \phi_4) P_1 = \phi_3 P_0 + \tau_4 P_2$ (4.4.34)

$\tau_4 P_2 = \phi_4 P_1$ (4.4.35)

$\tau_3 P_1 = \phi_3 P_0$ (4.4.36)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.4.37)

Put the values of P_1 and P_2 by solving Eqs. (4.4.34)- (4.4.36) in Eq. (4.4.37)

$P_0 (1 + \phi_3 / \tau_3 + \phi_4 \phi_3 / \tau_4 \tau_3) = 1$ (4.4.38)

The availability of the subsystem S2 is given by Eq. (4.4.38)

$R_{S2\,(t)} = e^{-0.076t}$ (4.4.39)

Reliability Eq. for the subsystem S2 is given by Eq. (4.4.39)

$M_{S2}(t) = 1 - e^{-7.5415t}$ (4.4.40)

The maintainability Eq. for the subsystem S2 is given by Eq. (4.4.40)

The other parameters for the subsystem S2 are computed as:

$D_{min.\,(S2)} = 0.9927$

MTBF= 13.1579 hr.

MTTR= 0.1326 hr. and

d= 99.2244

RAMD indices for subsystem S3

This subsystem S3 consists of two units D3 and D4 connected in series. Failure of unit D3 or D4 causes complete failure of the system. The differential equations associated with Fig. 4.15(c) are:

$P'_o(t) = - (\phi_5 + \phi_6) P_o(t) + \tau_5 P_1(t) + \tau_6 P_2(t)$ (4.4.41)

$P'_1(t) = - \tau_5 P_1(t) + \phi_5 P_0(t)$ (4.4.42)

$P'_2(t) = - \tau_6 P_2(t) + \phi_6 P_0(t)$ (4.4.43)

Under steady state conditions, the Eqs. (4.4.41)- (4.4.43) get reduced as:

$(\phi_5 + \phi_6) P_o = \tau_5 P_1 + \tau_6 P_2$ (4.4.44)

$\tau_5 P_1 = \phi_5 P_0$ (4.4.45)

$\tau_6 P_2 = \phi_6 P_0$ (4.4.46)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.4.47)

Putting the values of P_1 and P_2 from Eqs. (4.4.45) and (4.4.46) in Eq. (4.4.47)

$P_0 (1 + \phi_5 / \tau_5 + \phi_6 / \tau_6) = 1$ (4.4.48)

The availability of the subsystem S3 is given by Eq. (4.4.48)

$R_{S3\ (t)} = e^{-0.0333t}$ (4.4.49)

The reliability Eq. for the subsystem S3 is given by Eq. (4.4.49)

$M_{S3}\ (t) = 1 - e^{-0.3826t}$ (4.4.50)

The maintainability Eq. for the subsystem S3 is given by Eq. (4.4.50)

The other parameters for the subsystem S3 are computed as:

$D_{min.(S3)} = 0.9396$

MTBF= 30.03 hr.

MTTR= 2.6133 hr. and

d= 11.4914.

RAMD indices for subsystem S4

This subsystem has single unit D5 (Evaporator) only and failure of this unit causes complete failure of the system. The differential equations associated with Fig. 4.15(d) are:

$P'_o(t) = -\phi_7 P_o(t) + \tau_7 P_1(t)$ (4.4.51)

$P'_1(t) = -\tau_7 P_1(t) + \phi_7 P_0(t)$ (4.4.52)

Under steady state conditions, the Eqs. (4.4.51) and (4.4.52) get reduced as:

$\phi_7 P_o = \tau_7 P_1$ (4.4.53)

$\tau_7 P_1 = \phi_7 P_0$ (4.4.54)

Now, using the normalizing conditions

$P_0 + P_1 = 1$ (4.4.55)

The Eqs. (4.4.53) and (4.4.54) are solved to get the values of P_0 i.e.

$P_0 (1 + \phi_7 / \tau_7] = 1$ (4.4.56)

The availability for the subsystem S4 is given by Eq. (4.4.56)

$R_{S4\ (t)} = e^{-0.046t}$ (4.4.57)

The reliability Eq. for the subsystem S4 is given by Eq. (4.4.57)

$M_{S4}\ (t) = 1 - e^{-0.18t}$ (4.4.58)

The maintainability Eq. for the subsystem S4 is given by Eq. (4.4.58)

The other parameters for the subsystem S3 are computed as:

$D_{min.(S4)} = 0.8169$

MTBF= 21.7391hr.

MTTR= 5.5556 hr. and

d =3.9130.

System Reliability

The overall system reliability of Refrigeration system, $R_{sys}(t)$

$R_{sys}(t) = R_{S1}(t) \times R_{S2}(t) \times R_{S3}(t) \times R_{S4}(t)$

$R_{sys}(t) = e^{-0.132t} \times e^{-0.076t} \times e^{-0.0333t} \times e^{-0.046t} = e^{-0.2873t}$

$R_{sys}(t) = e^{-0.2873t}$

System Availability

The overall system availability of the Refrigeration system (A_{sys}) is computed as:

$A_{sys} = A_{S1} \times A_{S2} \times A_{S3} \times A_{S4}$

$A_{sys} = 0.9640 \times 0.9900 \times 0.9199 \times 0.7965 = 0.6993$

System Maintainability

The overall system maintainability of the Refrigeration system, $M_{sys}(t)$ is computed as:

$M_{sys}(t) = M_{S1}(t) \times M_{S2}(t) \times M_{S3}(t) \times M_{S4}(t)$

$M_{sys}(t) = 1-e^{-0.1165t}$

System Dependability

The overall system dependability of the Refrigeration system, $D_{min.(sys)}$ is computed as:

$D_{min.(sys)} = D_{min.(s1)} \times D_{min.(s2)} \times D_{min.(s3)} \times D_{min.(s4)}$

$D_{sys} = 0.9736 \times 0.9927 \times 0.9396 \times 0.8169 = 0.7419$

Table 4.4 Failure and repair rates of the subsystems of the Refrigeration system

Subsystem	Failure Rate (ϕ)	Repair Rate (τ)
S1	Compressor (ϕ_1)=0.066/hr.	Compressor (τ_1)=0.31/hr.
S3	Ammonia storage (ϕ_5)=0.0063/hr. Expansion valve (ϕ_6)=0.027/hr.	Ammonia storage (τ_5)=0.26/hr. Expansion valve (τ_6)=0.43/hr.
S2	Condenser (ϕ_3)=0.038/hr.	Condenser (τ_3)=0.36/hr.
S4	Evaporator (ϕ_7)=0.046/hr.	Evaporator (τ_7)=0.18/hr.

4.4.3 Performance modeling for the fuzzy-reliability analysis of the Refrigeration system

$$P'_1(t) = -X_1P_1(t) + \tau_5 P_5(t) + \tau_6 P_6(t) + \tau_7 P_7(t) + \tau_1 P_2(t) + \tau_3 P_3(t) \tag{4.4.59}$$

$$P'_2(t) = -X_2P_2(t) + \tau_1 P_8(t) + \tau_5 P_9(t) + \tau_6 P_{10}(t) + \tau_7 P_{11}(t) + \tau_3 P_4(t) + \phi_1 c P_1(t) \tag{4.4.60}$$

$$P'_3(t) = -X_3P_3(t) + \tau_3 P_{12}(t) + \tau_5P_{13}(t) + \tau_6P_{14}(t) + \tau_7P_{15}(t) + \tau_1P_4(t) + \phi_3c\, P_1(t) \qquad (4.4.61)$$

$$P'_4(t) = -X_4P_4(t) + \tau_1P_{16}(t) + \tau_3P_{17}(t) + \tau_5P_{18}(t) + \tau_6P_{19}(t) + \tau_7P_{20}(t) + \phi_3c\, P_2(t) + \phi_1cP_3(t) \qquad (4.4.62)$$

where

$X_1 = \phi_5(1-c)+\phi_6(1-c)+\phi_7(1-c)+\phi_1c+\phi_3c$, $X_2 = \phi_1(1-c)+\phi_5(1-c)+\phi_6(1-c)+\phi_7(1-c)+\tau_1+\phi_3c$,

$X_3=\phi_3(1-c)+\phi_5(1-c)+\phi_6(1-c)+\phi_7(1-c)+\tau_3+\phi_1c$,

$X_4=\phi_1(1-c)+\phi_3(1-c)+\phi_5(1-c)+\tau_3+\tau_1+\phi_6(1-c)+\phi_7(1-c)$

$P'_i(t) + \tau_jP_i(t) = \phi_j(1-c)\,P_1(t)$ (4.4.63) , where i= 5, 6, 7 and j=5, 6, 7

$P'_i(t) + \tau_jP_i(t) = \phi_j(1-c)\,P_2(t)$ (4.4.64), where i= 8, 9, 10, 11 and j=1, 5, 6, 7

$P'_i(t) + \tau_jP_i(t) = \phi_j(1-c)\,P_3(t)$ (4.4.65), where i= 12, 13, 14, 15 and j=3, 5, 6, 7

$P'_i(t) + \tau_jP_i(t) = \phi_j(1-c)\,P_4(t)$ (4.4.66), where i= 16, 17, 18, 19, 20 and j=1, 3, 5, 6, 7

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j = 1 \\ 0, \text{if } j \neq 1 \end{cases} \qquad (4.4.67)$$

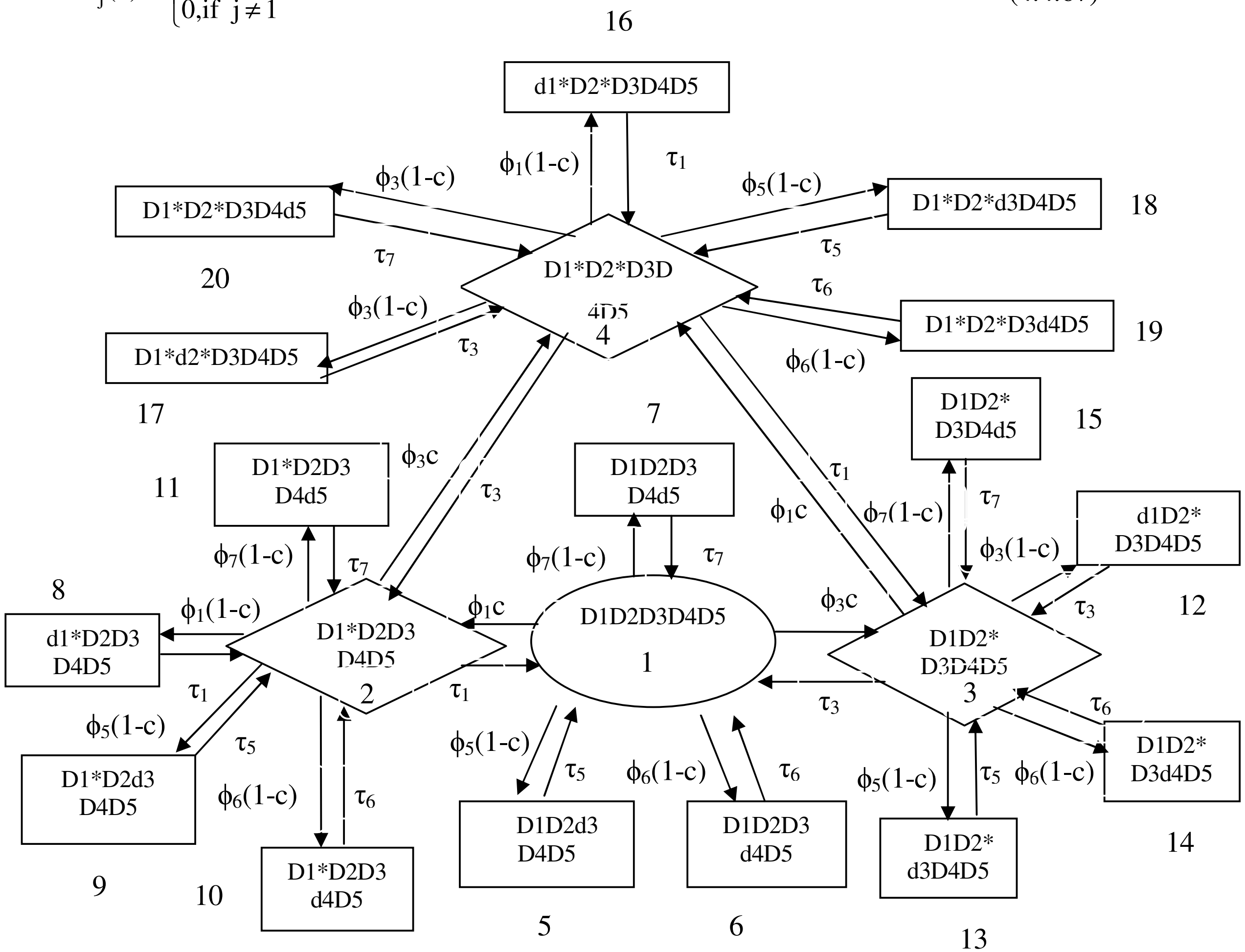


Fig. 4.16 State transition diagram of the Refrigeration system with imperfect fault coverage

The system of differential equations (4.4.59)- (4.4.66) with initial conditions given by Eq. (4.4.67) were solved with Runge-Kutta fourth order method. The numerical computations were carried out by taking that;

(i)The failure and repair rates of compressor (ϕ_1, τ_1) and its standby unit (ϕ_2, τ_2) are same.

(ii)The failure and repair rates of condenser (ϕ_3, τ_3) and its standby unit (ϕ_4, τ_4) are same.

The fuzzy-reliability of the Refrigeration system was computed for one year (i.e. time, *t*=30-360 days) for different choices of failure rates of the subsystems. The fuzzy reliability of the Refrigeration system, $R_{F3}(t)$ is composed of fuzzy-reliability of the system working with full capacity and its standby states i.e.

$$R_{F3}(t) = R_1(t) + \frac{1}{2}R_2(t) + \frac{1}{2}R_3(t) + \frac{1}{4}R_4(t) \qquad (4.4.68)$$

The fuzzy-reliability of the Refrigeration system is computed by the Eq. (4.4.68)

4.5 PERFORMANCE MODELING FOR THE FEEDING SYSTEM OF THE SUGAR PLANT

Performance modeling for the Feeding system is carried out by deriving mathematical equations for the development of the decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

4.5.1 Performance modeling for Decision Support Systems (DSS) of the Feeding system

State 1: The system is working with full capacity (with no standby)

State 2: The system is working with standby unit of Cutting system (E1*)

State 3: The system is working with standby unit of Bagasse carrying system (E3*)

State 4: The system is working with standby unit of Heat generating system (E4*)

State 5: The system is working with standby units of Cutting system (E1*) and Bagasse carrying system (E3*)

State 6: The system is working with standby units of Cutting system (E1*) and Heat generating system (E4*)

State 7: The system is working with standby units of Bagasse carrying system (E3*) and Heat generating system (E4*)

State 8: The system is working with standby units of Cutting system (A_1), Bagasse carrying system (E3*) and Heat generating system (E4*)

State 9 to 28: Failed states of the system due to complete failure of its subsystems i.e. E1, E2, E3 and E4

The transition diagram (Fig. 4.17) depicts a simulation model showing all the possible states of the Skim milk powder production system.

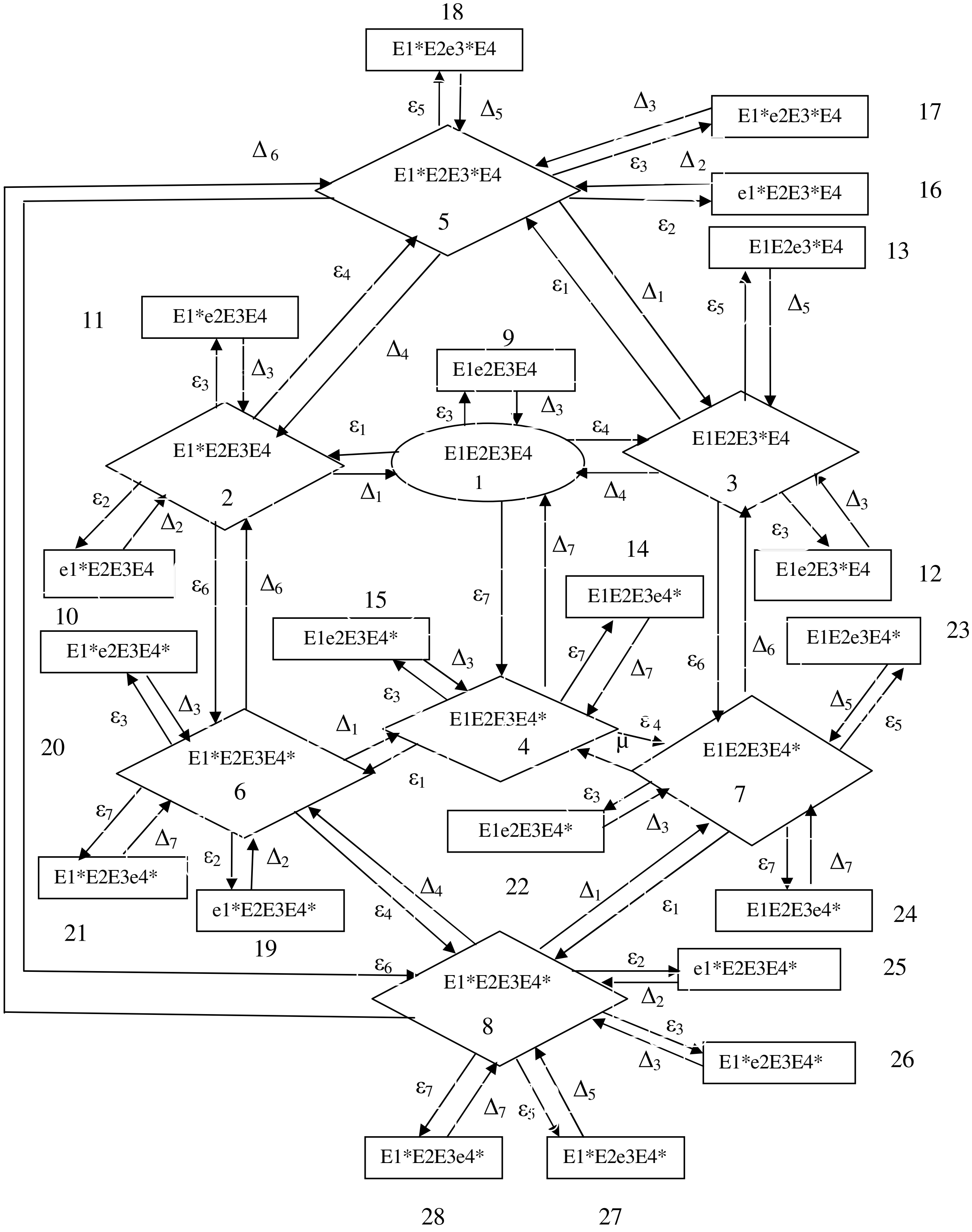


Fig. 4.17 State transition diagram of the Feeding system

E1, E2, E3 and E4: Indicates full working states of the subsystems

E1*, E3* and E4* : Indicates that the subsystems E1, E3 and E4 are working under cold standby states.

e1, e2, e3 and e4 : Indicates the failed states of the subsystems E1, E2, E3 and E4 resp.

ε_i= 1,2,3…..7 : The constant failures rate of the subsystems E1, E1*, E2, E3, E3*, E4 and E4* resp.

Δ_i=1, 2,3…..7 : The constant repair rate of the subsystems E1, E1*, E2, E3, E3*, E4 and E4* resp.

P_1, P_2, P_3, P_4, P_5, P_6, P_7 and P_8: Availability of the system under states 1, 2, 3, 4, 5, 6, 7 and 8 resp.

P_j (t), j=1, 2, 3… 28: The probability that the system is in jth state at time. *t*

The Mathematical equations (4.5.1)-(4.5.28) based on Markov-birth death process are developed for each state one by one out of 28 states of transition diagram (Fig. 4.17)

$P'_1(t)=- X_1P_1(t) + \Delta_1P_2(t) + \Delta_4P_3(t) + \Delta_7P_4(t) + \Delta_3P_9(t)$ (4.5.1)

$P'_2(t) = - X_2P_2(t) + \varepsilon_1P_1(t) + \Delta_4P_5(t) + \Delta_7P_6(t) + \Delta_2P_{10}(t) + \Delta_3P_{11}(t)$ (4.5.2)

$P'_3(t) = - X_3P_3(t) + \varepsilon_4P_1(t) + \Delta_6P_7(t) + \Delta_3P_{12}(t) + \Delta_5P_{13}(t)$ (4.5.3)

$P'_4(t) = - X_4P_4(t) + \varepsilon_7P_1(t) + \Delta_1P_6(t) + \Delta_4P_7(t) + \Delta_7P_{14}(t) +\Delta_3P_{15}(t)$ (4.5.4)

$P'_5(t) = - X_5P_5(t) + \varepsilon_4P_2(t) + \varepsilon_1P_3(t) + \Delta_2P_{16}(t) + \Delta_3P_{17}(t) + \Delta_5P_{18}(t)$ (4.5.5)

$P'_6(t) = - X_6P_6(t) + \varepsilon_6P_2(t) + \varepsilon_1P_4(t) + \Delta_4P_8(t) + \Delta_2P_{19}(t) +\Delta_3P_{20}(t) +\Delta_7P_{21}(t)$ (4.5.6)

$P'_7(t) = - X_7P_7(t) + \varepsilon_6P_3(t) + \varepsilon_4P_4(t) + \Delta_1P_8(t) + \Delta_3P_{22}(t) + \Delta_5P_{23}(t) + \Delta_7P_{24}(t)$ (4.5.7)

$P'_8(t) = - X_8P_8(t) + \varepsilon_6P_5(t) + \varepsilon_4P_6(t) + \varepsilon_1P_7(t) + \Delta_2P_{25}(t) + \Delta_3P_{26}(t) +\Delta_5P_{27}(t)$
$+\Delta_7 P_{28}(t)$ (4.5.8)

where

$X_1= (\varepsilon_1+\varepsilon_4+\varepsilon_7+\varepsilon_3)$, $X_2= (\Delta_1+\varepsilon_4+\varepsilon_7 +\varepsilon_2+\varepsilon_3)$, $X_3= (\Delta_4+\varepsilon_6+\varepsilon_3+\varepsilon_5)$, $X_4= (\Delta_7+\varepsilon_1+\varepsilon_4+ \varepsilon_7 +\varepsilon_3)$

$X_5= (\Delta_4+ \Delta_1+\varepsilon_2+\varepsilon_3+ \varepsilon_5)$, $X_6= (\Delta_6+\Delta_1+\varepsilon_4+ \varepsilon_2+\varepsilon_3+\varepsilon_7)$, $X_7= (\Delta_6+ \Delta_4+\varepsilon_1+\varepsilon_3+\varepsilon_5+\varepsilon_7)$,

$X_8= (\Delta_1 +\Delta_6+\Delta_4+\varepsilon_2+ \varepsilon_3+\varepsilon_5+\varepsilon_7)$

$P'_9 (t) + \Delta_3P_9 (t) = \varepsilon_3P_1 (t)$ (4.5.9)

$P'_i (t) + \Delta_jP_i (t) = \varepsilon_jP_2 (t)$ (4.5.10), where *i*=10, 11 and *j*=2, 3

$P'_i (t) + \Delta_jP_i (t) = \varepsilon_jP_3 (t)$ (4.5.11), where *i*=12, 13 and *j*=3,5

$P'_i (t) + \Delta_jP_i (t) = \varepsilon_jP_4 (t)$ (4.5.12), where *i*=14, 15 and *j*=7, 3

$P'_i (t) + \Delta_jP_i (t) = \varepsilon_jP_5 (t)$ (4.5.13), where *i*=16, 17, 18 and *j*=2, 3, 5

$P'_i (t) + \Delta_jP_i (t) = \varepsilon_jP_6 (t)$ (4.5.14), where *i*=19, 20, 21 and *j*=2, 3, 7

$P'_{22} (t) + \Delta_3P_{22} (t) = \varepsilon_3P_7 (t)$ (4.5.15), where *i*=22, 23, 24 and *j*= 3, 5, 7

$P'_{25} (t) + \Delta_2P_{25} (t) = \varepsilon_2P_8 (t)$ (4.5.16), where *i*=25, 26, 27, 28 and *j*= 2, 3, 5, 7

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j = 1 \\ 0, \text{if } j \neq 1 \end{cases} \qquad (4.5.17)$$

The system of differential equations (4.5.1) - (4.5.28) with initial conditions given by Eq. (4.5.17) was solved by Runge-Kutta fourth order method. The numerical computations were out by taking that

(i) The failure and repair rates of Cutting system (ε_1, Δ_1) and its standby unit (ε_2, Δ_2) are same.

(ii) The failure and repair rates of Bagasse carrying system (ε_4, Δ_4) and its standby unit (ε_5, Δ_5) are same.

(iii) The failure and repair rates of Heat generating system (ε_6, Δ_6) and its standby unit (ε_7, Δ_7) are same.

The numerical computations were carried out for one year (i.e. time, *t*=30-360 days) for different choices of failure and repair rates of the subsystems. The data regarding failure and repair rates of all the subsystems were taken from the plant personnel. The reliability of the system, $R_5(t)$ is composed of the sum of the reliability of the system working with full capacity and its standby states i.e.

$$R_5(t) = R_1(t) + R_2(t) + R_3(t) + R_4(t) + R_5(t) + R_6(t) + R_7(t) + R_8(t) \qquad (4.5.18)$$

The reliability of the Feeding system is computed by the equation (4.5.18)

The management is interested to get the steady state availability of the system. The steady state probabilities of the system are obtained by imposing the following restrictions; d/dt→0, as t→∞. The equations (4.5.1) - (4.5.16) get reduced to the following system of Eqs.

$$X_1P_1=\Delta_1P_2+\Delta_4P_3+\Delta_7P_4+\Delta_3P_9 \qquad (4.5.19)$$

$$X_2P_2 = \varepsilon_1P_1 + \Delta_4P_5 + \Delta_7P_6 + \Delta_2P_{10} + \Delta_3P_{11} \qquad (4.5.20)$$

$$X_3P_3 = \varepsilon_4P_1 + \Delta_6P_7 + \Delta_3P_{12} + \Delta_5P_{13} \qquad (4.5.21)$$

$$X_4P_4 = \varepsilon_7P_1+\Delta_1P_6+\Delta_4P_7+\Delta_7P_{14}+\Delta_3P_{15} \qquad (4.5.22)$$

$$X_5P_5 = \varepsilon_4P_2+\varepsilon_1P_3+\Delta_2P_{16}+\Delta_3P_{17}+\Delta_5P_{18} \qquad (4.5.23)$$

$$X_6P_6 = \varepsilon_6P_2 + \varepsilon_1P_4 + \Delta_4P_8 + \Delta_2P_{19} + \Delta_3P_{20} + \Delta_7P_{21} \qquad (4.5.24)$$

$$X_7P_7 = \varepsilon_6P_3 + \varepsilon_4P_4 + \Delta_1P_8 + \Delta_3P_{22} + \Delta_5P_{23} + \Delta_7P_{24} \qquad (4.5.25)$$

$$X_8P_8 = \varepsilon_6P_5 + \varepsilon_4P_6 + \varepsilon_1P_7 + \Delta_2P_{25} + \Delta_3P_{26} + \Delta_5P_{27} + \Delta_7P_{28} \qquad (4.5.26)$$

$$\Delta_3P_9 = \varepsilon_3P_1 \qquad (4.5.27)$$

$\Delta_j P_i = \varepsilon_j P_2$ (4.5.28), where i=10, 11 and *j*= 2, 3

$\Delta_j P_i = \varepsilon_j P_3$ (4.5.29), where i=12, 13 and *j*= 3, 5

$\Delta_j P_i = \varepsilon_j P_4$ (4.5.30), where i=14, 15 and j= 7, 3

$\Delta_j P_i = \varepsilon_j P_5$ (4.5.31), where i=16, 17, 18 and j=2, 3, 5

$\Delta_j P_i = \varepsilon_j P_6$ (4.5.32), where i=19, 20, 21 and j=2, 3, 7

$\Delta_j P_i = \varepsilon_j P_7$ (4.5.33), where i=22, 23, 24 and j=3, 5, 7

$\Delta_j P_i = \varepsilon_j P_8$ (4.5.34), where i=25, 26, 27, 28 and j=2, 3, 5, 7

The values of P_2, P_3, P_4, P_5, P_6, P_7 and P_8 in terms of P_1 are obtained by solving the Eqs. (4.5.28)- (4.5.34) by recursive method

$$\begin{aligned}P_2/P_1={}&-(K5\varepsilon_4^2\Delta_4^2-K5\varepsilon_1^2\Delta_1^2-K1\varepsilon_1^2\Delta_1^2+K5\varepsilon_6^2\Delta_6^2+K1K3K4K5K7+K1K3K5\varepsilon_1\Delta_1+\\&K1K4K6\varepsilon_1\Delta_1+K3K5K6\varepsilon_1\Delta-K1K3K5\varepsilon_4\Delta_4+K3K5K7\varepsilon_1\Delta_1+K4K5K6\varepsilon_1\Delta_1-\\&K1K4K5\varepsilon_6\Delta_6-K4K5K7\varepsilon_4\Delta_4-K3K5K7\varepsilon_6\Delta_6+K1\varepsilon_1\varepsilon_4\Delta_1\Delta_4+K6\varepsilon_1\varepsilon_4\Delta_1\Delta_4\\&+K7\varepsilon_1\varepsilon_4\Delta_1\Delta_4-K6\varepsilon_1\varepsilon_6\Delta_1\Delta_6-2K5\varepsilon_4\varepsilon_6\Delta_4\Delta_6)/(\varepsilon_1^2\Delta_1^3+\varepsilon_4^2\Delta_1\Delta_4^2+K2K5\varepsilon_1\Delta_1^2-\\&K3K5\varepsilon_1\Delta_1^2-K4K6\varepsilon_1\Delta_1^2-2\varepsilon_1\varepsilon_4\Delta_1^2\Delta_4-\varepsilon_1\varepsilon_6\Delta_1^2\Delta_6-K2K5\varepsilon_4\Delta_1\Delta_4+K3K5\varepsilon_4\Delta_1\Delta_4\\&+K3K6\varepsilon_4\Delta_1\Delta_4+K3K7\varepsilon_4\Delta_1\Delta_4+K4K6\varepsilon_4\Delta_1\Delta_4+K2K5\varepsilon_6\Delta_1\Delta_6+K3K5\varepsilon_6\Delta_1\Delta_6\\&+2K4K5\varepsilon_6\Delta_1\Delta_6-\varepsilon_4\varepsilon_6\Delta_1\Delta_4\Delta_6-K2K3K5K6\Delta_1-K2K3K5K7\Delta_1-K2K4K5K6\Delta_1-\\&K3K4K5K7\Delta_1)\end{aligned} \qquad (4.5.35)$$

$$\begin{aligned}P_3/P_1 ={}& (K1\varepsilon_4^2\Delta_4^2-K5\varepsilon_1^2\Delta_1^2+K5\varepsilon_4^2\Delta_4^2 +K6\beta_4^2\Delta_4^2+K7\beta_4^2\Delta_4^2-K5\beta_6^2\Delta_6^2-K1K2K4K5K6+\\&K1K2K5\beta_1\Delta_1-K1K2K5\beta_4\Delta_4+K4K5K6\beta_1\Delta_1+K1K4K6\beta_4\Delta_4-K2K5K6\beta_4\Delta_4\\&+K1K4K5\beta_6\Delta_6-K2K5K7\beta_4\Delta_4-K4K5K7\beta_4\Delta_4+K2K5K6\beta_6\Delta_6-K1\beta_1\beta_4\Delta_1\Delta_4\\&+2K5\beta_1\beta_6\Delta_1\Delta_6-K6\beta_4\beta_6\Delta_4\Delta_6)/(\beta_4^2\Delta_4^3+\beta_1^2\Delta_1^2\Delta_4-K2K5\beta_4\Delta_4^2+K3K5\beta_4\Delta_4^2\\&+K3K6\beta_4\Delta_4^2+K3K7\beta_4\Delta_4^2+K4K6\beta_4\Delta_4^2-2\beta_1\beta_4\Delta_1\Delta_4^2-\beta_4\beta_6\Delta_4^2\Delta_6+K2K5\beta_1\Delta_1\Delta_4-\\&K3K5\beta_1\Delta_1\Delta_4-K4K6\beta_1\Delta_1\Delta_4+K2K5\beta_6\Delta_4\Delta_6+K3K5\beta_6\Delta_4\Delta_6+2K4K5\beta_6\Delta_4\Delta_6-\\&\beta_1\beta_6\Delta_1\Delta_4\Delta_6-K2K3K5K6\Delta_4-K2K3K5K7\Delta_4 -K4K5K6\Delta_4K3K4K5K7\Delta_4)\end{aligned} \qquad (4.5.36)$$

$$\begin{aligned}P_4/P_1={}&(2K5\beta_6^2\Delta_6^2 -K7\beta_4^2\Delta_4^2 -K6\beta_4^2\Delta_4^2 -K1K2K3K5K6-K1K2K3K5K7 +K3K5K6\varepsilon_1\Delta_1+\\&K3K5K7\varepsilon_1\Delta_1+K1K3K6\varepsilon_4\Delta_4+K1K3K7\varepsilon_4\Delta_4+K1K2K5\varepsilon_6\Delta_6+K1K3K5\varepsilon_6\Delta_6\\&+K2K5K6\varepsilon_4\Delta_4+K2K5K7\varepsilon_4\Delta_4-K2K5K6\varepsilon_6\Delta_6-K3K5K7\varepsilon_6\Delta_6-K1\varepsilon_1\varepsilon_6\Delta_1\Delta_6\\&+K6\varepsilon_1\varepsilon_4\Delta_1\Delta_4+K7\varepsilon_1\varepsilon_4\Delta_1\Delta_4-2K5\varepsilon_1\varepsilon_6\Delta_1\Delta_6-K6\varepsilon_1\varepsilon_6\Delta_1\Delta_6-K1\varepsilon_4\varepsilon_6\Delta_4\Delta_6-2K5\varepsilon_4\varepsilon_6\Delta_4\Delta_6+\\&K6\varepsilon_4\varepsilon_6\Delta_4\Delta_6)/ (\varepsilon_1^2\Delta_1^2\Delta_6+\varepsilon_4^2\Delta_4^2\Delta_6+ K2K5\varepsilon_6\Delta_6^2 +K3K5\varepsilon_6\Delta_6^2+ 2K4K5\varepsilon_6\Delta_6^2-\\&\varepsilon_1\varepsilon_6\Delta_1\Delta_6^2-\varepsilon_4\varepsilon_6\Delta_4\Delta_6^2 +K2K5\varepsilon_1\Delta_1\Delta_6 -K3K5\varepsilon_1\Delta_1\Delta_6 -K4K6\varepsilon_1\Delta_1\Delta_6 -K2K5\varepsilon_4\Delta_4\Delta_6 +\\&K3K5\varepsilon_4\Delta_4\Delta_6+K3K6\varepsilon_4\Delta_4\Delta_6+K3K7\varepsilon_4\Delta_4\Delta_6+K4K6\varepsilon_4\Delta_4\Delta_6-2\varepsilon_1\varepsilon_4\Delta_1\Delta_4\Delta_6-\\&K2K3K5K6\Delta_6-K2K3K5K7\Delta_6-K2K4K5K6\Delta_6+ -K3K4K5K7\Delta_6)\end{aligned} \qquad (4.5.37)$$

$$P_5/P_1 = -(\varepsilon_1^3\Delta_1^3+\varepsilon_4^3\Delta_4^3-\varepsilon_1\varepsilon_4^2\Delta_1\Delta_4^2-\varepsilon_1^2\varepsilon_4\Delta_1^2\Delta_4+\varepsilon_1\varepsilon_6^2\Delta_1\Delta_6^2-2\varepsilon_1^2\varepsilon_6\Delta_1^2\Delta_6+\varepsilon_4\varepsilon_6^2\Delta_4\Delta_6^2-2\varepsilon_4^2\varepsilon_6\Delta_4^2\Delta_6-K1K2\varepsilon_1^2\Delta_1^2-K1K3\varepsilon_4^2\Delta_4^2-K4K6\varepsilon_1^2\Delta_1^2-K4K7\varepsilon_4^2\Delta_4^2+K1K2K4K6\varepsilon_1\Delta_1+K1K3K4K7\varepsilon_4\Delta_4+K1K2\varepsilon_1\varepsilon_4\Delta_1\Delta_4+K1K3\varepsilon_1\varepsilon_4\Delta_1\Delta_4+K2K6\varepsilon_1\varepsilon_4\Delta_1\Delta^4-K1K4\varepsilon_1\varepsilon_6\Delta_1\Delta_6+K2K7\varepsilon_1\varepsilon_4\Delta_1\Delta_4+K3K6\varepsilon_1\varepsilon_4\Delta_1\Delta_4+K3K7\varepsilon_1\varepsilon_4\Delta_1\Delta_4+K4K6\varepsilon_1\varepsilon_4\Delta_1\Delta_4+K4K7\varepsilon_1\varepsilon_4\Delta_1\Delta_4-K2K6\varepsilon_1\varepsilon_6\Delta_1\Delta_6-K1K4\varepsilon_4\varepsilon_6\Delta_4\Delta_6-K3K7\varepsilon_4\varepsilon_6\Delta_4\Delta_6)/(\beta_1^2\Delta_1^3\Delta_4+\beta_4^2\Delta_1\Delta_4^3-2\beta_1\beta_4\Delta_1^2\Delta_4^2+K2K5\beta_1\Delta_1^2\Delta_4-K3K5\beta_1\Delta_1^2\Delta_4-K2K5\beta_4\Delta_1\Delta_4^2-K4K6\beta_1\Delta_1^2\Delta_4+K3K5\beta_4\Delta_1\Delta_4^2+K3K6\beta_4\Delta_1\Delta_4^2+K3K7\beta_4\Delta_1\Delta_4^2+K4K6\beta_4\Delta_1\Delta_4^2-\beta_1\beta_6\Delta_1^2\Delta_4\Delta_6-\beta_4\beta_6\Delta_1\Delta_4^2\Delta_6-K2K3K5K6\Delta_1\Delta_4-K2K3K5K7\Delta_1\Delta_4-K2K4K5K6\Delta_1\Delta_{4+}-K3K4K5K7\Delta_1\Delta_4+K2K5\beta_6\Delta_1\Delta_4\Delta_6+K3K5\beta_6\Delta_1\Delta_4\Delta_6+2K4K5\beta_6\Delta_1\Delta_4\Delta_6) \tag{4.5.38}$$

$$P_6/P_1 =(\beta_4^3\Delta_4^3-2\beta_1\beta_4^2\Delta_1\Delta_4^2+\beta_1^2\beta_4\Delta_1^2\Delta_4+\beta_1\beta_6^2\Delta_1\Delta_6^2-\beta_1^2\beta_6\Delta_1^2\Delta_6+\beta_4\beta_6^2\Delta_4\Delta_6^2-2\beta_4^2\beta_6\Delta_4^2\Delta_6+K3K5\beta_1^2\Delta_1^2-K1K3\beta_4^2\Delta_4^2-K2K5\beta_4^2\Delta_4^2-K2K5\beta_6^2\Delta_6^2-K4K7\beta_4^2\Delta_4^2+\beta_1\beta_4\beta_6\Delta_1\Delta_4\Delta_6-K1K2K3K4K5K7-K1K2K3K5\beta_1\Delta_1+K1K2K3K5\beta_4\Delta_4+K3K4K5K7\beta_1\Delta_1+K1K3K4K7\beta_4\Delta_4+K1K2K4K5\beta_6\Delta_6+K2K4K5K7\beta_4\Delta_4+K2K3K5K7\beta_6\Delta_6+K1K3\beta_1\beta_4\Delta_1\Delta_4+K2K5\beta_1\beta_4\Delta_1\Delta_4-K3K5\beta_1\beta_4\Delta_1\Delta_4-K1K4\beta_1\beta_6\Delta_1\Delta_6-K2K5\varepsilon_1\varepsilon_6\Delta_1\Delta_6+K4K7\varepsilon_1\varepsilon_4\Delta_1\Delta_4-K3K5\varepsilon_1\varepsilon_6\Delta_1\Delta_6-2K4K5\varepsilon_1\varepsilon_6\Delta_1\Delta_6-K1K4\varepsilon_4\varepsilon_6\Delta_4\Delta_6+2K2K5\varepsilon_4\varepsilon_6\Delta_4\Delta_6-K3K7\varepsilon_4\varepsilon_6\Delta_4\Delta_6)/(\varepsilon_1^2\Delta_1^3\Delta_6-\varepsilon_1\varepsilon_6\Delta_1^2\Delta_6^2+\varepsilon_4^2\Delta_1\Delta_4^2\Delta_6+K2K5\varepsilon_1\Delta_1^2\Delta_6-K3K5\varepsilon_1\Delta_1^2\Delta_6-K4K6\varepsilon_1\Delta_1^2\Delta_6+K2K5\varepsilon_6\Delta_1\Delta_6^2+K3K5\varepsilon_6\Delta_1\Delta_6^2+2K4K5\varepsilon_6\Delta_1\Delta_6^2-2\varepsilon_1\varepsilon_4\Delta_1^2\Delta_4\Delta_6-\varepsilon_4\varepsilon_6\Delta_1\Delta_4\Delta_6^2-K2K3K5K6\Delta_1\Delta_6-K2K3K5K7\Delta_1\Delta_6-K2K4K5K6\Delta_1\Delta_6-K3K4K5K7\Delta_1\Delta_6-K2K5\varepsilon_4\Delta_1\Delta_4\Delta_6+K3K5\varepsilon_4\Delta_1\Delta_4\Delta_6+K3K6\varepsilon_4\Delta_1\Delta_4\Delta_6+K3K7\varepsilon_4\Delta_1\Delta_4\Delta_6+K4K6\varepsilon_4\Delta_1\Delta_4\Delta_6) \tag{4.5.39}$$

$$P_7/P_1 =(2\varepsilon_1\varepsilon_4^2\Delta_1\Delta_4^2-\varepsilon_4^3\Delta_4^3-\varepsilon_1^2\varepsilon_4\Delta_1^2\Delta_4+\varepsilon_4^2\varepsilon_6\Delta_4^2\Delta_6-K3K5\varepsilon_1^2\Delta_1^2+K1K3\varepsilon_4^2\Delta_4^2+K2K5\varepsilon_4^2\Delta_4^2-K4K6\varepsilon_4^2\Delta_4^2-K3K5\varepsilon_6^2\Delta_6^2+\varepsilon_1\varepsilon_4\varepsilon_6\Delta_1\Delta_4\Delta_6-K1K2K3K4K5K6+K1K2K3K5\varepsilon_1\Delta_1-K1K2K3K5\varepsilon_4\Delta_4+K3K4K5K6\varepsilon_1\Delta_1+K1K3K4K6\varepsilon_4\Delta_4+K1K3K4K5\varepsilon_6\Delta_6+K2K4K5K6\varepsilon_4\Delta_4+K2K3K5K6\varepsilon_6\Delta_6-K1K3\varepsilon_1\varepsilon_4\Delta_1\Delta_4-K2K5\varepsilon_1\varepsilon_4\Delta_1\Delta_4+K3K5\varepsilon_1\varepsilon_4\Delta_1\Delta_4+K4K6\varepsilon_1\varepsilon_4\Delta_1\Delta_4+2K3K5\varepsilon_1\varepsilon_6\Delta_1\Delta_6-K2K5\varepsilon_4\varepsilon_6\Delta_4\Delta_6-K3K5\varepsilon_4\varepsilon_6\Delta_4\Delta_6-K3K6\varepsilon_4\varepsilon_6\Delta_4\Delta_6-2K4K5\varepsilon_4\varepsilon_6\Delta_4\Delta_6)/(\varepsilon_4^2\Delta_4^3\Delta_6-\varepsilon_4\varepsilon_6\Delta_4^2\Delta_6^2+\varepsilon_1^2\Delta_1^2\Delta_4\Delta_6-K2K5\varepsilon_4\Delta_4^2\Delta_6+K3K5\varepsilon_4\Delta_4^2\Delta_6+K2K5\varepsilon_6\Delta_4\Delta_6^2+K3K6\varepsilon_4\Delta_4^2\Delta_6+K3K5\varepsilon_6\Delta_4\Delta_6^2+K3K7\varepsilon_4\Delta_4^2\Delta_6+K4K6\varepsilon_4\Delta_4^2\Delta_6+2K4K5\varepsilon_6\Delta_4\Delta_6^2-2\varepsilon_1\varepsilon_4\Delta_1\Delta_4^2\Delta_6-\varepsilon_1\varepsilon_6\Delta_1\Delta_4\Delta_6^2-K2K3K5K6\Delta_4\Delta_6-K2K3K5K7\Delta_4\Delta_6-$$

$$\begin{aligned}&K2K4K5K6\Delta_4\Delta_6 - K3K4K5K7\Delta_4\Delta_6 + K2K5\varepsilon_1\Delta_1\Delta_4\Delta_6 - K3K5\varepsilon_1\Delta_1\Delta_4\Delta_6 - \\ &K4K6\varepsilon_1\Delta_1\Delta_4\Delta_6) \qquad (4.5.40)\end{aligned}$$

$$\begin{aligned}P_8/P_1 =& -(K3K5K7\varepsilon_1^2\Delta_1^2 - K5\varepsilon_6^3\Delta_6^3 - K6\varepsilon_4^3\Delta_4^3 + K1K3K6\varepsilon_4^2\Delta_4^2 + K2K5K6\varepsilon_4^2\Delta_4^2 + \\ & K1K4K5\varepsilon_6^2\Delta_6^2 + K2K5K6\varepsilon_6^2\Delta_6^2 + K4K6K7\varepsilon_4^2\Delta_4^2 + K3K5K7\varepsilon_6^2\Delta_6^2 + K6\varepsilon_1\varepsilon_4^2\Delta_1\Delta_4^2 \\ & - K7\varepsilon_1\varepsilon_4^2\Delta_1\Delta_4^2 + K7\varepsilon_1^2\varepsilon_4\Delta_1^2\Delta_4 + 2K5\varepsilon_1\varepsilon_6^2\Delta_1\Delta_6^2 - K5\varepsilon_1^2\varepsilon_6\Delta_1^2\Delta_6 + 2K5\varepsilon_4\varepsilon_6^2\Delta_4\Delta_6^2 - \\ & K5\varepsilon_4^2\varepsilon_6\Delta_4^2\Delta_6 - K6\varepsilon_4\varepsilon_6^2\Delta_4\Delta_6^2 + 2K6\varepsilon_4^2\varepsilon_6\Delta_4^2\Delta_6 - K1K2K3K5K7\varepsilon_1\Delta_1 - \\ & K1K2K3K5K6\varepsilon_4\Delta_4 - K3K4K5K6K7\varepsilon_1\Delta_1 - K1K3K4K6K7\varepsilon_4\Delta_4 - \\ & K1K2K4K5K6\varepsilon_6\Delta_6 - K1K3K4K5K7\varepsilon_6\Delta_6 - K2K4K5K6K7\varepsilon_4\Delta_4 - \\ & K2K3K5K6K7\varepsilon_6\Delta_6 + K1K3K7\varepsilon_1\varepsilon_4\Delta_1\Delta_4 + K1K2K5\varepsilon_1\varepsilon_6\Delta_1\Delta_6 + K2K5K7\varepsilon_1\varepsilon_4\Delta_1\Delta_4 \\ & + K3K5K6\varepsilon_1\varepsilon_4\Delta_1\Delta_4 - K4K6K7\varepsilon_1\varepsilon_4\Delta_1\Delta_4 + K1K3K5\varepsilon_4\varepsilon_6\Delta_4\Delta_6 - 2K3K5K7\varepsilon_1\varepsilon_6\Delta_1\Delta_6 \\ & + K4K5K6\varepsilon_1\varepsilon_6\Delta_1\Delta_6 + K1K4K6\varepsilon_4\varepsilon_6\Delta_4\Delta_6 - 2K2K5K6\varepsilon_4\varepsilon_6\Delta_4\Delta_6 + K3K6K7\varepsilon_4\varepsilon_6\Delta_4\Delta_6 \\ & + K4K5K7\varepsilon_4\varepsilon_6\Delta_4\Delta_6 - 2K1\varepsilon_1\varepsilon_4\varepsilon_6\Delta_1\Delta_4\Delta_6 - 2K5\varepsilon_1\varepsilon_4\varepsilon_6\Delta_1\Delta_4\Delta_6 - K6\varepsilon_1\varepsilon_4\varepsilon_6\Delta_1\Delta_4\Delta_6 - \\ & K7\varepsilon_1\varepsilon_4\varepsilon_6\Delta_1\Delta_4\Delta_6 + K1K2K3K4K5K6K7)/(\varepsilon_1^2\Delta_1^3\Delta_4\Delta_6 + \varepsilon_4^2\Delta_1\Delta_4^3\Delta_6 - 2\varepsilon_1\varepsilon_4\Delta_1^2\Delta_4^2\Delta_6 \\ & - \varepsilon_1\varepsilon_6\Delta_1^2\Delta_4\Delta_6^2 - \varepsilon_4\varepsilon_6\Delta_1\Delta_4^2\Delta_6^2 + K2K5\varepsilon_1\Delta_1^2\Delta_4\Delta_6 - K3K5\varepsilon_1\Delta_1^2\Delta_4\Delta_6 - K2K5\varepsilon_4\Delta_1\Delta_4^2\Delta_6 - \\ & K4K6\varepsilon_1\Delta_1^2\Delta_4\Delta_6 + K3K5\varepsilon_4\Delta_1\Delta_4^2\Delta_6 + K2K5\varepsilon_6\Delta_1\Delta_4\Delta_6^2 + K3K6\varepsilon_4\Delta_1\Delta_4^2\Delta_6 \\ & + K3K5\varepsilon_6\Delta_1\Delta_4\Delta_6^2 + K3K7\varepsilon_4\Delta_1\Delta_4^2\Delta_6 + K4K6\varepsilon_4\Delta_1\Delta_4^2\Delta_6 + 2K4K5\varepsilon_6\Delta_1\Delta_4\Delta_6^2 - \\ & K2K3K5K6\Delta_1\Delta_4\Delta_6 - K2K3K5K7\Delta_1\Delta_4\Delta_6 - K2K4K5K6\Delta_1\Delta_4\Delta_6 \\ & - K3K4K5K7\Delta_1\Delta_4\Delta_6) \qquad (4.5.41)\end{aligned}$$

where

$K1=\varepsilon_1+\varepsilon_4+\varepsilon_7$, $K2=\varepsilon_4+\varepsilon_7+\Delta_1$, $K3=\varepsilon_6+\Delta_4$, $K4=\varepsilon_1+\varepsilon_4+\Delta_7$, $K5=\Delta_1+\Delta_2$, $K6=\varepsilon_4+\Delta_1+\Delta_6$, $K7=\varepsilon_1+\Delta_4+\Delta_6$, $K8=\Delta_1+\Delta_4+\Delta_6$

Under normalized conditions i.e. sum of all the probabilities is equal to one

$\therefore$ $\sum_{i=1}^{28} P_i = 1$ i.e. $P_1+P_2+P_3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots + P_{28}=1$

$$P_1\left[1+\frac{P_2}{P_1}+\frac{P_3}{P_1}.......+\frac{P_{28}}{P_1}\right]=1 \qquad (5.4.42)$$

$$\begin{aligned}P_1=&[(1+\varepsilon_4/\Delta_4+\varepsilon_7/\Delta_7+(P_2/P_1)(1+\varepsilon_2/\Delta_2+\varepsilon_4/\Delta_4+\varepsilon_7/\Delta_7)+(P_3/P_1)(1+\varepsilon_4/\Delta_4+\varepsilon_6/\Delta_6+\varepsilon_7/\Delta_7) \\ & +(P_4/P_1)(1+\varepsilon_3/\Delta_3+\varepsilon_4/\Delta_4+\varepsilon_7/\Delta_7)+(P_5/P_1)(1+\varepsilon_2/\Delta_2+\varepsilon_4/\Delta_4+\varepsilon_6/\Delta_6+\varepsilon_7/\Delta_7)+(P_6/P_1)(1+ \\ & \varepsilon_3/\Delta_3+\varepsilon_4/\Delta_4+\varepsilon_6/\Delta_6+\varepsilon_7/\Delta_7)]^{-1} \qquad (4.5.43)\end{aligned}$$

The value of P_1 is obtained by putting the values of P_2/P_1, P_3/P_1, P_4/P_1, P_5/P_1, P_6/P_1, P_7/P_1, and P_8/P_1 from Eqs. (4.5.35)- (4.5.41) resp. in Eq. (4.5.43)

The steady state availability of the Feeding system, (A_{v5}) is summation of its working and standby states i.e.

$$A_{v5} = P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 \tag{4.5.44}$$

The Eq. (4.5.44) gives the steady state availability of the Feeding system.

4.5.2 Performance modeling for RAMD analysis of the Feeding system

The Feeding system is transformed in to four subsystems (S1-S4) as shown in Fig. 4.18.

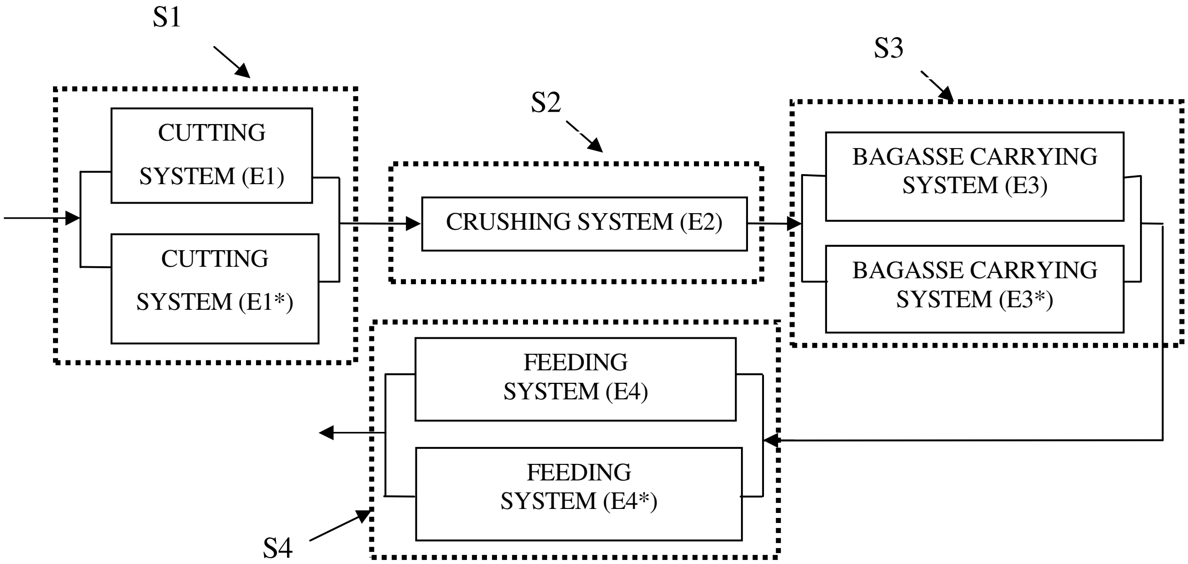
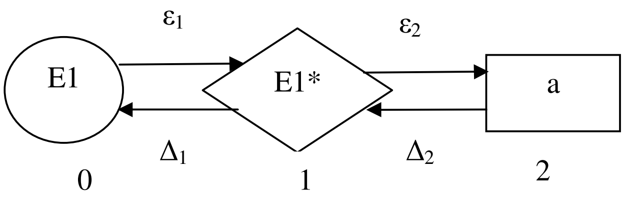
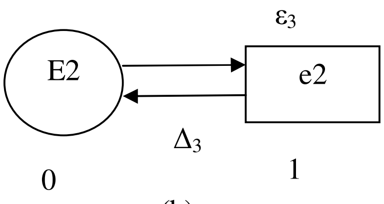


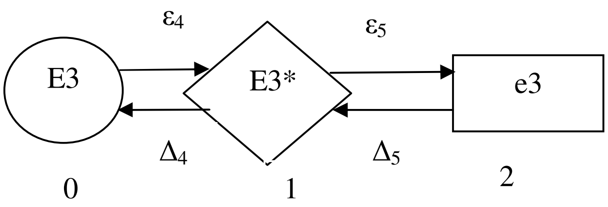
Fig. 4.18 Schematic representation of the Feeding system



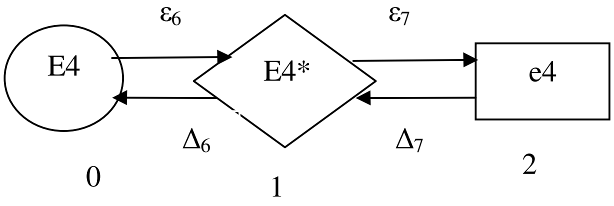
(a)



(b)



(c)



(d)

Fig. 4.19 State transition diagram of the subsystems of the Feeding system
(a) subsystem S1, (b) subsystem S2, (c) subsystem S3, (d) subsystem S4

The transition diagrams associated with the subsystems (S1- S4) are shown in Fig. 4.19((a)-(d)). The data regarding failure and repair rates of the subsystems is presented in table 4.5.

RAMD indices for subsystem S1

This subsystem has single unit (E1) only but it has its cold standby unit (E1*). Failure of both units causes complete failure of the system. The differential equations associated with Fig. 4.19 (a) are:

$P'_0(t) = - \varepsilon_1 P_0(t) + \Delta_1 P_1(t)$ (4.5.45)

$P'_1(t) = - (\Delta_1 + \varepsilon_2)P_1(t) + \varepsilon_1 P_0(t) + \Delta_4 P_2(t)$ (4.5.46)

$P'_2(t) = - \Delta_2 P_2(t) + \varepsilon_2 P_1(t)$ (4.5.47)

Under steady state conditions, the Eqs. (4.5.45)- (4.5.47) get reduced as:

$(\Delta_1 + \varepsilon_2)P_1 = \varepsilon_1 P_0 + \Delta_2 P_2$ (4.5.48)

$\Delta_2 P_2 = \varepsilon_2 P_1$ (4.5.49)

$\Delta_1 P_1 = \varepsilon_1 P_0$ (4.5.50)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.5.51)

Put the values of P_1 and P_2 by solving Eqs. (4.5.48)- (4.5.50) in Eq. (4.5.51)

$P_0 (1 + \varepsilon_1 / \Delta_1 + \varepsilon_2 \varepsilon_1 / \Delta_2 \Delta_1) = 1$ (4.5.52)

The availability of the subsystem S1 is given by Eq. (4.5.52)

$R_{S1} (t) = e^{-0.0172t}$ (4.5.53)

Reliability Eq. for the subsystem S1 is given by Eq. (4.5.53)

$M_{S1} (t) = 1-e^{-11.696t}$ (4.5.54)

The maintainability Eq. for the subsystem S1 is given by Eq. (4.5.54)

The others parameters for the subsystem S1 are computed as:

$D_{min. (S1)} = 0.9989$

MTBF= 58.1395 hr.

MTTR= 0.0855 hr. and

d= 679.9892.

RAMD indices for subsystem S2

This subsystem has single unit (E2) only and failure of this unit causes complete failure of the system. The differential equations associated with Fig. 4.19 (b) are:

$$P'_o(t) = -\varepsilon_3 P_o(t) + \Delta_3 P_1(t) \quad (4.5.55)$$

$$P'_1(t) = -\Delta_3 P_1(t) + \varepsilon_3 P_0(t) \quad (4.5.56)$$

Under steady state conditions, the Eqs. (4.5.55)- (4.5.56) get reduced as:

$$\varepsilon_3 P_o = \Delta_3 P_1 \quad (4.5.57)$$

$$\Delta_3 P_1 = \varepsilon_3 P_0 \quad (4.5.58)$$

Now, using the normalizing conditions

$$P_0 + P_1 = 1 \quad (4.5.59)$$

The Eqs. (4.5.57) and (4.5.58) are solved to get the values of P_0 i.e.

$$P_0 (1+\varepsilon_3 / \Delta_3) = 1 \quad (4.5.60)$$

The availability of the subsystem S2 is given by Eq. (4.5.60)

$$R_{S2\ (t)} = e^{-0.007t} \quad (4.5.61)$$

The reliability Eq. for the subsystem S2 is given by Eq. (4.5.61)

$$M_{S2}\ (t) = 1\text{-}e^{-0.13t} \quad (4.5.62)$$

The maintainability Eq. for the subsystem S2 is given by Eq. (4.5.62)

The other parameters for the subsystem S2 are computed as:

$D_{min.(S2)} = 0.9623$

MTBF= 142.8571hr.

MTTR= 0.0855 hr. and

d =679.9892.

RAMD indices for subsystem S3

This subsystem has single unit (E3) only but it has its cold standby unit (E3*). Failure of both units causes complete failure of the system. The differential equations associated with Fig. 4.19 (c) are:

$$P'_0(t) = -\varepsilon_4 P_0(t) + \Delta_4 P_1(t) \quad (4.5.63)$$

$$P'_1(t) = -(\Delta_4 + \varepsilon_5) P_1(t) + \varepsilon_4 P_0(t) + \Delta_5 P_2(t) \quad (4.5.64)$$

$$P'_2(t) = -\Delta_5 P_2(t) + \varepsilon_5 P_1(t) \quad (4.5.65)$$

Under steady state conditions, the Eqs. (4.5.63)- (4.5.65) get reduced as:

$$(\Delta_4 + \varepsilon_5) P_1 = \varepsilon_4 P_0 + \Delta_5 P_2 \quad (4.5.66)$$

$\Delta_5 P_2 = \varepsilon_5 P_1$ (4.5.67)

$\Delta_4 P_1 = \varepsilon_4 P_0$ (4.5.68)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.5.69)

Put the values of P_1 and P_2 by solving Eqs. (4.5.66)- (4.5.68) in Eq. (4.5.69)

$P_0 (1 + \varepsilon_4 / \Delta_4 + \varepsilon_5 \varepsilon_4 / \Delta_5 \Delta_4) = 1$ (4.5.70)

The availability of the subsystem S3 is given by Eq. (4.5.70)

$R_{S3\ (t)} = e^{-0.0017t}$ (4.5.71)

Reliability Eq. for the subsystem S3 is given by Eq. (4.5.71)

$M_{S3}(t) = 1 - e^{-7.1378t}$ (4.5.72)

The maintainability Eq. for the subsystem S3 is given by Eq. (4.5.72)

The other parameters for the subsystem S3 are computed as:

$D_{min.\ (S3)} = 0.9983$

MTBF= 58.8235 hr.

MTTR= 0.1401 hr. and

d= 420.00.

RAMD indices for subsystem S4

This subsystem has single unit (E4) only but it has its cold standby unit (E4*). Failure of both units causes complete failure of the system. The differential equations associated with Fig. 4.19 (d) are:

$P'_0(t) = -\varepsilon_6 P_0(t) + \Delta_6 P_1(t)$ (4.5.73)

$P'_1(t) = -(\Delta_6 + \varepsilon_7) P_1(t) + \varepsilon_6 P_0(t) + \Delta_7 P_2(t)$ (4.5.74)

$P'_2(t) = -\Delta_7 P_2(t) + \varepsilon_7 P_1(t)$ (4.5.75)

Under steady state conditions, the Eqs. (4.5.73)- (4.5.75 get reduced as:

$(\Delta_6 + \varepsilon_7) P_1 = \varepsilon_6 P_0 + \Delta_7 P_2$ (4.5.76)

$\Delta_7 P_2 = \varepsilon_7 P_1$ (4.5.77)

$\Delta_6 P_1 = \varepsilon_6 P_0$ (4.5.78)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.5.79)

Put the values of P_1 and P_2 by solving Eqs. (4.5.76)- (4.5.78) in Eq. (4.5.79)

$P_0 (1 + \varepsilon_6 / \Delta_6 + \varepsilon_7 \varepsilon_6 / \Delta_7 \Delta_6) = 1$ (4.5.80)

The availability of the subsystem S4 is given by Eq. (4.5.80)

$R_{S4}(t) = e^{-0.016t}$ (4.5.81)

Reliability Eq. for the subsystem S4 is given by Eq. (4.5.81)

$M_{S4}(t) = 1-e^{-5.1786t}$ (4.5.82)

The maintainability Eq. for the subsystem S4 is given by Eq. (4.5.82)

The other parameters for the subsystem S3 are computed as:

$D_{min.\,(S4)} = 0.9977$

MTBF= 62.50 hr.

MTTR= 0.1931 hr. and

d= 323.75.

System Reliability

The overall system reliability of Feeding system, $R_{sys}(t)$

$R_{sys}(t) = R_{S1}(t) \times R_{S2}(t) \times R_{S3}(t) \times R_{S4}(t)$

$R_{sys}(t) = e^{-0.0172t} \times e^{-0.007t} \times e^{-0.0017t} \times e^{-0.016t} = e^{-0.031t}$

$R_{sys}(t) = e^{-0.031t}$

System Availability

The overall system availability of the Feeding system (A_{sys}) is computed as:

$A_{sys} = A_{S1} \times A_{S2} \times A_{S3} \times A_{S4}$

$A_{sys} = 0.9985 \times 0.9489 \times 0.9976 \times 0.9969 = 0.9423$

System Maintainability

The overall system maintainability of the Feeding system, $M_{sys}(t)$ is computed as:

$M_{sys}(t) = M_{S1}(t) \times M_{S2}(t) \times M_{S3}(t) \times M_{S4}(t)$

$M_{sys}(t) = 1-e^{-0.1233t}$

System Dependability

The overall system dependability of the Feeding system, $D_{min.\,(sys)}$ is computed as:

$D_{min.\,(sys)} = D_{min.\,(S1)} \times D_{min.\,(S2)} \times D\ min_{.\,(S3)} \times D_{min.\,(S4)}$

$D_{sys} = 0.9736 \times 0.9927 \times 0.9396 \times 0.8169 = 0.7419$

Table 4.5 Failure and repair rates of the subsystems of the Feeding system

Subsystem	Failure Rate (ε)	Repair Rate (Δ)
S1	Cutting system (ε_1)=0.0086/hr.	Cutting system (Δ_1)=0.22/hr.
S2	Crushing system (ε_3)=0.007/hr.	Crushing system (Δ_3)=0.13/hr.
S3	Bagasse carrying system (ε_4)=0.0085/hr.	Bagasse carrying system (Δ_4)=0.17/hr.
S4	Heat generating system (ε_6)=0.008/hr.	Heat generating system (Δ_6)=0.14/hr.

4.5.3 Performance modeling for the fuzzy-reliability analysis of the Feeding system

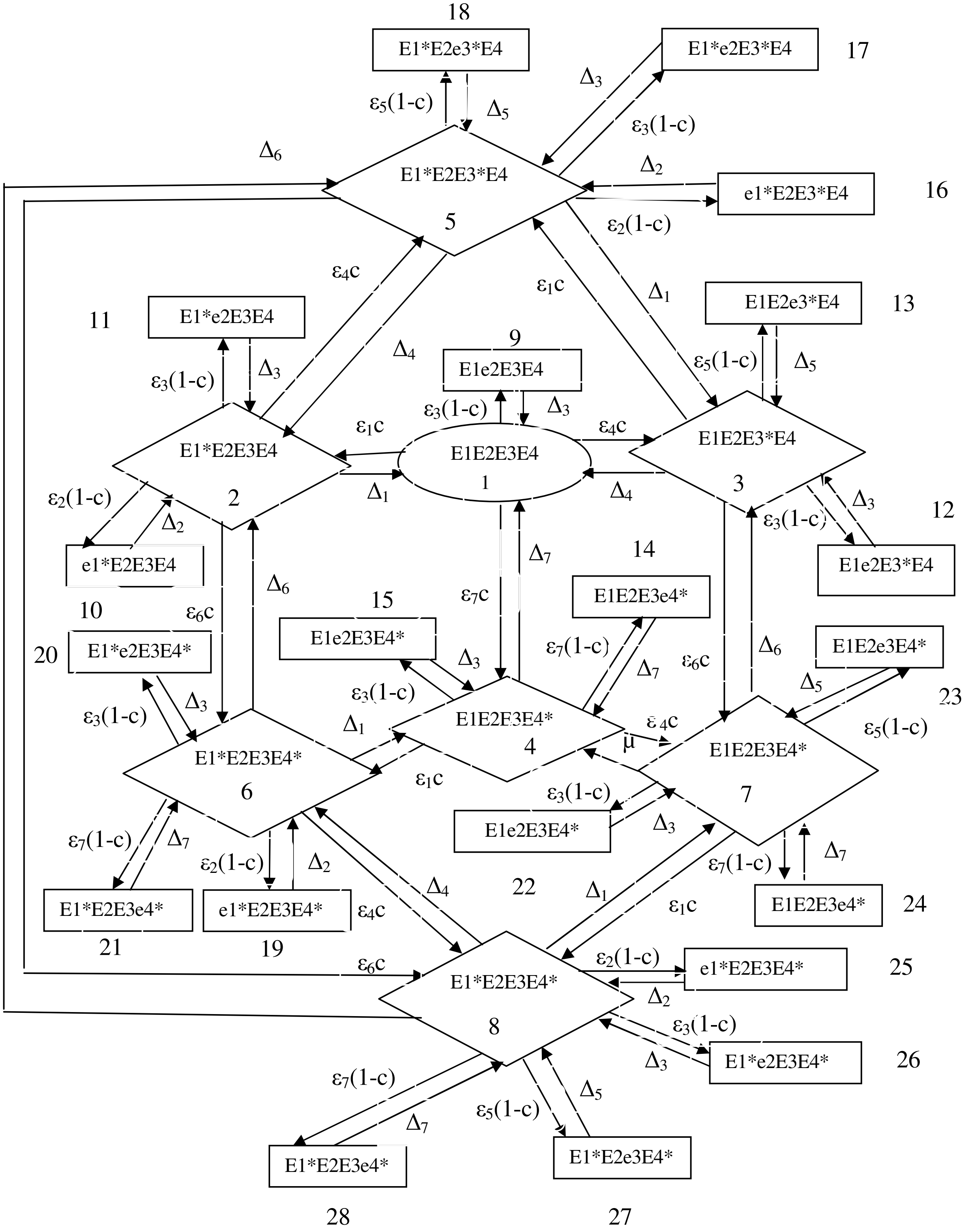


Fig. 4.20 State transition diagram of the Feeding system with imperfect fault coverage

State 1: The system is working with full capacity (with no standby)

State 2: The system is working with first standby unit of Compressor (E1*)

State 3: The system is working with standby unit of Condenser (E3*)

State 4: The system is working with standby units of Compressor (E1*) and Condenser (E3*).

State 5 to 20: Failed states of the system due to complete failure of its subsystems i.e. A, B, C, D and E.

$$P'_1(t) = -X_1P_1(t) + \Delta_5 P_5(t) + \Delta_6P_6(t) + \Delta_7P_7(t)+\Delta_1P_2(t)+\Delta_3P_3(t) \tag{4.5.83}$$

$$P'_2(t) = -X_2P_2(t) + \Delta_1 P_8(t) + \Delta_5P_9(t) + \Delta_6P_{10}(t)+ \Delta_7P_{11}(t) + \Delta_3P_4(t) + \varepsilon_1cP_1(t) \tag{4.5.84}$$

$$P'_3(t) = -X_3P_3(t) + \Delta_3 P_{12}(t) + \Delta_5P_{13}(t) + \Delta_6P_{14}(t) + \Delta_7P_{15}(t) +\Delta_1P_4(t) + \varepsilon_3c P_1(t) \tag{4.5.85}$$

$$P'_4(t) = -X_4P_4(t)+\Delta_1P_{16}(t)+\Delta_3P_{17}(t) + \Delta_5P_{18}(t) + \Delta_6P_{19}(t) +\Delta_7P_{20}(t) + \varepsilon_3c P_2(t) + \varepsilon_1cP_3(t) \tag{4.5.86}$$

where

$X_1= \varepsilon_5(1-c)+\varepsilon_6(1-c) +\varepsilon_7(1-c)+\varepsilon_1c+\varepsilon_3c$, $X_2 = \varepsilon_1(1-c)+\varepsilon_5(1-c)+\varepsilon_6(1-c) +\varepsilon_7(1-c)+ \Delta_1+\varepsilon_3c$,

$X_3=\varepsilon_3(1-c)+\varepsilon_5(1-c)+\varepsilon_6(1-c)+\varepsilon_7(1-c)+ \Delta_3+\varepsilon_1c$,

$X_4=\varepsilon_1(1-c)+\varepsilon_3(1-c)+\varepsilon_5(1-c)+\Delta_3+\Delta_1+\varepsilon_6(1-c) +\varepsilon_7(1-c)$

$P'_5(t) + \Delta_5P_5(t) = \varepsilon_5(1-c) P_1(t)$ (4.5.87), where i= 5, 6, 7 and j=5, 6, 7

$P'_8(t) + \Delta_1P_8(t) = \varepsilon_1(1-c) P_2(t)$ (4.5.88), where i= 8, 9, 10 , 11and j=1, 5, 6, 7

$P'_{12}(t) + \Delta_3P_{12}(t) = \varepsilon_3(1-c) P_3(t)$ (4.5.890), where i= 12, 13, 14, 15 and j=3, 5, 6, 7

$P'_{16}(t) + \Delta_1P_{17}(t) = \varepsilon_1(1-c) P_4(t)$ (4.5.90), where i= 16, 17, 18, 19, 20 and j=1, 3, 5, 6, 7

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j = 1 \\ 0, \text{if } j \neq 1 \end{cases} \tag{4.5.91}$$

The system of differential equations (4.5.83) to (4.5.90) with initial conditions given by Eq. (4.5.91) was solved by Runge-Kutta fourth order method. The numerical computations were carried out by taking that

(i) The failure and repair rates of Compressor (ε_1, Δ_1) and its standby unit (ε_2, Δ_2) are same.

(ii) The failure and repair rates of Condenser (ε_3, Δ_3) and its standby unit (ε_4, Δ_4) are same.

The fuzzy-reliability of the Feeding system was computed for one year (i.e. time, *t*=30-360 days) for different choices of failure rates of the subsystems. The fuzzy-reliability of the Feeding system, $R_{F5}(t)$ is composed of the fuzzy-reliability of the system working with full capacity and its standby states i.e.

$$R_{F5}(t) = R_1(t) + \frac{1}{2}R_2(t) + \frac{1}{2}R_3(t) + \frac{1}{4}R_4(t) \qquad (4.5.92)$$

4.6 PERFORMANCE MODELING FOR THE CRUSHING SYSTEM OF THE SUGAR PLANT

Performance modeling for the Crushing system is carried out by deriving mathematical equations for the development of the decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

4.6.1 Performance modeling for Decision Support Systems (DSS) of the Crushing system

The transition diagram (Fig. 4.21) depicts a simulation model showing all the possible states of the Crushing system.

State 1: The system is working with full capacity (with no standby)

State 2: The system is working with standby unit of crushing unit (F3)

State 3 to 7: Failed states of the system due to complete failure of its subsystems i.e. F1, F2 and F3.

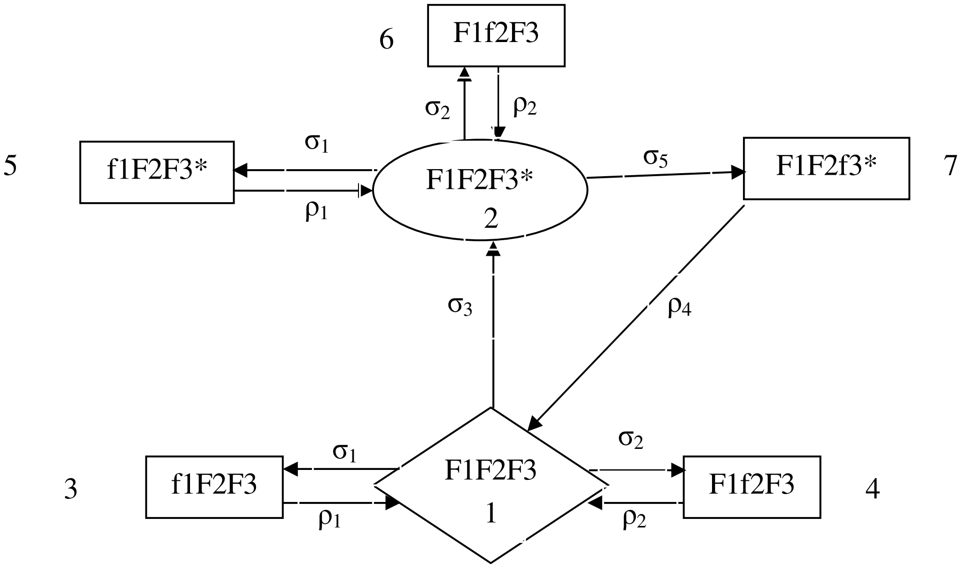


Fig. 4.21 State transition diagram of the Crushing system

F1, F2 and F3 : Indicates full working states of the subsystems

F3* : Indicates that the subsystem F3 is working under standby state

f1, f2 and f3 : Indicates the failed states of the subsystems

P_1 (t) : Probability of the system working with full capacity

P_2 (t) : Probability of the system working under standby state

σ_i = 1,2,3, 4 : The constant failures rates of the subsystems F1, F2, F3 and F3* resp.

ρ_i = 1,2,3, 4 : The constant repair rates of the subsystems F1, F2, F3 and F3* resp.

$P_j(t)$, j= 0,1,2 : The probability that the system is in j^th^ state at time, *t*

The mathematical equations (4.6.1)-(4.6.7) based on Markov-birth death process are developed for each state one by one out of 7 states of transition diagram (Fig. 4.21).

$$P'_1(t) = - X_1P_1(t) + \rho_1P_3(t) + \rho_4P_7(t) + \rho_2P_4(t) \qquad (4.6.1)$$

$$P'_2(t) = - X_2P_2(t) + \rho_1P_5(t) + \rho_2P_6(t) + \sigma_3P_1(t) \qquad (4.6.2)$$

where

$X_1= (\sigma_1+\sigma_3+\sigma_2)$, $X_2= (\sigma_1 +\sigma_2+\sigma_4)$

$P'_i(t) + \rho_j P_i(t) = \sigma_j P_i(t)$ (4.6.3), where i=3, 4 and j=1, 2

$P'_i(t) + \rho_j P_i(t) = \sigma_j P_2(t)$ (4.6.4), where i= 5, 6, 7 and j=1, 2, 4

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j = 1 \\ 0, \text{if } j \neq 1 \end{cases} \qquad (4.6.5)$$

The system of differential equations (4.6.1)-(4.6.4) with initial conditions given by Eq. (4.6.5) was solved by Runge-Kutta fourth order method. The numerical computations were carried out by taking that the failure and repair rates of the Milling train (σ_3, ρ_3) subsystem and its standby unit (σ_4, ρ_4) is same and numerical computations were carried out for one year (i.e. time, *t=30-360* days) for different choices of failure and repair rates of the subsystems. The reliability, $R_6(t)$ of the Crushing system is composed of reliability of the system working with full capacity and its standby states i.e.

$$R_6(t) = P_1(t)+P_2(t)) \qquad (4.6.6)$$

The Eq. (4.6.6) is used to compute the reliability of the Crushing system

The management is interested to get the steady state or long run availability of the system. The steady state probabilities of the system are obtained by imposing the following restrictions i.e. d/dt→0, as t→∞. The equations (4.6.1)-(4.6.4) get reduced to the following system of Eqs.

$$X_1P_1 = \rho_1P_3 +\rho_4P_7+\rho_2P_4 \qquad (4.6.7)$$

$$X_2P_2 = \rho_1P_5+\rho_2P_6+ \sigma_3P_1 \qquad (4.6.8)$$

where

$X_1= (\sigma_1+\sigma_3+\sigma_2)$, $X_2= (\sigma_1 +\sigma_2+\sigma_4)$

$\rho_j P_i = \sigma_jP_1$ (4.6.9), where i=3, 4 and j=1, 2

$\rho_j P_i = \sigma_j P_2$ (4.6.10), where *i*= 5, 6, 7 and *j*=1, 2, 4

Under normalized conditions i.e. sum of all the probabilities is equal to one.

$\therefore \quad \sum_{i=1}^{7} Pi = 1$ i.e. $P_1+P_2+P_3 \ldots\ldots\ldots\ldots\ldots\ldots +P_7=1$

$$P_1\left[1+\frac{P_2}{P_1}+\frac{P_3}{P_1}+.....+\frac{P_7}{P_1}\right]=1 \tag{4.6.11}$$

$$P_1=[(1+\frac{\sigma_3}{\sigma_4}+\frac{\sigma_1}{\rho_1}+\frac{\sigma_2}{\rho_2})+\frac{\sigma_3}{\sigma_4}(\frac{\sigma_1}{\rho_1}+\frac{\sigma_2}{\rho_2}+\frac{\sigma_4}{\rho_4})]^{-1}$$

$$P1=\frac{\sigma_3}{\sigma_4} P_2$$

The steady state availability of the system, A_{v6} is summation of its working and standby states i.e.

$$A_{v6}=P_1+P_2 \tag{4.6.12}$$

The Eq. (4.6.12) is used to calculate steady state availability of the Crushing system.

4.6.2 Performance modeling for RAMD analysis of the Crushing system

The Crushing system is transformed in to four subsystems (S1-S3) as shown in Fig. 4.22. The transition diagrams associated with the subsystems (S1- S3) are shown in Fig. 4.23((a)-(c)). The data regarding failure and repair rates of the subsystems is presented in table 4.6.

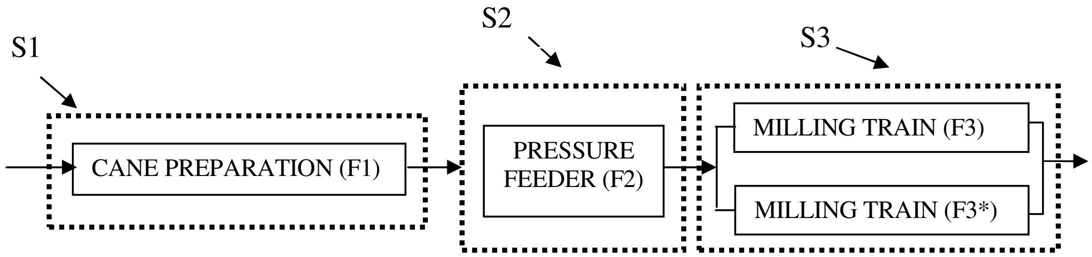
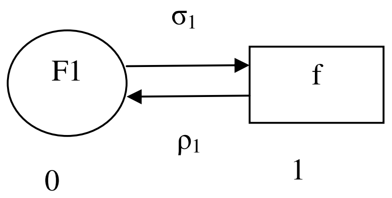
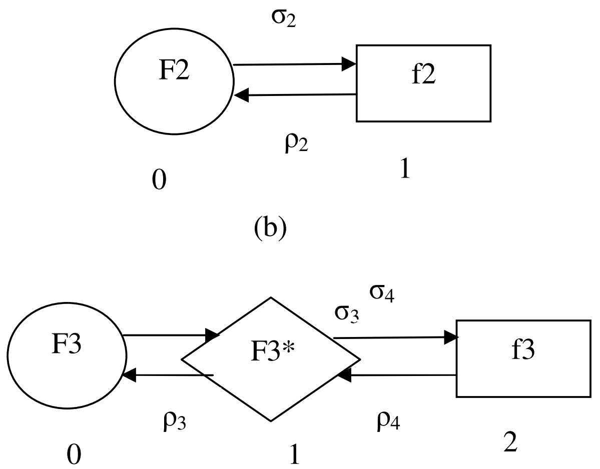


Fig. 4.22 Schematic representation of the Crushing system



(a)



(b)

(c)

Fig. 4.23 State transition diagram of subsystems of Crushing system:
(a) subsystem S1, (b) subsystem S2, (c) subsystem S3

RAMD indices for subsystem S1

This subsystem has single unit (F1) only and failure of this unit causes complete failure of the system. The differential equations associated with Fig. 4.23 (a) are

$P'_o(t) = -\sigma_1 P_o(t) + \rho_1 P_1(t)$ (4.6.13)

$P'_1(t) = -\rho_1 P_1(t) + \sigma_1 P_0(t)$ (4.6.14)

Under steady state conditions, the Eqs. (4.6.13)- (4.6.14) get reduced as:

$\rho_j P_i = \sigma_j P_1$ (4.6.15), where i=3, 4 and j=1, 2

$\rho_j P_i = \sigma_j P_2$ (4.6.16), where i= 5, 6, 7 and j=1, 2, 4

Now, using the normalizing conditions

$P_0 + P_1 = 1$ (4.6.17)

The Eqs. (4.6.15) and (4.6.16) are solved to get the values of P_0 i.e.

$P_0 (1+\sigma_1 / \rho_1] = 1$ (4.6.18)

The availability of the subsystem S1 is given by Eq. (4.6.18)

$R_{S1\ (t)} = e^{-0.0057t}$ (4.6.19)

The reliability Eq. for the subsystem S1 is given by Eq. (4.6.19)

$M_{S1}\ (t) = 1-e^{-0.016t}$ (4.6.20)

The maintainability Eq. for the subsystem S1 is given by Eq. (4.6.20)

The others parameters for the subsystem S1 are computed as:

$D_{min.(S1)} = 0.7280$

MTBF= 175.4386hr.

MTTR= 62.5hr. and

d =2.8070

RAMD indices for subsystem S2

This subsystem has single unit (F2) only and failure of this unit causes complete failure of the system. The differential equations associated with Fig. 4.23 (b) are:

$P'_o(t) = -\sigma_2 P_o(t) + \rho_2 P_1(t)$ (4.6.21)

$P'_1(t) = -\rho_2 P_1(t) + \sigma_2 P_0(t)$ (4.6.22)

Under steady state conditions, the Eqs. (4.6.21) and (4.6.22) get reduced as

$\sigma_2 P_o = \rho_2 P_1$ (4.6.23)

$\rho_2 P_1 = \sigma_2 P_0$ (4.6.24)

Now, using the normalizing conditions

$P_0 + P_1 = 1$ (4.6.25)

The Eqs. (4.6.23) and (4.6.24) are solved to get the values of P_0 i.e.

$P_0 (1+\sigma_2 /\rho_2] = 1$ (4.6.26)

The availability of the subsystem S2 is given by Eq. (4.6.26)

$R_{S2\ (t)} = e^{-0.0082t}$ (4.6.27)

The reliability Eq. for the subsystem S2 is given by Eq. (4.6.27)

$M_{S2}\ (t) = 1\text{-}e^{-0.021t \dots}$ (4.6.28)

The maintainability Eq. for the subsystem S2 is given by Eq. (4.6.28)

The other parameters for the subsystem S2 are computed as:

$D_{min.(S2)} = 0.6931$

MTBF= 121.9512hr.

MTTR= 47.6190 hr. and

d =2.5610

RAMD indices for subsystem S3

This subsystem has single unit (F3) only but it has its cold standby unit (F3*). Failure of both units causes complete failure of the system. The differential equations associated with Fig. 4.23 (c) are:

$P'_0(t) = - \sigma_3 P_0(t) + \rho_3 P_1(t)$ (4.6.29)

$P'_1(t) = - (\rho_3 + \sigma_4)P_1(t) + \sigma_3 P_0(t) + \rho_4 P_2(t)$ (4.6.30)

$P'_2(t) = - \rho_4 P_2(t) + \sigma_4 P_1(t)$ (4.6.31)

Under steady state conditions, the Eqs. (4.6.29)- (4.6.31) get reduced as:

$(\rho_3 + \sigma_4)P_1 = \sigma_3 P_0 + \rho_4 P_2$ (4.6.32)

$\rho_4 P_2 = \sigma_4 P_1$ (4.6.33)

$\rho_3 P_1 = \sigma_3 P_0$ (4.6.34)

Now, using the normalizing conditions:

$P_0 + P_1 + P_2 = 1$ (4.6.35)

Put the values of P_1 and P_2 by solving Eqs. (4.6.32)- (4.6.34) in eqn. (4.6.35)

$P_0 (1 + \sigma_3 / \rho_3 + \sigma_4 \sigma_3 / \rho_4 \rho_3) = 1$ (4.6.36)

The availability of the subsystem S3 is given by Eq. (4.6.36)

$R_{S3} (t) = e^{-0.0152t}$ (4.6.37)

Reliability Eq. for the subsystem S3 is given by Eq. (4.6.37)

$M_{S3} (t) = 1 - e^{-0.3335t}$ (4.6.38)

The maintainability Eq. for the subsystem S3 is given by Eq. (4.6.38)

The other parameters for the subsystem S2 are computed as:

$D_{min. (S3)} = 0.9980$, MTBF= 65.7895 hr., MTTR= 2.9987 hr. and d= 21.9391.

Table 4.6 Failure and repair rates of the subsystems of the Crushing system

Subsystem	Failure rate of subsystems (σ)	Repair rate of subsystems (ρ)
S1	Cane preparation (σ_1)=0.0057/hr.	Cane preparation (ρ_1)=0.016/hr.
S2	Pressure feeder (σ_2)=0.0082/hr.	Pressure feeder (ρ_2)=0.021/hr.
S3	Milling train (σ_3)=0.0076/hr.	Milling train (ρ_3)=0.032/hr.

System Reliability

The overall system reliability of Crushing system, $R_{sys} (t)$

$R_{sys} (t) = R_{S1} (t) \times R_{S2} (t) \times R_{S3} (t)$

$R_{sys} (t) = e^{-0.0057t} \times e^{-0.0082t} \times e^{-0.0152t} = e^{-0.0218t}$

$R_{sys} (t) = e^{-0.0218t}$

System Availability

The overall system availability of the Crushing system (A_{sys}) is computed as

$A_{sys} = A_{S1} \times A_{S2} \times A_{S3}$

$A_{sys} = 0.7373 \times 0.7192 \times 0.9564 = 0.5072$

System Maintainability

The overall system maintainability of Crushing system, $M_{sys} (t)$ is computed as:

$M_{sys} (t) = M_{S1}(t) \times M_{S2}(t) \times M_{S3}(t)$

$M_{sys}(t) = 1 - e^{-0.00884t}$

System Dependability

The overall system dependability of the Crushing system, $D_{\text{min. (sys)}}$ is computed as:

$D_{\text{min. (sys)}} = D_{\text{min. (S1)}} \times D_{\text{min. (S2)}} \times D_{\text{min. (S3)}}$

$D_{sys}=0.7280 \times 0.6931 \times 0.9980=0.5036$

4.6.3 Performance modeling for the fuzzy-reliability analysis of the Crushing system

The mathematical equations (4.6.45) to (4.6.51) are developed based on Markov birth-death process to each state one by one out of 7 states of transition diagram (Fig. 4.24).

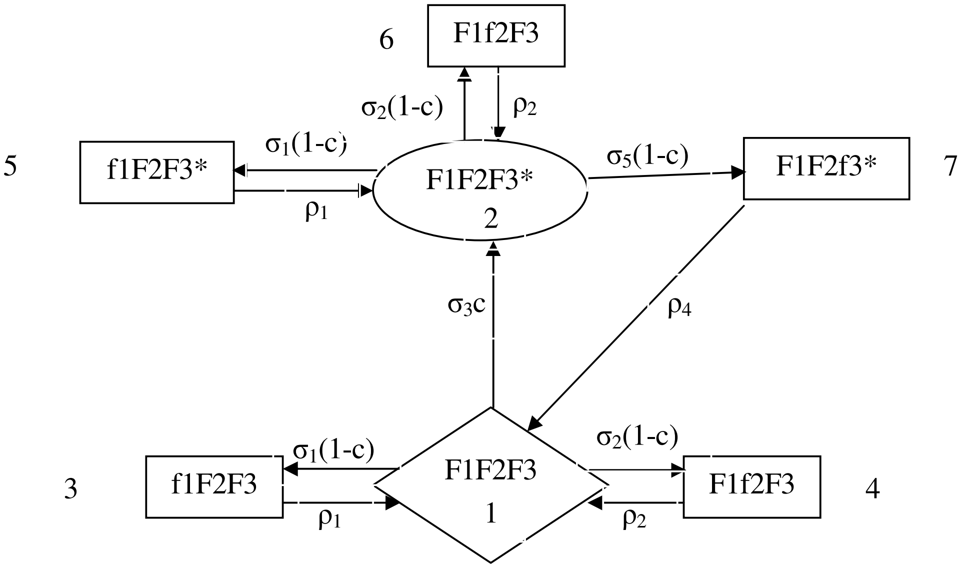


Fig. 4.24 State transition diagram of the Crushing system with imperfect fault coverage

$$P'_1(t) = - X_1P_1(t) + \rho_1P_3(t) + \rho_4P_7(t) + \rho_2P_4(t) \qquad (4.6.46)$$

$$P'_2(t) = - X_2P_2(t) + \rho_1P_5(t) + \rho_2P_6(t) + \sigma_3cP_1(t) \qquad (4.6.47)$$

Where, $X_1= \sigma_1(1-c)+\sigma_3c+\sigma_2(1-c)$, $X_2= \sigma_1(1-c) +\sigma_2(1-c)+\sigma_4(1-c)$

similarly

$$P'_3(t) + \rho_1 P_3(t) = \sigma_1(1-c) P_1(t) \qquad (4.6.48)$$

$$P'_4(t) + \rho_2 P_4(t) = \sigma_2(1-c) P_1(t) \qquad (4.6.49)$$

$$P'_5(t) + \rho_1 P_5(t) = \sigma_1(1-c) P_2(t) \qquad (4.6.50)$$

$$P'_6(t) + \rho_2 P_6(t) = \sigma_2(1-c) P_2(t) \qquad (4.4.51)$$

$$P'_7(t) + \rho_4 P_7(t) = \sigma_4(1-c) P_2(t) \qquad (4.4.52)$$

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j = 1 \\ 0, \text{if } j \neq 1 \end{cases}$$

(4.4.53)

The system of differential equations (4.6.46) to (4.6.52) with initial conditions given by Eq. (4.6.53) has been solved by adaptive step-size control Runge-Kutta method. The numerical computations have been carried out by taking that the failure and repair rates of Milling train (σ_3, ρ_3) and its standby unit (σ_4, ρ_4) are same.

The fuzzy-reliability of the Crushing system is computed for one year (i.e. time, *t=30-360* days). The fuzzy-reliability, $R_6(t)$ of the Crushing system is composed of reliability of the system working with full capacity and its standby states i.e.

$$R_6(t) = P_1(t) + \frac{1}{2}P_2(t) \qquad (4.6.54)$$

The Eq. (4.6.54) is used to compute the fuzzy-reliability of the Crushing system.

4.7 PERFORMANCE MODELING FOR THE REFINING SYSTEM OF THE SUGAR PLANT

Performance modeling for the Refining system is carried out by deriving mathematical equations for the development of the decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

4.7.1 Performance modeling for Decision Support System (DSS) of the Refining system

The transition diagram (Fig. 4.25) depicts a simulation model showing all the possible states of the Refining system.

State 1: The system is working with full capacity (with no standby)
State 2: The system is working with standby unit of filter (G1)
State 3: The system is working with standby unit of sulphonation (G3)
State 4: The system is working with standby unit of filter (G3*)

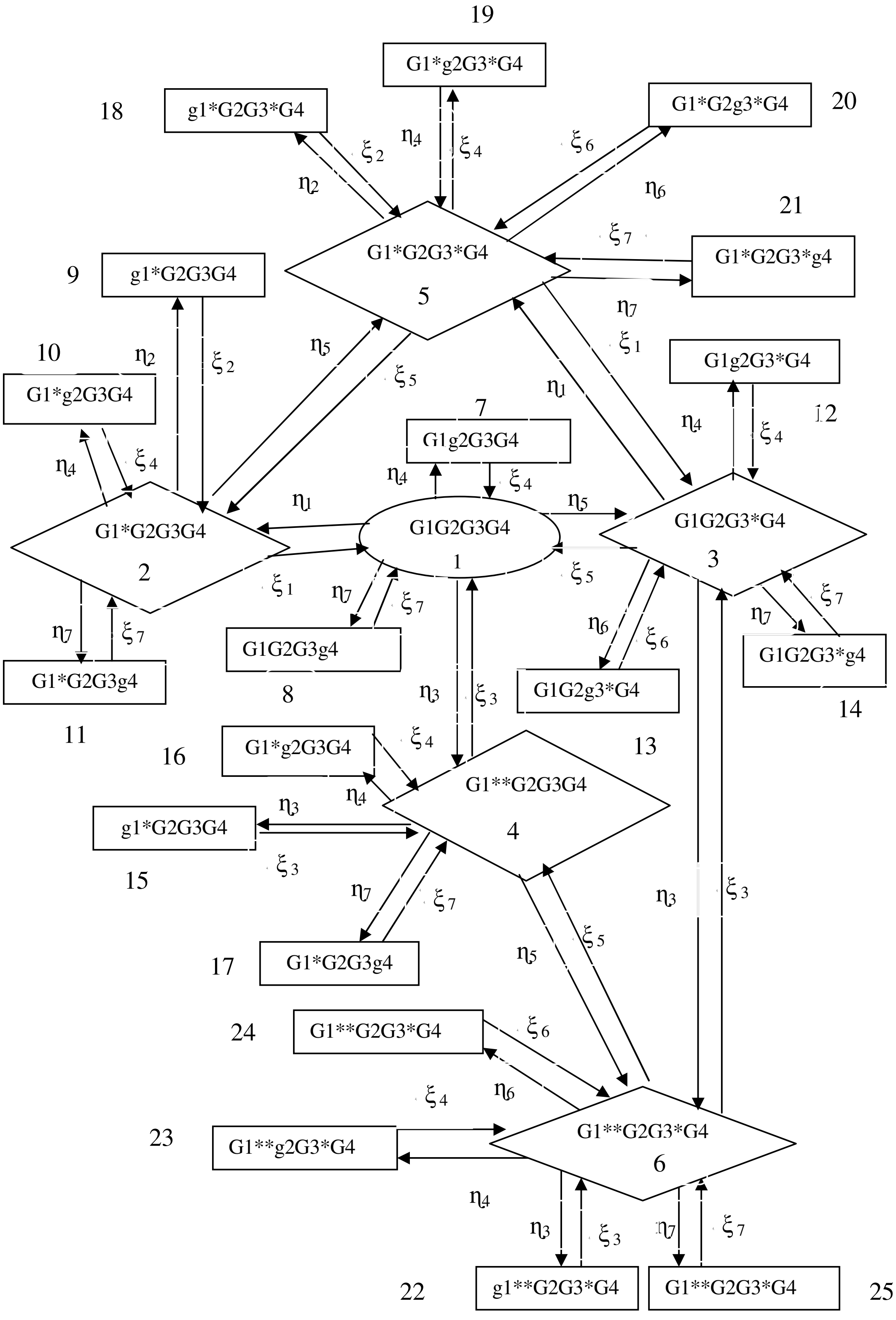


Fig. 4.25 State transition diagram of the Refining system

State 5: The system is working with standby units of Filter (G1*) and Sulphonation (G3*)

State 6: The system is working with standby units of Filter (G1**) and Sulphonation (G3*)

State 7 to 25: Failed states of the system due to complete failure of its subsystems i.e. G1, G2, G3 and G4.

G1, G2, G3 and G4 : Indicates full working states of the subsystems

G1*, G1**, G3 : Indicates that the subsystems A and C are working under cold standby states

g1, g2, g3 and g4 : Indicates the failed states of the subsystems G1, G2, G3 and G4 resp.

η_j= 1, 2, 3…..7 : The constant failures rate of the subsystems G1, G1*, G1**, G2, G3, G3* and G4 resp.

ξ_i=1, 2, 3…..7 : The constant repair rate of the subsystems G1, G1*,G1**, G2, G3, G3* and G4 resp.

P_1 : Probability of the system working with full capacity

P_2, P3…P_6 : Probability of the system working under cold standby states

$P_j(t)$, j=1,2,3,…..25 : Probability that the system is in j^{th} state at time, *t*

The mathematical equations (4.7.1)-(4.7.12) based on Markov birth-death process are developed for each state one by one out of 25 states of transition diagram (Fig. 4.25).

$P'_1(t) = - X_1P_1(t) + \xi_1P_2(t) + \xi_5P_3(t) + \xi_3P_4(t) + \xi_4P_7(t) + \xi_7P_8(t)$ (4.7.1)

$P'_2(t) = - X_2P_2(t) + \eta_1P_1(t) + \xi_5P_5(t) + \xi_2P_9(t) + \xi_4P_{10}(t) + \xi_7P_{11}(t)$ (4.7.2)

$P'_3(t) = - X_3P_3(t) + \eta_5P_1(t) + \xi_1P_5(t) + \xi_3P_6(t) + \xi_4P_{12}(t) + \xi_6P_{13}(t) + \xi_7P_{14}(t)$ (4.7.3)

$P'_4(t) = - X_4P_4(t) + \eta_3P_1(t) + \xi_5P_6(t) + \xi_3P_{15}(t) + \xi_4P_{16}(t) +\xi_7P_{17}(t)$ (4.7.4)

$P'_5(t) = - X_5P_5(t) + \eta_5P_2(t) + \eta_1P_3(t) + \xi_2P_{18}(t) + \xi_4P_{19}(t) + \xi_6P_{20}(t) + \xi_7P_{21}(t)$ (4.7.5)

$P'_6(t) = - X_6P_6(t) + \eta_3P_3(t) + \eta_5P_4(t) + \xi_3P_{22}(t) + \xi_4P_{23}(t) +\xi_6P_{24}(t) +\xi_7P_{25}(t)$ (4.7.6)

where

$X_1= (\eta_1+\eta_5+\eta_3+\eta_4+\eta_7)$, $X_2= (\xi_1+\eta_5+\eta_2 +\eta_4+\eta_7)$, $X_3= (\xi_5+\eta_1+\eta_3+\eta_4+ \eta_6+\eta_7)$,

$X_4= (\xi_3+\eta_5+\eta_3+ \eta_4 +\eta_7)$, $X_5= (\xi_5+ \xi_1+\eta_2+\eta_4+ \eta_6+\eta_7)$, $X_6= (\xi_3+\xi_5+\eta_3+ \eta_4+\eta_6+\eta_7)$

$P'_i(t) + \xi_j P_i(t) = \eta_j P_1(t)$ (4.7.7), where *i*=7, 8 and j=4, 7

$P'_i(t) + \xi_j P_i(t) = \eta_j P_2(t)$ (4.7.8), where *i*=9, 10, 11 and j=2,4, 7

$P'_i(t) + \xi_j P_i(t) = \eta_j P_3(t)$ (4.7.9), where *i*=12, 13, 14 and j=4,6, 7

$P'_i(t) + \xi_j P_i(t) = \eta_j P_4(t)$ (4.7.10), where *i*=15, 16, 17 and j=3, 4, 7

$P'_i(t) + \xi_j P_i(t) = \eta_j P_5(t)$ (4.7.11), where *i*=18, 19, 20, 21 and *j*=2, 4, 6, 7

$P'_i(t) + \xi_j P_i(t) = \eta_j P_6(t)$ (4.7.12), where i=22, 23, 24, 25 and j=3, 4, 6, 7

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j = 1 \\ 0, \text{if } j \neq 1 \end{cases} \quad (4.7.13)$$

The system of differential equations (4.7.1)-(4.7.12) with initial conditions given by Eq. (4.7.13) was solved by Runge-Kutta fourth order method. The numerical computations were carried out by taking that

(i) The failure and repair rates of filter (η_1, ξ_1) and its standby units (η_2, ξ_2) and (η_3, ξ_3) are same.

(ii) The failure and repair rates of sulphonation (η_5, ξ_5) and its standby units (η_6, ξ_6) are same.

The numerical computations were carried out for one year (i.e. time, t=30-360 days) for different choices of failure and repair rates of the subsystems. The reliability, $R_7(t)$ of the Refining system is composed of reliability of the system working with full capacity and its standby states i.e.

$$R_7(t) = R_1(t)+R_2(t)+R_3(t)+R_4(t)+R_5(t)+R_6(t) \quad (4.7.14)$$

The Eq. (4.7.14) is used to compute the reliability of the Refining system.

The management is interested to get the steady state availability of the system. The steady state probabilities of the system are obtained by imposing the following restrictions; d/dt→0, as t→∞ i.e. d/dt→0, as t→∞. The equations (4.7.1)-(4.7.12) get reduced to the following system of Eqs.

$$X_1P_1 = \xi_1P_2 + \xi_5P_3 + \xi_3P_4 + \xi_4P_7 + \xi_7P_8 \quad (4.7.15)$$

$$X_2P_2 = \eta_1P_1 + \xi_5P_5 + \xi_2P_9 + \xi_4P_{10} + \xi_7P_{11} \quad (4.7.16)$$

$$X_3P_3 = \eta_5P_1 + \xi_1P_5 + \xi_3P_6 + \xi_4P_{12} + \xi_6P_{13} + \xi_7P_{14} \quad (4.7.17)$$

$$X_4P_4 = \eta_3P_1 + \xi_5P_6 + \xi_3P_{15} + \xi_4P_{16} + \xi_7P_{17} \quad (4.7.18)$$

$$X_5P_5 = \eta_5P_2 + \eta_1P_3 + \xi_2P_{18} + \xi_4P_{19} + \xi_6P_{20} + \xi_7P_{21} \quad (4.7.19)$$

$$X_6P_6 = \eta_3P_3 + \eta_5P_4 + \xi_3P_{22} + \xi_4P_{23} + \xi_6P_{24} + \xi_7P_{25} \quad (4.7.20)$$

where

$X_1 = (\eta_1+\eta_5+\eta_3+\eta_4+\eta_7)$, $X_2 = (\xi_1+\eta_5+\eta_2+\eta_4+\eta_7)$, $X_3 = (\xi_5+\eta_1+\eta_3+\eta_4+\eta_6+\eta_7)$,

$X_4 = (\xi_3+\eta_5+\eta_3+\eta_4+\eta_7)$, $X_5 = (\xi_5+\xi_1+\eta_2+\eta_4+\eta_6+\eta_7)$, $X_6 = (\xi_3+\xi_5+\eta_3+\eta_4+\eta_6+\eta_7)$

$\xi_j P_i = \eta_j P_1$ (4.7.21), where i=7, 8 and j=4, 7

$\xi_j P_i = \eta_j P_2$ (4.7.22), where i=9, 10, 11 and j=2,4, 7

$\xi_j P_i = \eta_j P_3$ (4.7.23), where i=12, 13, 14 and j=4,6, 7

$\xi_j P_i = \eta_j P_4$ (4.7.24), where i=15, 16, 17 and j=3, 4, 7

$\xi_j P_i = \eta_j P_5$ (4.7.25), where *i*=18, 19, 20, 21 and *j*=2, 4, 6, 7

$\xi_j P_i = \eta_j P_6$ (4.7.26), where *i*=22, 23, 24, 25 and *j*=3, 4, 6, 7

The values of P_1 to P_6 are obtained by solving the Eqs. (4.7.21)- (4.7.26) by recursive method

$$P_2/P_1=(K1K4\eta_1-\eta_1^2\xi_1+K3K5\eta_1+K4K5\eta_1-\eta_1\eta_3\xi_3+\eta_1\eta_5\xi_5)/(K2K3K5+K2K4K5-K2\eta_1\xi_1+K4\eta_1\xi_1-K3\eta_5\xi_5-K4\eta_5\xi_5) \quad (4.7.27)$$

$$P_3/P_1=(\eta_5^2\xi_5^2+K4K5\eta_1\xi_1+K2K5\eta_3\xi_3+K1K4\eta_5\xi_5-K2K5\eta_5\xi_5-\eta_1\eta_5\xi_1\xi_5-\eta_3\eta_5\xi_3\xi_5-K1K2K4K5)/(K3\eta_5\xi_5^2+K4\eta_5\xi_5^2-K2K3K5\xi_5-K2K4K5\xi_5+K2\eta_1\xi_1\xi_5-K4\eta_1\xi_1\xi_5) \quad (4.7.28)$$

$$P_4/P_1=-(K1K2\eta_1\xi_1-\eta_5^2\xi_5^2-\eta_1^2\xi_1^2+K3K5\eta_1\xi_1-K2K5\eta_3\xi_3+K1K3\eta_5\xi_5+K2K5\eta_5\xi_5-\eta_1\eta_3\xi_1\xi_3+2\eta_1\eta_5\xi_1\xi_5+\eta_3{*}\ \eta_5\xi_3\xi_5-K1K2K3K5)/(K2K3K5\xi_3+K2K4K5\xi_3-K2\eta_1\xi_1\xi_3+K4\eta_1\xi_1\xi_3-K3\eta_5\xi_3\xi_5-K4\eta_5\xi_3\xi_5) \quad (4.7.29)$$

$$P_5/P_1=-(K1K2K4\eta_1-K4\eta_1^2\xi_1-K2\eta_1\eta_3\xi_3+K2\eta_1\eta_5\xi_5+K3\eta_1\eta_5\xi_5+K4\eta_1\eta_5\xi_5)/(K3\eta_5\xi_5^2+K4\eta_5\xi_5^2-K2K3K5\xi_5-K2K4K5\xi_5+K2\eta_1\xi_1\xi_5-K4\eta_1\xi_1\xi_5) \quad (4.7.30)$$

$$P_6/P_1=(K1K2K4\eta_1\xi_1-K4\eta_5^2\xi_5^2-K1K2K3K4K5-K4\eta_1^2\xi_1^2+K3K4K5\eta_1\xi_1+K2K3K5\eta_3\xi_3+K1K3K4\eta_5\xi_5+K2K4K5\eta_5\xi_5-K2\eta_1\eta_3\xi_1\xi_3+2K4\eta_1\eta_5\xi_1\xi5-K3\eta_3\eta_5\xi_3\xi_5)/(K3\eta_5\xi_3\xi_5^2+K4\eta_5\xi_3\xi_5^2-K2K3K5\xi_3\xi_5-K2K4K5\ \xi_3\ \xi_5+K2\eta_1\xi_1\xi_3\xi_5-K4\eta_1\xi_1\xi_3\xi_5)\ldots.(4.7.31)$$

where

$K1=\eta_1+\eta_5+\eta_3+\eta_7$, $K2=\xi_1+\eta_5$, $K3=\xi_5+\eta_1+\eta_3$, $K4=\xi_3+\eta_5$, $K5=\xi_5+\xi_1$, $K6=\xi_3+\xi_5$

Under normalized conditions i.e. sum of all the probabilities is equal to one.

$$\therefore \quad \sum_{i=1}^{25} P_i = 1 \text{ i.e. } P_1+P_2+P_3\ldots\ldots\ldots\ldots\ldots\ldots\ldots+P_{25}=1$$

$$P_1\left[1+\frac{P_2}{P_1}+\frac{P_3}{P_1}\ldots\ldots+\frac{P_{25}}{P_1}\right]=1 \quad (4.7.32)$$

The value of P_1 is obtained by putting the values of P_2/P_1, P_3/P_1, P_4/P_1, P_5/P_1, P_6/P_1 from Eqs. (4.7.27)- (4.7.31) resp. in Eq. (4.7.32)

$$P_1=[1+\eta_4/\xi_4+\eta_7/\xi_7+(K1K4\eta_1-\eta_1^2\xi_1+K3K5\eta_1+K4K5\eta_1-\eta_1\eta_3\xi_3+\eta_1\eta_5\xi_5)/(K2K3K5+K2K4K5-K2\eta_1\ \xi_1+K4\eta_1\xi_1-K3\eta_5\xi_5-K4\eta_5\xi_5)$$

$$\begin{aligned}
&(1+\eta_2/\xi_2+\eta_4/\xi_4+\eta_7/\xi_7)+(\eta_5^2\xi_5^2+K4K5\eta_1\xi_1+K2K5\eta_3\xi_3+K1K4\eta_5\xi_5-K2K5\eta_5\xi_5-\\
&\eta_1\eta_5\xi_1\xi_5-\eta_3\eta_5\xi_3\xi_5-K1K2K4K5)/(K3\eta_5\xi_5^2+K4\eta_5\xi_5^2-K2K3K5\xi 5-K2K4K5\xi_5\\
&+K2\eta_1\xi_1\xi_5-K4\eta_1\xi_1\xi_5)(1+\eta_4/\xi_4+\eta_6/\xi_6+\eta_7/\xi_7)-(K1K2\eta_1\xi_1-\eta_5^2\xi_5^2-\eta_1^2\xi_1^2+K3K5\eta_1\xi_1-\\
&K2K5\eta_3\xi_3+K1K3\eta_5\xi_5+K2K5\eta_5\xi_5-\eta 1\eta_3\xi_1\xi_3+2\eta_1\eta_5\xi_1\xi_5+\eta_3\eta_5\xi_3\xi 5-\\
&K1K2K3K5)/(K2K3K5\xi_3+K2K4K5\xi_3-K2\eta_1\xi_1\xi_3+K4\eta_1\xi_1\xi_3-K3\eta_5\xi_3\xi_5-K4\eta_5\xi_3\xi_5)(1+\\
&\eta_3/\xi_3+\eta_4/\xi_4+\eta_7/\xi_7)-(K1K2K4\eta_1-K4\eta_1^2\xi_1-K2\eta_1\eta_3\xi_3+K2\eta_1\eta_5\xi_5+\\
&K3\eta_1\eta_5\xi_5+K4\eta_1\eta_5\xi_5)/(K3\eta_5\xi_5^2+K4\eta_5\xi_5^2-K2K3K5\xi_5-K2K4K5\xi_5+K2\eta_1\xi_1\xi_5-\\
&K4\eta_1\xi_1\xi_5)(1+\eta_2/\xi_2+\eta_4/\xi_4+\eta_6/\xi_6+\eta_7/\xi_7)+(K1K2K4\eta_1\xi_1-K4\eta_5^2\xi_5^2-K1K2K3K4K5-\\
&K4\eta_1^2\xi_1^2+K3K4K5\eta_1\xi_1+K2K3K5\eta_3\xi_3+K1K3K4\eta_5\xi_5+K2K4K5\eta_5\xi_5-K2\eta_1\eta_3\\
&\xi_1\xi_3+2K4\eta_1\eta_5\xi_1\xi_5-K3\eta_3\eta_5\xi_3\xi_5)/(K3\eta_5\xi_3\xi_5^2+K4\eta_5\xi_3\xi_5^2-K2K3K5\xi_3\xi_5-\\
&K2K4K5\xi_3\xi_5+K2\eta_1\xi_1\xi_3\xi_5-K4\eta_1\xi_1\xi_3\xi_5)(1+\eta_3/\xi_3+\eta_4/\xi_4+\eta_6/\xi_6+\eta_7/\xi_7)]^{-1} \qquad (4.7.33)
\end{aligned}$$

The steady state availability, A_{v7} of the Refining system i.e. A_{v7} is summation of its working and standby states i.e.

$$A_{v7}= P_1 + P_2 + P_3 + P_4 + P_5 + P_6 \qquad (4.7.34)$$

The Eq. (4.7.34) gives the steady state availability of the Refining system.

4.7.2 Performance modeling for RAMD analysis of the Refining system

The Refining system is transformed in to four subsystems (S1-S4) as shown in Fig. 4.26. The transition diagrams associated with the subsystems (S1- S4) are shown in Fig. 4.27((a)-(d)). The data regarding failure and repair rates of the subsystems is presented in table 4.7.

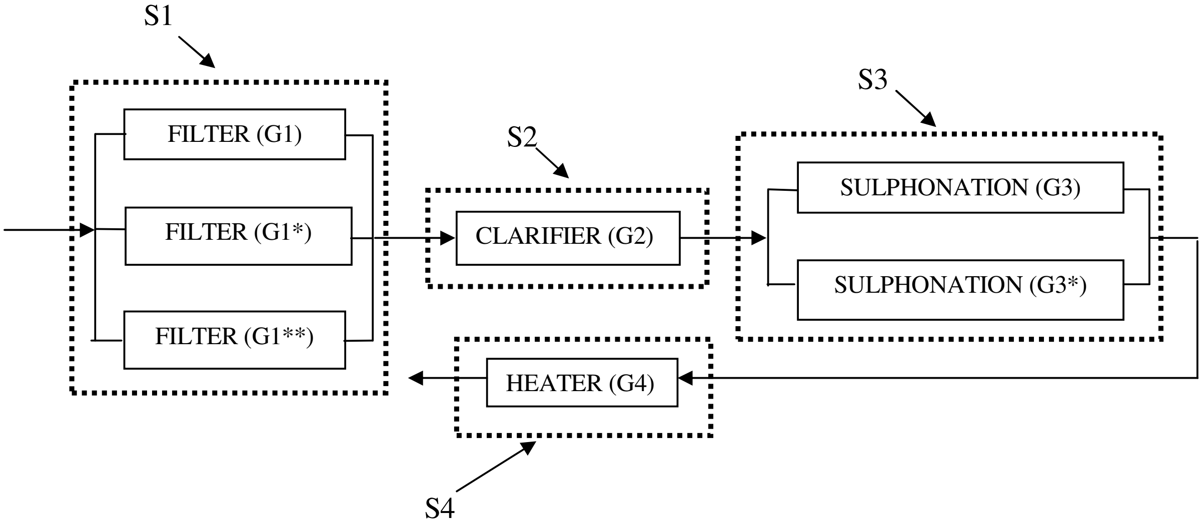


Fig. 4.26 Schematic representation of the subsystems of the Refining system

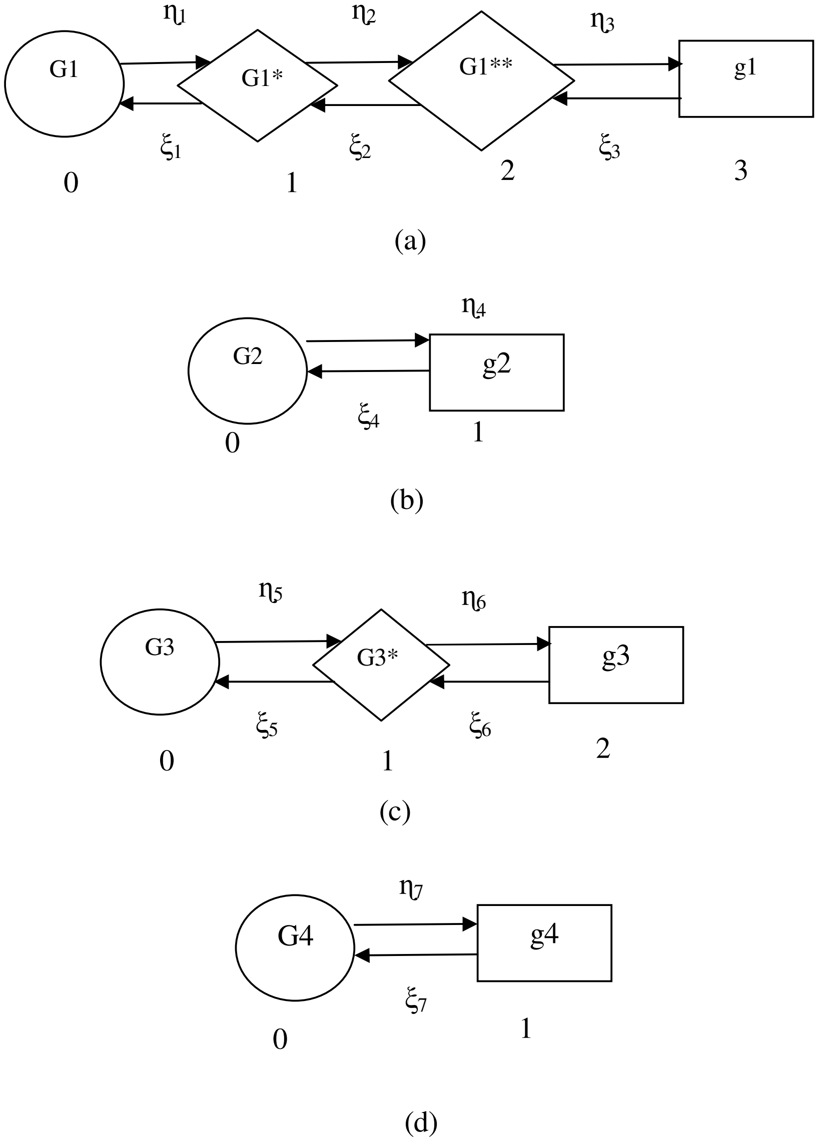


Fig. 4.27 State transition diagram of the subsystems of the Refining system
(a) subsystem S1, (b) subsystem S2, (c) subsystem S3, (d) subsystem S4

RAMD indices for subsystem S1

This subsystem has single unit (G1) only but it is provided with two cold standby units (G2 and G3). Failure of all the three units causes complete failure of this subsystem. The differential equations associated with Fig. 4.27 (a) are

$$P'_o(t) = -\eta_1 P_o(t) + \xi_1 P_1(t) \quad (4.7.35)$$

$$P'_1(t) = -(\xi_1+\eta_2)\, P_1(t) + \eta_1 P_0(t) + \xi_2 P_2(t) \quad (4.7.36)$$

$$P'_2(t) = -(\xi_2+\eta_3)\, P_2(t) + \eta_2 P_1(t) + \xi_3 P_3(t) \quad (4.7.37)$$

$$P'_3(t) = -\xi_3 P_3(t) + \eta_3 P_2(t) \quad (4.7.38)$$

Under steady state conditions, the Eqs. (4.7.35)-o (4.7.38) get reduced as

$\eta_1 P_o = \xi_1 P_1$ (4.7.39)

$(\xi_1+\eta_2)\ P_1 = \eta_1 P_0 + \xi_2 P_2$ (4.7.40)

$(\xi_2+\eta_3)\ P_2 = \eta_2 P_1 + \xi_3 P_3$ (4.7.41)

$\xi_3 P_3 = \eta_3 P_2$ (4.7.42)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.7.43)

Putting the values of P_1 and P_2 by solving the Eqs. (4.7.39)- (4.7.42) in Eq. (4.7.43)

$P_0\,[1+\eta_1/\xi_1 + (\eta_1\eta_2)/(\xi_1\xi_2)] = 1$ (4.7.44)

The availability of the subsystem S1 is given by Eq. (4.7.44)

$R_{S1\ (t)} = e^{-0.018t}$ (4.7.45)

The reliability Eq. for the subsystem S1is given by Eq. (4.7.45)

$M_{S1}\ (t) = 1-e^{-9.551836t}$ (4.7.46)

The maintainability Eq. for the subsystem S1is given Eq. (4.7.46)

The others parameters for the subsystem S1 are computed as

$D_{min.(S1)} = 0.998620$

MTBF= 55.556 hr.

MTTR= 0.1047 hr. and

d =5.3066

RAMD indices for subsystem S2

This subsystem has only one unit (G2) and failure of this unit causes complete failure of the system. The differential equations associated with Fig. 4.27 (b) are

$P'_0(t) = -\eta_4 P_0(t) + \xi_4 P_1(t)$ (4.7.47)

$P'_1(t) = -\ \xi_4 P_1(t) + \eta_4 P_0(t)$ (4.7.48)

Under steady state conditions, the Eqs. (4.7.47) and (4.7.48) get reduced as

$\eta_4 P_0 = \xi_4 P_1$ (4.7.49)

$\xi_4 P_1 = \eta_4 P_{0.}$ (4.7.50)

Now, using the normalizing conditions

$P_0 + P_1 = 1$ (4.7.51)

The Eqs. (4.7.49) and (4.7.50) are solved to get the value of P_0 i.e.

$P_0\,(1+\eta_4/\xi_4) = 1$ (4.7.51)

The availability of the subsystem S2 is given by Eq. (4.7.51)

$R_{S2\ (t)} = e^{-0.0057t}$ (4.7.52)

Reliability Eq. for the subsystem S2 is given by Eq. (4.7.52)

$M_{S2}(t) = 1\text{-}e^{-0.54t}$ (4.7.53)

Maintainability Eq for the subsystem S2 is given by Eq. (4.7.53)

The other parameters for the subsystem S2 are computed as

$D_{min.(S2)} = 0.99237630$

MTBF= 175.4386 hr.

MTTR= 1.852 hr. and

d= 94.7268

RAMD indices for subsystem S3

This subsystem has single unit only but it is provided with one cold standby unit. Failure of both units causes complete failure of this subsystem. The differential equations associated with Fig. 4.27 (c) are

$P'_0(t) = -\eta_5 P_0(t) + \xi_5 P_1(t)$ (4.7.54)

$P'_1(t) = -(\xi_5 + \eta_6) P_1(t) + \eta_5 P_0(t) + \xi_6 P_2(t)$ (4.7.55)

$P'_2(t) = -\xi_6 P_2(t) + \eta_6 P_1(t)$ (4.7.56)

Under steady state conditions, the Eqs. (4.7.54)-(4.7.56) get reduced as

$\eta_5 P_0 = \xi_5 P_1$ (4.7.57)

$(\xi_5 + \eta_6) P_1 = \eta_5 P_0 + \xi_6 P_2$ (4.7.58)

$\xi_6 P_2 = \eta_6 P_1$ (4.7.59)

Now, using the normalizing conditions

$P_0 + P_1 = 1$ (4.7.60)

Now, solving the Eqs. (4.7.57)-(4.7.59) and putting the values of P_1 in Eq. (4.7.60)

$P_0 (1 + \eta_5 / \xi_5 + \eta_6 \eta_5 / \xi_6 \xi_5) = 1$ (4.7.61)

The availability of the subsystem S3 is given by Eq. (4.7.61)

$R_{S3\,(t)} = e^{-0.006t}$ (4.7.62)

Reliability Eq for the subsystem S3 is given by Eq. (4.7.62)

$M_{S3}(t) = 1\text{-}e^{-1.632t}$ (4.7.63)

The maintainability Eq. for the subsystem S3 is given by Eq. (4.7.63)

Similarly, the other parameters for subsystem S3 are

$D_{min.\,(S3)} = 0.99732$

MTBF= 166.667 hr.

MTTR= 0.61274 hr. and

d= 272.

RAMD indices for subsystem S4

This subsystem has only one unit and failure of this unit causes complete failure of the system. The differential equations associated with Fig. 4.27 (d) are

$P'_0(t) = -\eta_7 P_0(t) + \xi_7 P_1(t)$ (4.7.64)

$P'_1(t) = -\xi_7 P_1(t) + \eta_7 P_0(t)$ (4.7.65)

Under steady state conditions, the Eqs. (4.7.64) and (4.7.65) get reduced as

$\eta_7 P_0 = \xi_7 P_1$ (4.7.66)

$\xi_7 P_1 = \eta_7 P_0$ (4.7.67)

Now, using the normalizing conditions

$P_0 + P_1 = 1$ (4.7.68)

The Eqs. (4.7.66) and (4.7.67) are solved to get the value of P_0 i.e.

$P_0 (1 + \eta_7 / \xi_7) = 1$ (4.7.69)

The availability of the subsystem S4 is given by Eq. (4.7.69).

$R_{S4\,(t)} = e^{-0.0086t}$ (4.7.70)

Reliability Eq. for the subsystem S4 is given by Eq. (4.7.70)

$M_{S4}(t) = 1 - e^{-0.051t}$ (4.7.71)

The maintainability Eq. for the subsystem S4 is given by Eq. (4.7.71)

The other parameters for the subsystem S4 are computed as

$D_{min.(S4)} = 0.8827$

MTBF =116.279 hr.

MTTR= 19.6079 hr. and

d= 5.93.

Table 4.7 Failure and repair rates of the subsystems of the Refining system

Subsystem	**Failure Rate (η)**	**Repair Rate (ξ)**
S1	Filter ($\eta_1=\eta_2=\eta_3$)=0.006/hr.	Filter ($\xi_1=\xi_2=\xi_3$)=0.134/hr.
S2	Clarifier (η_4)=0.0057/hr.	Clarifier (ξ_4)=0.54/hr.
S3	Sulphonation ($\eta_5= \eta_6$)=0.003/hr.	Sulphonation ($\xi_5= \xi_6$)=0.048/hr.
S4	Heater (η_7)=0.0086/hr.	Heater (ξ_7)=0.051/hr.

System Reliability

The overall system reliability of Refining system, $R_{sys}(t)$

$R_{sys}(t) = R_{S1}(t) \text{ x } R_{S2}(t) \text{ x } R_{S3}(t) \text{ x } R_{S4}(t)$

$R_{sys}(t) = e^{-0.018t} \text{ x } e^{-0.0057t} \text{ x } e^{-0.006t} \text{ x } e^{-0.0086t} = e^{-0.001946t}$

$R_{sys}(t) = e^{-0.001946t}$

System Availability

The overall system availability of the Refining system (A_{sys}) is computed as

$A_{sys} = A_{S1} \text{ x } A_{S2} \text{ x } A_{S3} \text{ x } A_{S4}$

$A_{sys} = 0.99862 \text{x } 0.99237 \text{x} 0.99732 \text{x } 0.8827 = 0.8724$

System Maintainability

The overall system maintainability of Refining system, $M_{sys}(t)$ is computed as

$M_{sys}(t) = M_{S1}(t) \text{ x } M_{S2}(t) \text{ x } M_{S3}(t) \text{ x } M_{S4}(t)$

$M_{sys}(t) = 1 - e^{-0.0451t}$

System Dependability

The overall system dependability of the Refining system, $D_{\text{min. (sys)}}$ is computed as

$D_{\text{min. (sys)}} = D_{\text{min. (S1)}} \text{ x } D_{\text{min. (S2)}} \text{ x } D \text{ min}_{\text{. (S3)}} \text{ x } D_{\text{min. (S4)}}$

$D_{sys} = 0.99862 \text{x} 0.99237 \text{x} 0.99732 \text{x} 0.8827 \quad = 0.8724$

4.7.3 Performance modeling for the fuzzy-reliability analysis of the Refining system

The mathematical equations (4.7.74) - (4.7.85) are developed based on Markov birth-death process to each state one by one out of 25 states of transition diagram (Fig. 4.28) and the Eqs. for fuzzy-reliability are derived as

$P'_1(t) = - X_1P_1(t) + \xi_1P_2(t) + \xi_5P_3(t) + \xi_3P_4(t) + \xi_4P_7(t) + \xi_7P_8(t)$ (4.7.74)

$P'_2(t) = - X_2P_2(t) + \eta_1cP_1(t) + \xi_5P_5(t) + \xi_2P_9(t) + \xi_4P_{10}(t) + \xi_7P_{11}(t)$ (4.7.75)

$P'_3(t) = - X_3P_3(t) + \eta_5cP_1(t) + \xi_1P_5(t) + \xi_3P_6(t) + \xi_4P_{12}(t) + \xi_6P_{13}(t) + \xi_7P_{14}(t)$ (4.7.76)

$P'_4(t) = - X_4P_4(t) + \eta_3cP_1(t) + \xi_5P_6(t) + \xi_3P_{15}(t) + \xi_4P_{16}(t) + \xi_7P_{17}(t)$ (4.7.77)

$P'_5(t) = - X_5P_5(t) + \eta_5cP_2(t) + \eta_1c\,P_3(t) + \xi_2P_{18}(t) + \xi_4P_{19}(t) + \xi_6P_{20}(t) + \xi_7P_{21}(t)$ (4.7.78)

$P'_6(t) = - X_6P_6(t) + \eta_3cP_3(t) + \eta_5cP_4(t) + \xi_3P_{22}(t) + \xi_4P_{23}(t) + \xi_6P_{24}(t) + \xi_7P_{25}(t)$ (4.7.79)

where

$X_1 = \eta_1c + \eta_5c + \eta_3c + \eta_4(1-c) + \eta_7(1-c)$, $X_2 = \xi_1 + \eta_5c + \eta_2(1-c) + \eta_4(1-c) + \eta_7(1-c)$,

$X_3 = \xi_5 + \eta_1c + \eta_3c + \eta_4(1-c) + \eta_6(1-c) + \eta_7(1-c)$, $X_4 = \xi_3 + \eta_5c + \eta_3(1-c) + \eta_4(1-c) + \eta_7(1-c)$,

$X_5 = \xi_5 + \xi_1 + \eta_2(1-c) + \eta_4(1-c) + \eta_6(1-c) + \eta_7(1-c)$,

$X_6 = \xi_3 + \xi_5 + \eta_3(1-c) + \eta_4(1-c) + \eta_6(1-c) + \eta_7(1-c)$

$P'_i(t) + \xi_j P_i(t) = \eta_j(1-c)\, P_1(t)$ (4.7.80), where i=7, 8 and j=4, 7

$P'_i(t) + \xi_j P_i(t) = \eta_j(1-c)\, P_2(t)$ (4.7.81), where i=9, 10, 11 and j=2,4, 7

$P'_i(t) + \xi_j P_i(t) = \eta_j(1-c)\, P_3(t)$ (4.7.82), where i=12, 13, 14 and j=4,6, 7

$P'_i(t) + \xi_j P_i(t) = \eta_j(1-c)\, P_4(t)$ (4.7.83), where i=15, 16, 17 and j=3, 4, 7

$P'_i(t) + \xi_j P_i(t) = \eta_j(1-c)\, P_5(t)$ (4.7.84), where i=18, 19, 20, 21 and j=2, 4, 6, 7

$P'_i(t) + \xi_j P_i(t) = \eta_j(1-c)\, P_6(t)$ (4.7.85), where i=22, 23, 24, 25 and j=3, 4, 6, 7

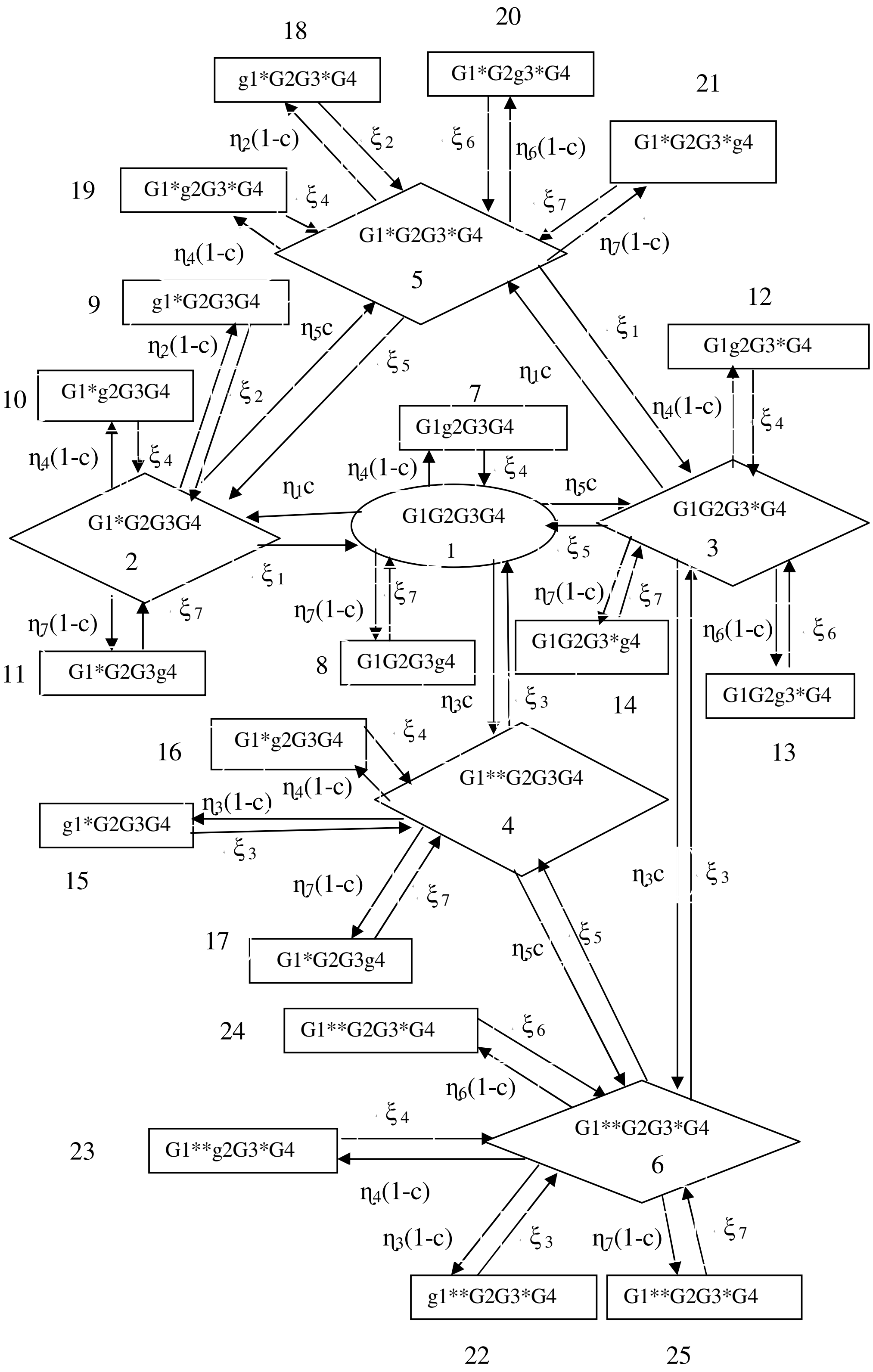


Fig. 4.28 State transition diagram of the Refining system with imperfect fault coverage

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j = 1 \\ 0, \text{if } j \neq 1 \end{cases} \tag{4.7.86}$$

The system of differential equations (4.7.74) - (4.7.85) with initial conditions given by Eq. (4.7.86) was solved by adaptive step-size control Runge-Kutta method. The numerical computations have been carried out by taking that

(i) The failure and repair rates of filter (η_1, ξ_1) and its standby units (η_2, ξ_2) and (η_3, ξ_3) are same.

(ii) The failure and repair rates of sulphonation (η_5, ξ_5) and its standby units (η_6, ξ_6) are same.

The fuzzy-reliability of the Refining system was computed for one year (i.e. time, *t*=30-360 days) for different choices of failure rates of the subsystems. The fuzzy reliability, $R_{F6}(t)$ of the system is composed of the sum of reliability full capacity and its standby states of the system.

$$R_{F6}(t) = P_1(t)+\frac{3}{4}P_2(t) +\frac{3}{4}P_3(t) +\frac{3}{4}P_4(t) +\frac{1}{2}P_5(t) +\frac{1}{2}P_6(t) \tag{4.7.87}$$

The Eq. (4.7.87) is used to compute the fuzzy reliability of the Refining system.

4.8 PERFORMANCE MODELING FOR THE EVAPORATION SYSTEM OF THE SUGAR PLANT

Performance modeling for the Evaporation system is carried out by deriving mathematical equations for the development of the decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

4.8.1 Performance modeling for Decision Support Systems (DSS) of the Evaporation system

The transition diagram (Fig. 4.29) depicts a simulation model showing all the possible states of the Evaporation system. Fig. 4.29) depicts a simulation model showing all the possible states of the evaporator system.

State 1: The system is working with full capacity (with no standby)

State 2: The system is working with standby unit of Evaporator unit (H1*)

State 3: The system is working with standby unit of Vacuum pan unit (H3*)

State 4: The system is working with standby units of Evaporator unit (H1*) and Vacuum pan unit (H3*)

State 5 to 12: Failed states of the system due to complete failure of its subsystems i.e. H1, H1*, H2, H3 and H3*.

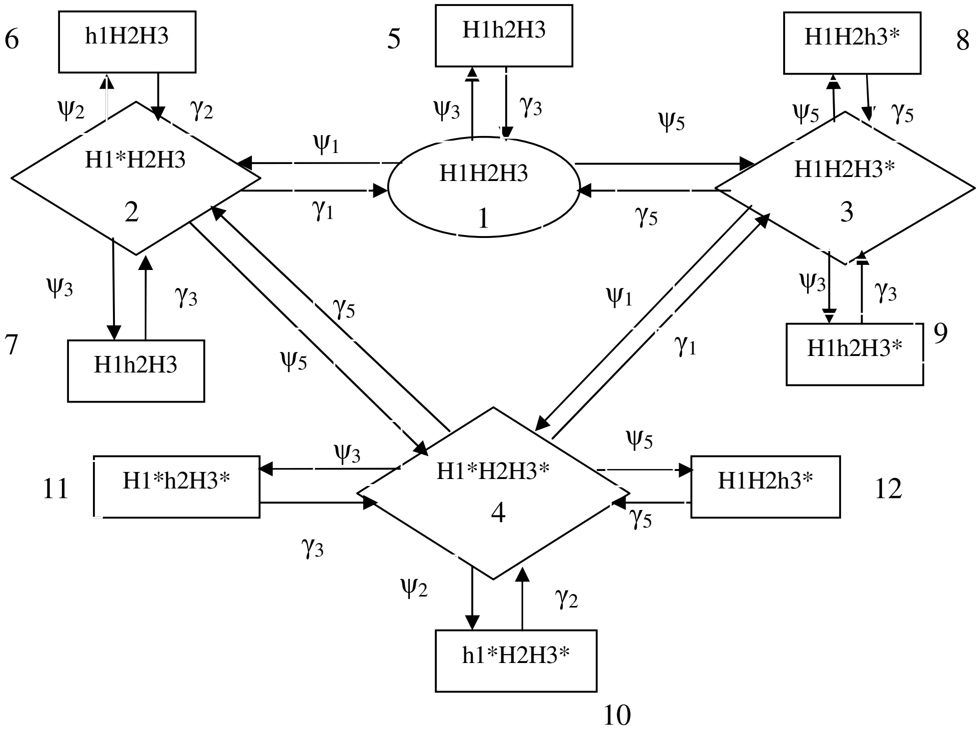


Fig. 4.29 State transition diagram of the Evaporation system

H1, H2 and H3: Indicates full working states of the subsystems.

H1* and H3*: Indicates the subsystems H1 and H3 are working under cold standby state

h1, h2 and h3: Indicates the failed states of the subsystems H1, H2 and H3 resp.

ψ_i= 1,2,3,4 and 5: The constant failures rate of the subsystems H1, H1*, H2, H3 and H3* resp.

γ_i=1, 2,3,4 and 5: The constant repair rate of the subsystems H1, H1*, H2, H3 and H3* resp.

P_1, P_2, P_3 and P_4: Availability of the system under states 1, 2, 3 and 4 resp.

P_j (t), j=1, 2, 3… 12: The probability that the system is in j^{th} state at time, *t*

The mathematical equations (4.8.1)-(4.8.12) based on Markov birth-death processes are developed for each state one by one out of 12 states of transition diagram (Fig. 4.29).

$P'_1(t) = - X_1P_1(t) + \gamma_1P_2(t) + \gamma_3P_5(t) + \gamma_5P_3(t)$ (4.8.1)

$P'_2(t) = - X_2P_2(t) + \psi_1P_1(t) + \gamma_2P_6(t) + \gamma_3P_7(t) + \gamma_5P_4(t)$ (4.8.2)

$P'_3(t) = - X_3P_3(t) + \psi_5P_1(t) + \gamma_5P_8(t) + \gamma_3P_9(t) + \gamma_1P_4(t)$ (4.8.3)

$P'_4(t) = - X_4P_4(t) + \psi_5P_2(t) + \psi_1P_3(t) + \gamma_2P_{10}(t) + \gamma_3P_{11}(t) +\gamma_5P_{12}(t)$ (4.8.4)

where

$X_1= (\psi_1+\psi_3+\psi_5)$, $X_2= (\gamma_1+\psi_2 +\psi_3+\psi_5)$, $X_3= (\gamma_5+\psi_1+\psi_3+\psi_5)$, $X_4= (\gamma_5+ \gamma_1+\psi_2+ \psi_3 +\psi_5)$

$P'_5(t) + \gamma_3 P_5(t) = \psi_3 P_1(t)$ (4.8.5)

$P'_i(t) + \gamma_j P_i(t) = \psi_j P_2(t)$ (4.8.6), where *i*= 6, 7 and *j*= 2, 3

$P'_i(t) + \gamma_j P_8(t) = \psi_j P_3(t)$ (4.8.7), where *i*= 8, 9 and *j*= 5, 3

$P'_i(t) + \gamma_j P_i(t) = \psi_j P_4(t)$ (4.8.8), where *i*=10, 11, 12 and *j*= 2, 3, 5

with initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j=1 \\ 0, \text{if } j \neq 1 \end{cases} \qquad (4.8.9)$$

The system of differential equations (4.8.1)-(4.8.8) with initial conditions given by Eq. (4.8.9) was solved by adaptive step-size control Runge-Kutta method. The numerical computations have been carried out by taking that

(i)The failure and repair rates of evaporator unit (ψ_1, γ_1) and its standby unit (ψ_2, γ_2) are same.

(ii)The failure and repair rates of Vacuum pan unit (ψ_4, γ_4) and its standby unit (ψ_5, γ_5) are same.

The numerical computations were carried out for one year (i.e. time, *t*=30-360 days) for different choices of failure and repair rates of the subsystems. The reliability, $R_8(t)$ of the evaporator system is composed of reliability of the system working with full capacity and its standby states i.e.

$R_8(t) = R_1(t)+R_2(t)+R_3(t)+R_4(t)$ (4.8.10)

The Eq. (4.8.10) is used to compute the reliability of the evaporator system.

The steady state probabilities of the system are obtained by imposing the following restrictions; d/dt→0, as t→∞. The equations (4.8.11)-(4.8.26) get reduced to the following system of Eqs.

$X_1P_1 = \gamma_1P_2 +\gamma_3P_5+\gamma_5P_3$ (4.8.11)

$X_2P_2 = \psi_1P_1+\gamma_2P_6+\gamma_3P_7+\gamma_5P_4$ (4.8.12)

$X_3P_3 = \psi_5P_1+\gamma_5P_8+\gamma_3P_9+\gamma_1P_4$ (4.8.13)

$X_4P_4 = \psi_5P_2+ \psi_1P_3+\gamma_2P_{10}+\gamma_3P_{11}+\gamma_5P_{12}$ (4.8.14)

where

$X_1= (\psi_1+\psi_3+\psi_5)$, $X_2= (\gamma_1+\psi_2 +\psi_3+\psi_5)$, $X_3= (\gamma_5+\psi_1+\psi_3+\psi_5)$, $X_4= (\gamma_5+ \gamma_1+\psi_2+ \psi_3 +\psi_5)$

$\gamma_3 P_5 = \psi_3P_1$ (4.8.15)

$\gamma_2 P_6 = \psi_2 P_2$ (4.8.16), where i= 6, 7 and j= 2, 3

$\gamma_5 P_8 = \psi_5 P_3$ (4.8.17), where i= 8, 9 and j= 5, 3

$\gamma_2 P_{10} = \psi_2 P_4$ (4.8.18), where i=10, 11, 12 and j= 2, 3, 5

Under normalized conditions i.e. sum of all the probabilities is equal to one.

$\therefore \quad \sum_{i=1}^{12} P_i = 1$ i.e. $P_1+P_2+P_3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots + P_{12}=1$

$$P_1\left[1+\frac{P_2}{P_1}+\frac{P_3}{P_1}+\frac{P_4}{P_1}+\ldots\ldots\ldots+\frac{P_{12}}{P_1}\right]=1 \tag{4.8.19}$$

$$P_1 = [(1+\frac{1}{L}+\frac{1}{N}+\frac{1}{M}) + \frac{\beta_3}{\alpha_3} + \frac{1}{L}(\frac{\beta_2}{\alpha_2}+\frac{\beta_3}{\alpha_3}) + \frac{1}{N}(\frac{\beta_5}{\alpha_5}+\frac{\beta_3}{\alpha_3}) + \frac{1}{M}(\frac{\beta_2}{\alpha_2}+\frac{\beta_3}{\alpha_3}+\frac{\beta_5}{\alpha_5})]^{-1} \tag{4.8.20}$$

$P_2= P_1/L$, $P_3= P_1/N$, $P_4= P_1/M$

The Eq. (4.8.20) is used to calculate steady state availability of Evaporation system.

where, $L=k2/(\psi_1+A.B)$, $M=F.G$, $N=\gamma_5.D/E$

where, $A=(\gamma_5.k2.k3)(k1.k2-\psi_1.\gamma_1)/(\gamma_1.\gamma_5.(k2+k3))$, $B=1-(\psi_5.\gamma_5)/(k3.(k1.k2-\psi_1.\gamma_1))$

$D=(k3/k2)-1$, $E=(k1.k2-\psi_1.\gamma_1)+(\psi_5.\gamma_5)/k2$, $N=\gamma_5.D/E$

$F=\gamma_1.\gamma_5.(k2+k3)/(k2.k3.(k1.k2-\psi_1.\gamma_1))$, $G=k3((k1.k2-\psi_1.\gamma_1)-\psi_5.\gamma_5)/(k3.(k1.k2-\psi_1.\gamma_1))$,

$M=F.G$: where, $k1=\psi_1+\psi_5$, $k2=\gamma_1+\psi_5$, $k3=\psi_1+\gamma_5$, $k4=\gamma_1+\gamma_5$

$$A_{v8}= P_1+ P_2+ P_3+ P_4 \tag{4.8.21}$$

The Eq. (4.8.21) gives the steady state availability of the Evaporation system

4.8.2 Performance modeling for RAMD analysis of the Evaporation system

The Evaporation system is transformed in to four subsystems (S1-S3) as shown in Fig. 4.30. The transition diagrams associated with the subsystems (S1- S3) are shown in Fig. 4.31((a)-(c)). The data regarding failure and repair rates of the subsystems is presented in table 4.8.

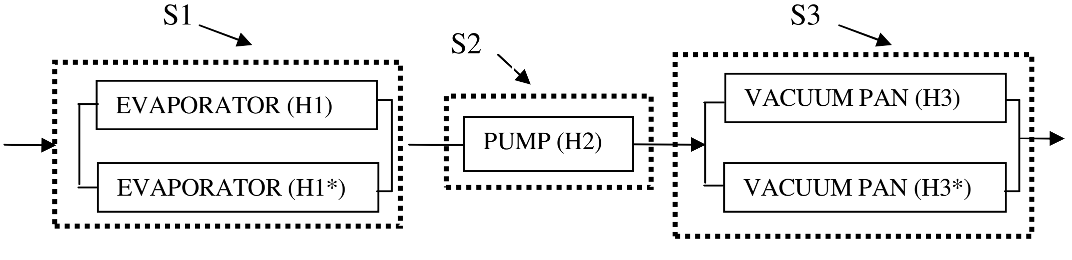


Fig. 4.30 Schematic representation of the Evaporation system

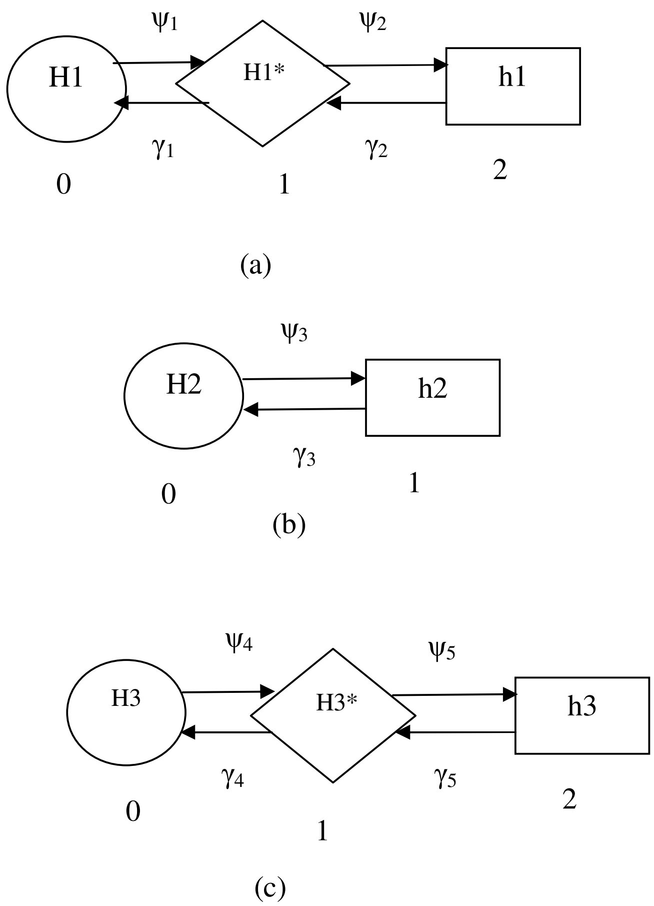


Fig. 4.31 State transition diagram of subsystems of the Evaporation system
(a) subsystem S1, (b) subsystem S2, (c) subsystem S3

RAMD indices for subsystem S1

This subsystem has single unit (H1) only but it has its cold standby unit (H1*). Failure of both units causes complete failure of the system. The differential equations associated with Fig. 4.31 (a) are

$P'_0(t) = - \psi_1 P_0(t) + \gamma_1 P_1(t)$ (4.8.22)

$P'_1(t) = - (\gamma_1 + \psi_2)P_1(t) + \psi_1 P_0(t) + \gamma_2 P_2(t)$ (4.8.23)

$P'_2(t) = - \gamma_2 P_2(t) + \psi_2 P_1(t)$ (4.8.24)

Under steady state conditions, the Eqs. (4.8.22)- (4.8.24) get reduced as

$(\gamma_1 + \psi_2)P_1 = \psi_1 P_0 + \gamma_2 P_2$ (4.8.25)

$\gamma_2 P_2 = \psi_2 P_1$ (4.8.26)

$\gamma_1 P_1 = \psi_1 P_0$ (4.8.27)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.8.28)

Put the values of P_1 and P_2 by solving Eqs. (4.8.25) to (4.8.26) in eqn. (4.8.27)

$P_0\,(1+\psi_1/\gamma_1+\psi_2\,\psi_1/\gamma_2\gamma_1)=1$ (4.8.29)

The availability of the subsystem S1 is given by Eq. (4.8.29)

$R_{S1}\,(t)=e^{-0.0034t}$ (4.8.30)

Reliability Eq. for the subsystem S1 is given by Eq. (4.8.30)

$M_{S1}\,(t)=1\text{-}e^{-0.61342t}$ (4.8.31)

Maintainability Eq. for the subsystem S1 is given by Eq. (4.8.31)

The others parameters for the subsystem S1 are computed as:

$D_{min.\,(S1)}=0.9960$

MTBF= 294.1176 hr.

MTTR= 1.6302 hr. and

d= 180.4152

RAMD indices for subsystem S2

This subsystem has single unit (H2) only and failure of this unit causes complete failure of the system. The differential equations associated with the Fig. 4.31 (b) are

$P'_o(t)=-\psi_3P_o(t)+\gamma_3P_1(t)$ (4.8.32)

$P'_1(t)=-\gamma_3P_1(t)+\psi_3P_0(t)$ (4.8.33)

Under steady state conditions, the Eqs. (4.8.32) to (4.8.33) get reduced as

$\psi_3P_o=\gamma_3P_1$ (4.8.34)

$\gamma_3P_1=\psi_3P_0$ (4.8.35)

Now, using the normalizing conditions

$P_0+P_1=1$ (4.8.36)

The Eqs. (4.8.34) and (4.8.35) are solved to get the values of P_0 i.e.

$P_0\,(1+\psi_3/\gamma_3]=1$ (4.8.37)

The availability of the subsystem S2 is given by Eq. (4.8.37)

$R_{S2\,(t)}=e^{-0.0082t}$ (4.8.38)

The reliability Eq. for the subsystem S2 is given by Eq. (4.8.38)

$M_{S2}\,(t)=1\text{-}e^{-0.014t}$ (4.8.39)

The maintainability Eq. for the subsystem S2 is given by Eq. (4.8.39)

The others parameters for the subsystem S1 are computed as

$D_{min.(S2)}=0.4043$

MTBF= 121.9512hr.

MTTR= 71.4286.5 hr. and

d =1.7073.

RAMD indices for subsystem S3

This subsystem has single unit (H3) only but it has its cold standby unit (H3*). Failure of both units causes complete failure of the system. The differential equations associated with Fig. 4.31 (c) are

$P'_0(t) = -\psi_4 P_0(t) + \gamma_4 P_1(t)$ (4.8.40)

$P'_1(t) = -(\gamma_4 + \psi_5)P_1(t) + \psi_4 P_0(t) + \gamma_5 P_2(t)$ (4.8.41)

$P'_2(t) = -\gamma_5 P_2(t) + \psi_5 P_1(t)$ (4.8.42)

Under steady state conditions, the Eqs. (4.8.40)- (4.8.42) get reduced as

$(\gamma_4 + \psi_5)P_1 = \psi_4 P_0 + \gamma_5 P_2$ (4.8.43)

$\gamma_5 P_2 = \psi_5 P_1$ (4.8.44)

$\gamma_4 P_1 = \psi_4 P_0$ (4.8.45)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.8.46)

Put the values of P_1 and P_2 by solving Eqs. (4.8.43) to (4.8.44) in eqn. (4.8.45)

$P_0 (1 + \psi_4 / \gamma_4 + \psi_5 \psi_4 / \gamma_5 \gamma_4) = 1$ (4.8.47)

The availability of the subsystem S3 is given by Eq. (4.8.47)

$R_{S3}(t) = e^{-0.0064t}$ (4.8.48)

Reliability Eq. for the subsystem S3 is given by Eq. (4.8.48)

$M_{S3}(t) = 1 - e^{-0.3335t}$ (4.8.49)

The maintainability Eq. for the subsystem S3 is given by Eq. (4.8.49)

The others parameters for the subsystem S1 are computed as:

$D_{min. (S3)} = 0.9944$

MTBF= 156.25 hr.

MTTR= 1.196 hr. and

d= 130.5664.

Table 4.8 Failure and repair rates of the subsystems of the evaporator system

Subsystem	**Failure Rate (ψ)**	**Repair Rate (γ)**
S1	Evaporator (ψ_1)=0.0017/hr.	Evaporator (γ_1)=0.0017/hr.
S2	Pump (ψ_3)=0.0082/hr.	Pump (γ_3)=0.014/hr.
S3	Vacuum pan (ψ_4)=0.0032/hr.	Vacuum pan (γ_4)=0.35/hr.

System Reliability

The overall system reliability of Evaporation system, $R_{sys}(t)$

$R_{sys}(t) = R_{S1}(t) \times R_{S2}(t) \times R_{S3}(t)$

$R_{sys}(t) = e^{-0.0034t} \times e^{-0.0082t} \times e^{-0.0064t} = e^{-0.018t}$

$R_{sys}(t) = e^{-0.018t}$

System Availability

The overall system availability of the Evaporation system (A_{sys}) is computed as

$A_{sys} = A_{S1} \times A_{S2} \times A_{S3}$

$A_{sys} = 0.9945 \times 0.6306 \times 0.9924 = 0.6224$

System Maintainability

The overall system maintainability of Evaporation system, $M_{sys}(t)$ is computed as

$M_{sys}(t) = M_{S1}(t) \times M_{S2}(t) \times M_{S3}(t)$

$M_{sys}(t) = 1 - e^{-0.01347t}$

System Dependability

The overall system dependability of the Evaporation system, $D_{min.\,(sys)}$ is computed as

$D_{min.\,(sys)} = D_{min.\,(S1)} \times D_{min.\,(S2)} \times D_{min.\,(S3)}$

$D_{sys} = 0.9960 \times 0.4043 \times 0.9944 = 0.400$

4.8.3 Performance modeling for the fuzzy-reliability analysis of the Evaporation system

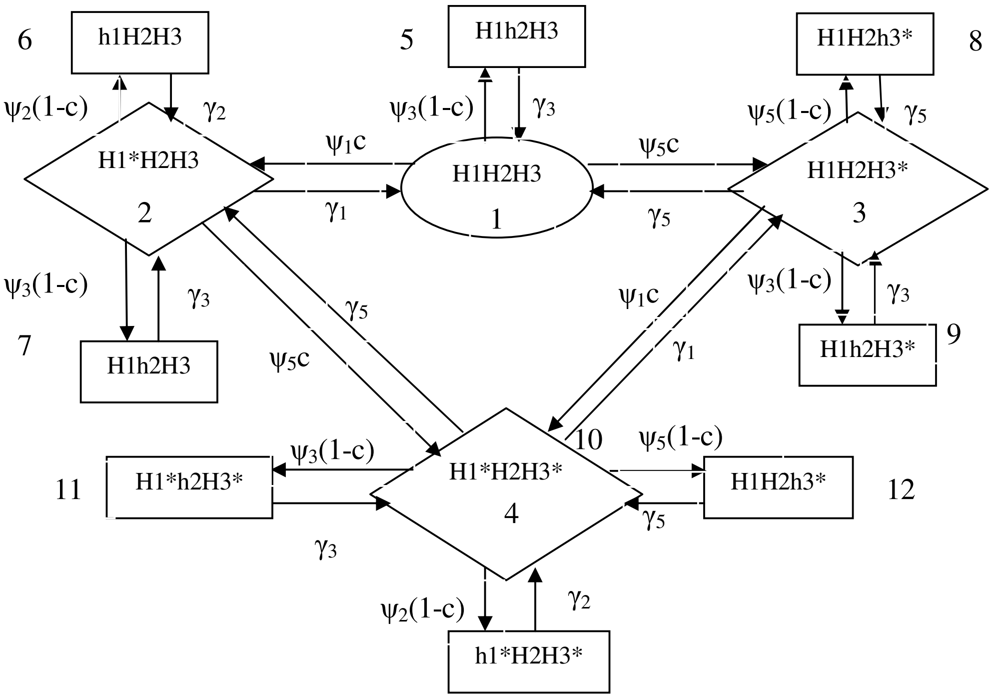


Fig. 4.32 State transition diagram of the Evaporation system with imperfect fault coverage

The mathematical equations (4.8.50) to (4.8.71) based on Markov birth-death process were derived to each state one by one out of 12 states of transition diagram (Fig. 4.32).

$$P'_1(t) = -X_1P_1(t) + \gamma_1P_2(t) + \gamma_3P_5(t) + \gamma_5P_3(t) \tag{4.8.51}$$

$$P'_2(t) = -X_2P_2(t) + \psi_1cP_1(t) + \gamma_2P_6(t) + \gamma_3P_7(t) + \gamma_5P_4(t) \tag{4.8.52}$$

$$P'_3(t) = -X_3P_3(t) + \psi_5cP_1(t) + \gamma_5P_8(t) + \gamma_3P_9(t) + \gamma_1P_4(t) \tag{4.8.53}$$

$$P'_4(t) = -X_4P_4(t) + \psi_5cP_2(t) + \psi_1cP_3(t) + \gamma_2P_{10}(t) + \gamma_3P_{11}(t) + \gamma_5P_{12}(t) \tag{4.8.54}$$

where

$X_1 = \psi_1c+\psi_3(1-c)+\psi_5c$, $X_2 = \gamma_1+\psi_2(1-c)+\psi_3(1-c)+\psi_5c$,

$X_3 = \gamma_5+\psi_1c+\psi_3(1-c)+\psi_5(1-c)$, $X_4 = \gamma_5+\gamma_1+\psi_2(1-c)+\psi_3(1-c)+\psi_5(1-c)$

$$P'_5(t) + \gamma_3 P_5(t) = \psi_3(1-c) P_1(t) \tag{4.8.55}$$

$P'_6(t) + \gamma_2 P_6(t) = \psi_2(1-c) P_2(t)$ (4.8.56), where *i*= 6, 7 and *j*= 2, 3

$P'_8(t) + \gamma_5 P_8(t) = \psi_5(1-c) P_3(t)$ (4.8.57), where *i*= 8, 9 and *j*= 5, 3

$P'_{10}(t) + \gamma_2 P_{10}(t) = \psi_2(1-c) P_4(t)$ (4.8.58), where *i*=10, 11, 12 and *j*= 2, 3, 5

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j = 1 \\ 0, \text{if } j \neq 1 \end{cases}$$

(4.8.59)

The system of differential equations (4.8.51) to (4.8.58) with initial conditions given by Eq. (4.8.59) was solved by adaptive step-size control Runge-Kutta method. The numerical computations have been carried out by taking that

(i) The failure and repair rates of Evaporator subsystem (ψ_1, γ_1) and its standby unit (ψ_2, γ_2) are same.

(ii) The failure and repair rates of Vacuum pan subsystem (ψ_4, γ_4) and its standby unit (ψ_5, γ_5) are same.

The fuzzy-reliability of the Evaporation system was computed for one year (i.e. time, *t*=30-360 days) for different choices of failure rates of the subsystems. The fuzzy-reliability, $R_{F8}(t)$ of the Evaporation system is composed of reliability of the system working with full capacity and its standby states i.e.

$$R_{F8}(t) = R_1(t) + \frac{1}{2}R_2(t) + \frac{1}{2}R_3(t) + \frac{1}{4}R_4(t) \tag{4.8.60}$$

The Eq. (4.8.60) is used to compute the fuzzy-reliability of the Evaporation system

4.9 PERFORMANCE MODELING FOR THE CRYSTALLIZATION SYSTEM OF THE SUGAR PLANT

Performance modeling for the Crystallization system is carried out by deriving mathematical equations for the development of the decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

4.9.1 Performance modeling for Decision Support Systems (DSS) for the Crystallization system

The transition diagram (Fig. 4.33) depicts a simulation model showing all the possible states of the Crystallization system.

State 1: The system is working with full capacity (with no standby)

State 2: The system is working with standby unit of Crystallization (J1*)

State 3: The system is working with standby unit of Centrifugal pump (J2*)

State 4: The system is working with standby unit of Crystallization and Centrifugal pump (J1* and J2*)

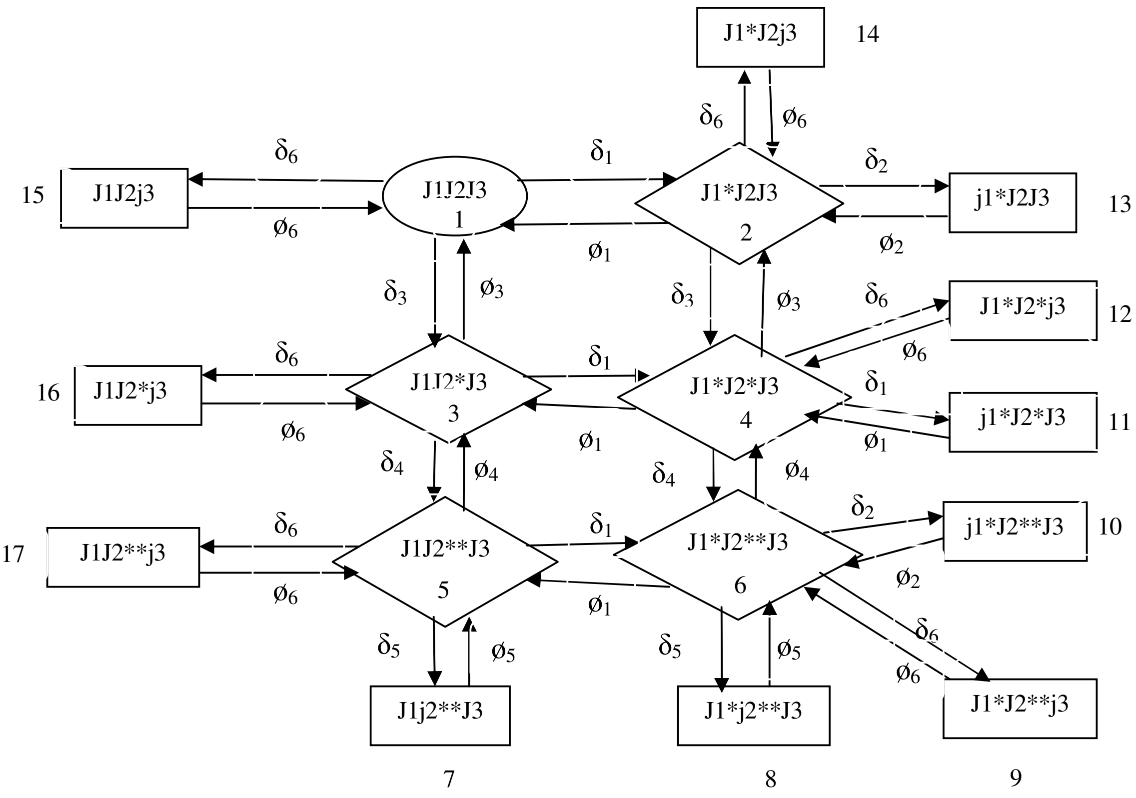


Fig. 4.33 State transition diagram of the Crystallization system

State 5: The system is working with standby unit of Centrifugal pump (J2**)

State 6: The system is working with standby units of Crystallization (J1*) and Centrifugal pump (J2*)

State 7 to 17: Failed states of the system due to complete failure of its subsystems i.e. J1, J2 and J3

J1, J2 and J3: Indicates full working states of the subsystems.

J1*, J2* and J2**: Indicates that the subsystems J1, J2 and J3 are working under cold standby states.

j1, j2 and j3 : Indicates the failed states of the subsystems J1, J2 and J3 resp.

δ_i= 1,2,3…..6 : The constant failures rate of the subsystems J1, J1*,J2, J2*, J2** and J3 resp.

$ø_i$=1, 2,3…..6 : The constant repair rate of the subsystems J1, J1*,J2, J2*, J2** and J3 resp.

P_1, P_2, P_3, P_4, P_5 and P_6: Fuzzy availability of the system under states 1, 2, 3, 4, 5 and 6 resp.

P_j (t), j=1, 2, 3… 17 : The probability that the system is in j^{th} state at time, *t*

The mathematical equations (4.9.1)-(4.9.17) are developed to each state one by one out of 17 states of transition diagram (Fig. 4.33)

$P'_1(t) = - X_1P_1(t) + ø_1P_2(t) + ø_3P_3(t) + ø_6P_{15}(t)$ (4.9.1)

$P'_2(t) = - X_2P_2(t) + \delta_1P_1(t) + ø_2P_{13}(t) +ø_3P_4(t) +ø_6P_{14}(t)$ (4.9.2)

$P'_3(t) = - X_3P_3(t) + ø_1P_4(t) + \delta_3P_1(t)+ ø_4P_5(t) + ø_6P_{16}(t)$ (4.9.3)

$P'_4(t) = - X_4P_4(t) + \delta_1P_3(t) + ø_1P_{11}(t) + \delta_3P_2(t) +ø_4P_6(t)+ø_6P_{12}(t)$ (4.9.4)

$P'_5(t) = - X_5P_5(t) + ø_1P_6(t) + \delta_4 cP_3(t) + ø_5P_7(t) + ø_6P_{17}(t)$ (4.9.5)

$P'_6(t) = - X_6P_6(t) + \delta_1P_5(t) + ø_1P_{10}(t) + \delta_4P_4(t) +ø_5P_8(t) +ø_6P_9(t)$ (4.9.6)

where

$X_1= \delta_1+\delta_3+\delta_6$, $X_2=ø_1+\delta_2+\delta_3 +\delta_6$, $X_3=\delta_1+ ø_3+\delta +\delta_6$,

$X_4= ø_1+\delta_1+ ø_3+\delta_4+ \delta_6$, $X_5= \delta_1+ ø_4+\delta_5+\delta_6$,$X_6= ø_1+\delta_2+ ø_4+\delta +\delta_6$

$P'_7 (t) + ø_5P_7 (t) = \delta_5P_5 (t)$ (4.9.7)

$P'_i (t) + ø_jP_i (t) = \delta_jP_6 (t)$ (4.9.8), where *i*=8, 9, 10 and *j*=5, 6, 1

$P'_i (t) + ø_jP_i (t) = \delta_j P_4 (t)$ (4.9.9), where *i*=11, 12 and *j*=1, 6

$P'_i (t) + ø_jP_i (t) = \delta_jP_2 (t)$ (4.9.10), where *i*=13, 14 and *j*=2, 6

$P'_{15} (t) + ø_6P_{15} (t) = \delta_6 P_1 (t)$ (4.9.11)

$P'_{16} (t) + ø_6P_{16} (t) = \delta_6P_3 (t)$ (4.9.12)

$P'_{17} (t) + ø_6P_{17} (t) = \delta_6P_5 (t)$ (4.9.13)

With initial conditions

$$P_j(0)=\begin{cases}1,\text{if } j=1\\ 0,\text{if } j\neq 1\end{cases}$$

(4.9.14)

The system of differential equations (4.9.1)-(4.9.13) with initial conditions given by Eq. (4.9.14) was solved by the Runge-Kutta fourth order method. The numerical computations have been carried out by taking that

(i) The failure and repair rates of Crystallization subsystem (δ_1, $\emptyset_1$) and its standby unit (δ_2, $\emptyset_2$) are same.

(ii) The failure and repair rates of Centrifugal Pump subsystem (δ_3, $\emptyset_3$) and its standby units (δ_4, $\emptyset_4$ and δ_5, $\emptyset_5$) are same.

The numerical computations were carried out for one year (i.e. time, *t*=30-360 days) for different choices of failure and repair rates of the subsystems. The reliability of the system, $R_9(t)$ is composed of reliability of the system working with full capacity and its standby states i.e.

$$R_9(t)=P_1(t)+P_2(t)+P_3(t)+P_4(t)+P_5(t)+P_6(t) \qquad (4.9.15)$$

The reliability of the Crystallization system is computed by Eq. (4.9.15)

The management is interested to get the steady state availability of the system. The steady state probabilities of the system are obtained by imposing the following restrictions; $d/dt\rightarrow 0$, as $t\rightarrow\infty$.

$$P'_1 = -X_1P_1 + \emptyset_1P_2 + \emptyset_3P_3 + \emptyset_6P_{15} \qquad (4.9.16)$$

$$P'_2 = -X_2P_2 + \delta_1P_1 + \emptyset_2P_{13} + \emptyset_3P_4 + \emptyset_6P_{14} \qquad (4.9.17)$$

$$P'_3 = -X_3P_3 + \emptyset_1P_4 + \delta_3P_1 + \emptyset_4P_5 + \emptyset_6P_{16} \qquad (4.9.18)$$

$$P'_4 = -X_4P_4 + \delta_1P_3 + \emptyset_1P_{11} + \delta_3P_2 + \emptyset_4P_6 + \emptyset_6P_{12} \qquad (4.9.19)$$

$$P'_5 = -X_5P_5 + \emptyset_1P_6 + \delta_4 cP_3 + \emptyset_5P_7 + \emptyset_6P_{17} \qquad (4.9.20)$$

$$P'_6 = -X_6P_6 + \delta_1P_5 + \emptyset_1P_{10} + \delta_4P_4 + \emptyset_5P_8 + \emptyset_6P_9 \qquad (4.9.21)$$

where

$X_1= \delta_1+\delta_3+\delta_6$, $X_2=\emptyset_1+\delta_2+\delta_3+\delta_6$, $X_3=\delta_1+\emptyset_3+\delta_4+\delta_6$,

$X_4= \emptyset_1+\delta_1+\emptyset_3+\delta_4+\delta_6$, $X_5= \delta_1+\emptyset_4+\delta_5+\delta_6$, $X_6= \emptyset_1+\delta_2+\emptyset_4+\delta_5+\delta_6$

$$P'_7 + \emptyset_5P_7 = \delta_5P_5 \qquad (4.9.22)$$

$P'_8 + \emptyset_5P_8 = \delta_5P_6$ (4.9.23), where *i*=8, 9, 10 and *j*=5, 6, 1

$P'_{11} + \emptyset_1P_{11} = \delta_1 P_4$ (4.9.24), where *i*=11, 12 and *j*=1,6

$P'_{13} + \emptyset_2P_{13} = \delta_2P_2$ (4.9.25), where *i*=13, 14 and *j*=2, 6

$$P'_{15} + \emptyset_6P_{15} = \delta_6 P_1 \qquad (4.9.26)$$

$$P'_{16} + \phi_6 P_{16} = \delta_6 P_3 \tag{4.9.27}$$

$$P'_{17} + \phi_6 P_{17} = \delta_6 P_5 \tag{4.9.28}$$

$P_2/P_1= (K1K4\delta_1-\delta_1^2\phi_1+K3K5\delta_1+K4K5\delta_1-\delta_1\delta_3\phi_3+\delta_1\delta_5\phi_5)/(K2K3K5+K2K4K5-$
$K2\delta_1\phi_1+K4\delta_1\phi_1- K3\delta_5\phi_5-K4\delta_5\phi_5)$

$P_3/P_1= (\delta_5^2\phi_5^2 +K4K5\delta_1\phi_1+K2K5\delta_3\phi_3 +K1K4\delta_5\phi_5 -K2K5\delta_5\phi_5-\delta_1\delta_5\phi_1\phi_5-\delta_3\delta_5\phi_3\phi_5-$
$K1K2K4K5)/(K3\delta_5\phi_5^2+K4\delta_5\phi_5^2-K2K3K5\phi_5 -K2K4K5\phi_5+K2\delta_1\phi_1\phi_5-K4\delta_1\phi_1\phi_5)$

$P_4/P_1=-(K1K2\delta_1\phi_1 -\delta_5^2\phi_5^2-\delta_1^2\phi_1^2+K3K5\delta_1\phi_1-K2K5\delta_3\phi_3+K1K3\delta_5\phi_5+K2K5\delta_5\phi_5-\delta_1\delta_3\phi_1\phi_3$
$+2\delta_1\delta_5\phi_1\phi_5+ \delta_3\delta_5\phi_3\phi_5-K1K2K3K5)/(K2K3K5\phi_3+K2K4K5\phi_3-K2\delta_1\phi_1\phi_3 +K4\delta_1\phi_1\phi_3-$
$K3\delta_5\phi_3\phi_5-K4\delta_5\phi_3\phi_5)$

$P_5/P_1=-(K1K2K4\delta_1 -K4\delta_1^2\phi_1-K2\delta_1\delta_3\phi_3+K2\delta_1\delta_5\phi_5+K3\delta_1\delta_5\phi_5+K4\delta_1\delta_5\phi_5)/$
$(K3\delta_5\phi_5^2+K4\delta_5\phi_5^2-K2K3K5\phi_5 - K2K4K5\phi_5+K2\delta_1\phi_1\phi_5 -K4\delta_1\phi_1\phi_5)$

$P_6/P_1= (K1K2K4\delta_1\phi_1 -K4\delta_5^2\phi_5^2-K1K2K3K4K5 -K4\delta_1^2\phi_1^2 +K3K4K5\delta_1\phi_1+K2K3K5\delta_3\phi_3$
$+K1K3K4\delta_5\phi_5 + K2K4K5\delta_5\phi_5-K2\delta_1\delta_3\phi_1\phi_3+2K4\delta_1\delta_5\phi_1\phi_5-K3\delta_3\delta_5\phi_3\phi_5)/$
$(K3\delta_5\phi_3\phi_5^2+K4\delta_5\phi_3\phi_5^2-K2K3K5\phi_3\phi_5 -K2K4K5\phi_3\phi_5+K2\delta_1\phi_1\phi_3\phi_5 -K4\delta_1\phi_1\phi_3\phi_5)$

$P_1=[(1+\delta_4/\phi_4+\delta_7/\phi_7+(K1K4\delta_1-\delta_1^2\phi_1 +K3K5\delta_1+K4K5\delta_1-\delta_1\delta_3\phi_3$
$+\delta_1\delta_5\phi_5)/(K2K3K5+K2K4K5 - K2\delta_1\phi_1+K4\delta_1\phi_1-K3\delta_5\phi_5-$
$K4\delta_5\phi_5)(1+\delta_2/\phi_2+\delta_4/\phi_4+\delta_7/\phi_7)+(\delta_5^2\phi_5^2 +K4K5\delta_1\phi_1+K2K5\delta_3\phi_3+ K1K4\delta_5\phi_5 -K2K5\delta_5\phi_5$
$-\delta_1\delta_5\phi_1\phi_5-\delta_3\delta_5\phi_3\phi_5-K1K2K4K5)/(K3\delta_5\phi_5^2+K4\delta_5\phi_5^2-K2K3K5\phi_5-$
$K2K4K5\phi_5+K2\delta_1\phi_1\phi_5-K4\delta_1\phi_1\phi_5)(1+\delta_4/\phi_4+\delta_6/\phi_6+\delta_7/\phi_7)-(K1K2\delta_1\phi_1-\delta_5^2\phi_5^2 -$
$\delta_1^2\phi_1^2+K3K5\delta_1\phi_1 - K2K5\delta_3\phi_3+K1K3\delta_5\phi_5+K2K5\delta_5\phi_5 -\delta_1\delta_3\phi_1\phi_3+2\delta_1\delta_5\phi_1\phi_5+\delta_3\delta_5\phi_3\phi_5-$
$K1K2K3K5)/(K2K3K5\phi_3+ K2K4K5\phi_3 -K2\delta_1\phi_1\phi_3+K4\delta_1\phi_1\phi_3-K3\delta_5\phi_3\phi_5-$
$K4\delta_5\phi_3\phi_5)(1+\delta_3/\phi_3+\delta_4/\phi_4+\delta_7/\phi_7)-(K1K2K4\delta_1 - K4\delta_1^2\phi_1-K2\delta_1\delta_3\phi_3+K2\delta_1\delta_5\phi_5$
$+K3\delta_1\delta_5\phi_5+K4\delta_1\delta_5\phi_5)/(K3\delta_5\phi_5^2+K4\delta_5\phi_5^2-K2K3K5\phi_5- K2K4K5\phi_5+K2\delta_1\phi_1\phi_5 -$
$K4\delta_1\phi_1\phi_5)(1+\delta_2/\phi_2+\delta_4/\phi_4+\delta_6/\phi_6+\delta_7/\phi_7) +(K1K2K4\delta_1\phi_1-K4\delta_5^2\phi_5^2 -K1K2K3K4K5-$
$K4\delta_1^2\phi_1^2+K3K4K5\delta_1\phi_1+ K2K3K5\delta_3\phi_3+K1K3K4\delta_5\phi_5+K2K4K5\delta_5\phi_5 -$
$K2\delta_1\delta_3\phi_1\phi_3+2K4\delta_1\delta_5\phi_1\phi_5-K3\delta_3\delta_5\phi_3\phi_5)/(K3\delta_5\phi_3\phi_5^2+K4\delta_5\phi_3\phi_5^2 -K2K3K5\phi_3\phi_5 -$
$K2K4K5\phi_3\phi_5 + K2\delta_1\phi_1\phi_3\phi_5-K4\delta_1\phi_1\phi_3\phi_5)(1+\delta_3/\phi_3+\delta_4/\phi_4+\delta_6/\phi_6+\delta_7/\phi_7)]^{-1}$

where

$K1=\delta_1+\delta_3+\delta_6$, $K2=\phi_1+\delta_2+\delta_3+\delta_6$, $K3=\delta_1+\phi_3+\delta_4+\delta_6$,
$K4=\phi_1+\delta_1+\phi_3+\delta_4+\delta_6$, $K5=\delta_1+\phi_4+\delta_5+\delta_6$

$$A_{v9} = P_1+P_2+P_3+P_4+P_5+P_6 \tag{4.9.29}$$

The Eq. (4.9.29) gives the steady state availability of the Crystallization system

4.9.2 Performance modeling for RAMD analysis of the Crystallization system

The Crystallization system is transformed in to three subsystems (S1-S3) as shown in Fig. 4.34. The transition diagrams associated with subsystems (S1-S3) are shown in Fig. 4.35((a)-(c)). The data regarding failure and repair rates of the subsystems is presented in table 4.9.

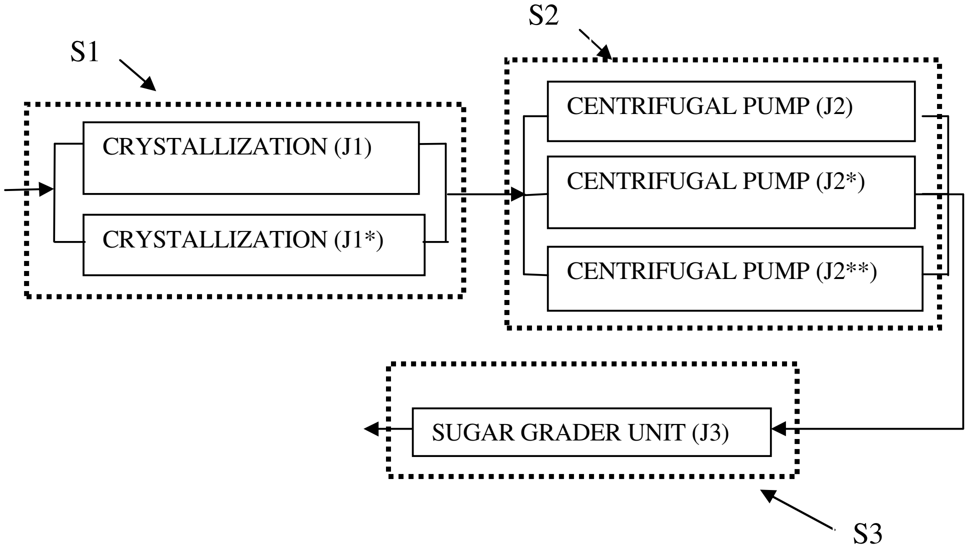


Fig. 4.34 Schematic representation of the subsystems of the Crystallization system

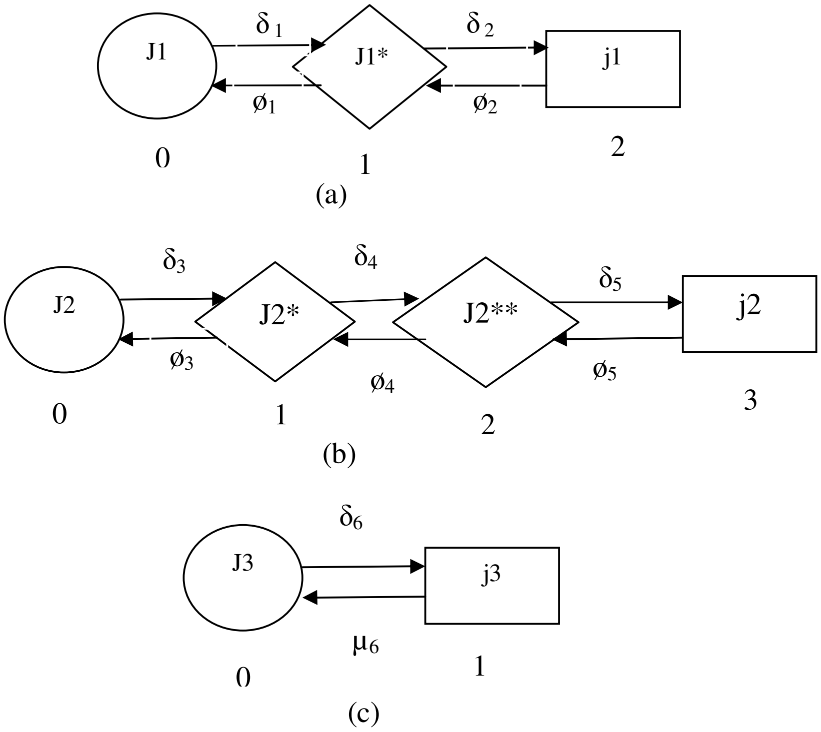


Fig. 4.35 State transition diagram of the subsystems of the Crystallization system

(a) subsystem S1, (b) subsystem S2, (c) subsystem S3

RAMD indices for subsystem S1

This subsystem S1 consists of two units J1 and J1* are connected in series. Failure of unit J1 or J1* causes complete failure of the system. The differential equations associated with the Fig. 4.35 (a) are

$P'_o(t) = -(\delta_1 + \delta_2)P_o(t) + \phi_1 P_1(t) + \phi_2 P_2(t)$ (4.9.30)

$P'_1(t) = -\phi_1 P_1(t) + \delta_1 P_0(t)$ (4.9.31)

$P'_2(t) = -\phi_2 P_2(t) + \delta_2 P_0(t)$ (4.9.32)

Under steady state conditions, the Eqs. (4.9.30)- (4.9.32) get reduced as:

$(\delta_1 + \delta_2)P_o = \phi_1 P_1 + \phi_2 P_2$ (4.9.33)

$\phi_1 P_1 = \delta_1 P_0$ (4.9.34)

$\phi_2 P_2 = \delta_2 P_0$ (4.9.35)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 = 1$ (4.9.36)

Putting the values of P_1 and P_2 from Eqs. (4.9.33) and (4.9.34) in Eq. (4.9.36)

$P_0 (1 + \delta_1 / \phi_1 + \delta_2 / \phi_2) = 1$ (4.9.37)

The availability of the subsystem S1 is given by Eq. (4.9.37)

$R_{S1\ (t)} = e^{-0.0024t}$ (4.9.38)

The reliability Eq. for the subsystem S1 is given by Eq. (4.9.38)

$M_{S1}\ (t) = 1 - e^{-0.9276t}$ (4.9.39)

The maintainability Eq. for the subsystem S1 is given by Eq. (4.9.39)

The others parameters for the subsystem S1 are computed as:

$D_{min.(S1)} = 0.9981$

MTBF= 416.6667 hr.

MTTR= 1.0780 hr. and

d= 386.5278.

RAMD indices for subsystem S2

This subsystem has single unit (J2) only but it has its cold standby unit (J2* and J2**). Failure of both units of J2 causes complete failure of the system. The differential equations associated with Fig. 4.35 (b) are

$P'_0(t) = -\delta_3 P_0(t) + \phi_3 P_1(t)$ (4.9.40)

$P'_1(t) = -(\phi_3 + \delta_4)P_1(t) + \delta_3 P_0(t) + \phi_4 P_2(t)$ (4.9.41)

$P'_2(t) = -\phi_4 P_2(t) + \delta_4 P_1(t)$ (4.9.42)

Under steady state conditions, the Eqs. (4.9.40)- (4.9.42) get reduced as

$(\phi_3 + \delta_4)P_1 = \delta_3 P_0 + \phi_4 P_2$ (4.9.43)

$ø_4P_2= δ_4P_1$ (4.9.44)

$ø_3P_1= δ_3P_0$ (4.9.45)

Now, using the normalizing conditions

$P_0 + P_1 + P_2 =1$ (4.9.46)

Put the values of P_1 and P_2 by solving Eqs. (4.9.43) to (4.9.44) in eqn. (4.9.46)

$P_0 (1+ δ_3 / ø_3 + δ_4 δ_3 / ø_4ø_3) =1$ (4.9.47)

The availability of the subsystem S2 is given by Eq. (4.9.47)

$R_{S2} (t) = e^{-0.0075t}$ (4.9.48)

Reliability Eq. for the subsystem S2 is given by Eq. (4.9.48)

$M_{S2} (t) = 1-e^{-2.12t}$ (4.9.49)

The maintainability Eq. for the subsystem S2 is given by Eq. (4.9.49)

The other parameters for the subsystem S2 are computed as:

$D_{min. (S2)}$= 0.9974

MTBF= 133.3333 hr.

MTTR= 0.4716 hr. and

d= 282.7124

RAMD indices for subsystem S3

This subsystem has single unit (J3) only and failure of this unit causes complete failure of the system. The differential equations associated with Fig. 4.35 (c) are:

$P'_o(t) = -δ_5P_o(t) + ø_5P_1(t)$ (4.9.50)

$P'_1(t) = -ø_5P_1(t) + δ_5P_0(t)$ (4.9.51)

Under steady state conditions, the Eqs. (4.9.50) to (4.9.51) get reduced as:

$Δ_5P_o = ø_5P_1$ (4.9.52)

$ø_5P_1= δ_5P_0$ (4.9.53)

Now, using the normalizing conditions

$P_0 + P_1 =1$ (4.9.54)

The Eqs. (4.9.52) and (4.9.53) are solved to get the values of P_0 i.e.

$P_0 (1+δ_5 /ø_5] =1$ (4.9.55)

The availability of the subsystem S3 is given by Eq. (4.9.55)

$R_{S3\ (t)} = e^{-0.008t}$ (4.9.56)

The reliability Eq. for the subsystem S3 is given by using Eq. (4.9.56)

$M_{S3} (t) = 1-e^{-0.014t}$ (4.9.57)

The maintainability Eq. for the subsystem S3 is given by using Eq. (4.9.57)

The other parameters for the subsystem S2 are computed as:

$D_{min.(S3)} = 0.4335$

MTBF= 125hr.

MTTR= 71.4286 hr. and

d =1.75

Table 4.9 Failure and repair rates of the subsystems of the Crystallization system

Subsystem	**Failure Rate (δ)**	**Repair Rate (ø)**
S1	Crystallization (δ_1)=0.0012/hr.	Crystallization ($ø_1$)=0.023/hr.
S2	Centrifugal pump (δ_3)=0.0025/hr.	Centrifugal pump ($ø_3$)=0.042/hr.
S3	Sugar grader unit (δ_6)=0.008/hr.	Sugar grader unit ($ø_6$)=0.014/hr.

System Reliability

The overall system reliability of Crystallization system, $R_{sys}(t)$

$R_{sys}(t) = R_{S1}(t) \times R_{S2}(t) \times R_{S3}(t)$

$R_{sys}(t) = e^{-0.0024t} \times e^{-0.0075t} \times e^{-0.008t} = e^{-0.00148t}$

$R_{sys}(t) = e^{-0.00148t}$

System Availability

The overall system availability of the Crystallization system (A_{sys}) is computed as

$A_{sys} = A_{S1} \times A_{S2} \times A_{S3}$

$A_{sys} = 0.9974 \times 0.9965 \times 0.6364 = 0.6993$

System Maintainability

The overall system maintainability of Crystallization system, $M_{sys}(t)$ is computed as

$M_{sys}(t) = M_{S1}(t) \times M_{S2}(t) \times M_{S3}(t)$

$M_{sys}(t) = 1-e^{-0.0137t}$

System Dependability

The overall system dependability of the Crystallization system, $D_{min.(sys)}$ is computed as:

$D_{min.(sys)} = D_{min.(S1)} \times D_{min.(S2)} \times D_{min.(S3)}$

$D_{sys}=0.9981 \times 0.9974 \times 0.4335 = 0.43155$

4.9.3 Performance modeling for the fuzzy-reliability analysis of the Crystallization system

State 1: The system is working with full capacity (with no standby).

State 2: The system is working with standby unit of Crystallization (J1*).

State 3: The system is working with standby unit of Centrifugal pump (J2*).

State 4: The system is working with standby unit of Crystallization and Centrifugal pump (J1* and J2*).

State 5: The system is working with standby unit of Centrifugal pump (J2**).

State 6: The system is working with standby units of Crystallization (J1*) and Centrifugal pump (J2**).

State 7 to 17: Failed states of the system due to complete failure of its sub-systems i.e. J1, J2 and J3.

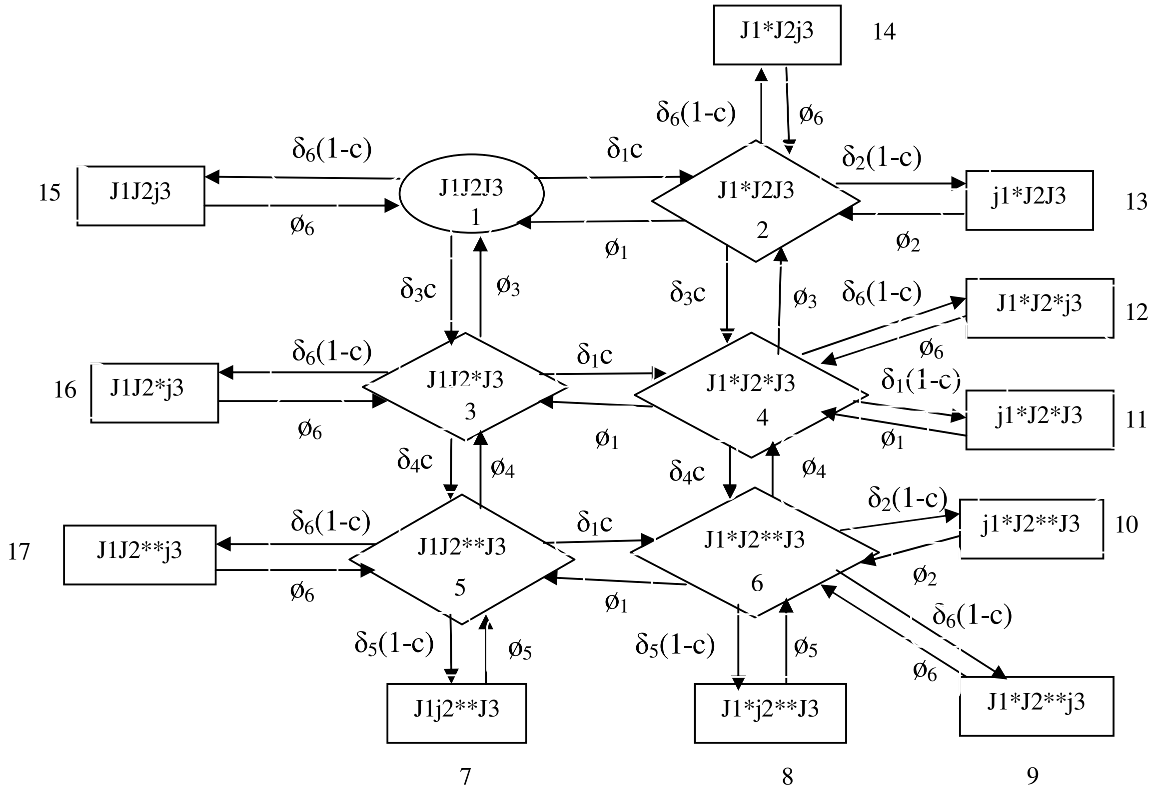


Fig. 4.36 State transition diagram of the Crystallization system with imperfect fault coverage

The mathematical equations (4.9.58) to (4.9.74) are developed to each state one by one out of 17 states of transition diagram (Fig. 4.36).

$$P'_1(t) = - X_1P_1(t) + ø_1P_2(t) + ø_3P_3(t) + ø_6P_{15}(t) \qquad (4.9.58)$$

$$P'_2(t) = - X_2P_2(t) + ø_1\,cP_1(t) + ø_2P_{13}(t) +ø_3P_4(t) +ø_6P_{14}(t) \qquad (4.9.59)$$

$$P'_3(t) = - X_3P_3(t) + ø_1P_4(t) + ø_3\,cP_1(t)+ ø_4P_5(t) + ø_6P_{16}(t) \qquad (4.9.60)$$

$$P'_4(t) = - X_4P_4(t) + ø_1\,cP_3(t) + ø_1P_{11}(t) + ø_3\,cP_2(t) +ø_4P_6(t)+ø_6P_{12}(t) \qquad (4.9.61)$$

$$P'_5(t) = - X_5P_5(t) + ø_1P_6(t) + ø_4\,cP_3(t) + ø_5P_7(t) + ø_6P_{17}(t) \qquad (4.9.62)$$

$$P'_6(t) = - X_6P_6(t) + ø_1\,cP_5(t) + ø_1P_{10}(t)+ ø_4\,cP_4(t) +ø_5P_8(t) +ø_6P_9(t). \qquad (4.9.63)$$

where ; $X_1= ø_1c+ø_3c+ø_6(1-c)$, $X_2=ø_1+ø_2(1-c)+ø_3c +ø_6(1-c)$, $X_3=ø_1c+ ø_3+ø_4c+ø_6(1-c)$,
$X_4= ø_1+ø_1(1-c)+ ø_3+ø_4c+ ø_6(1-c)$, $X_5= ø_1c+ ø_4+ø_5(1-c)+ø_6(1-c)$,
$X_6= ø_1+ø_2(1-c)+ ø_4+ø_5(1-c)+ø_6(1-c)$

$$P'_7 (t) + ø_5P_7 (t) = ø_5 (1-c)P_5 (t) \qquad (4.9.64)$$

$P'_i (t) + ø_jP_j (t) = ø_j (1-c)P_6 (t)$ (4.9.65), where i=8,9,10 and j=5,6,1

$P'_i (t) + ø_jP_i (t) = ø_j(1-c) P_4 (t)$ (4.9.66), where i=11,12 and j=1,6

$P'_i (t) + ø_iP_j (t) = ø_j (1-c)P_2 (t)$ (4.9.67), where i=13,14 and j=2,6

$$P'_{15} (t) + ø_6P_{15} (t) = ø_6 (1-c) P_1 (t) \qquad (4.9.68)$$

$$P'_{16} (t) + ø_6P_{16} (t) = ø_6 (1-c)P_3 (t). \qquad (4.9.69)$$

$$P'_{17} (t) + ø_6P_{17} (t) = ø_6 (1-c)P_5 (t) \qquad (4.9.70)$$

With initial conditions

$$P_j(0) = \begin{cases} 1, \text{if } j = 1 \\ 0, \text{if } j \neq 1 \end{cases} \qquad (4.9.71)$$

The system of differential equations (4.9.64)-(4.9.76) with initial conditions given by Eq. (4.9.77) was solved with Runge-Kutta fourth order method. The numerical computations were carried out by taking that

(i) The failure and repair rates of Crystallization subsystem ($ø_1$, $ø_1$) and its standby unit ($ø_2$, $ø_2$) are same.

(ii) The failure and repair rates of Centrifugal Pump subsystem ($ø_3$, $ø_3$) and its standby units ($ø_4$, $ø_4$ and $ø_5$, $ø_5$) are same.

The fuzzy-reliability of the Crystallization system was computed for one year (i.e. time, *t*=30-360 days) for different choices of failure rates of the subsystems. The fuzzy availability of the system, $R_{F9}(t)$ is composed of fuzzy-reliability of the system working with full capacity and its standby states i.e.

$$R_{F9}(t) = P_1(t)+\frac{1}{2}P_2(t) +\frac{1}{2}P_3(t) +\frac{1}{4}P_4(t) +\frac{1}{2}P_5(t) +\frac{1}{4}P_6(t) \qquad (4.9.72)$$

The fuzzy-reliability of the Crystallization system is computed by the Eq. (4.9.72)

CHAPTER 5: PERFORMANCE OPTIMIZATION

5.1 INTRODUCTION

Genetic algorithm is considered to be potential search and an optimization technique for complex engineering optimization problems. The performance optimization i.e. determination of optimal availability of the dairy plant (Skim milk powder production, Butter oil production, Steam generation and Refrigeration system) and sugar plant (Feeding system, Crushing system, Refining system, Evaporation system and Crystallization system) is highly influenced by the failure and repair rates parameters of each subsystem of the system of the plant. It is essential that each system should run failure free for long duration of time with full capacity and efficiency under real condition. In real situations, it is observed that the operative systems are always subjected to random failures depending upon actual working conditions and the maintenance strategies. Genetic Algorithm is hereby proposed to coordinate the failure and repair rate parameters of each subsystem for stable system performance i.e. optimum system availability

To use GA for solving the given problem, the chromosomes are to be coded in real structures. Unlike, unsigned fixed point integer coding parameters are mapped to a specified interval [X_{min}, X_{max}], where X_{min} and X_{max} are the minimum and the maximum values of system parameters respectively. The maximum value of the availability function is concerned with the optimal values of the failure and repair rate parameters of the system. To test the method, the failure and repair rates are determined simultaneously for the optimal value of the system availability. The effect of number of generations, population size, crossover probability and mutation probability on availability of the system is investigated. To specify the computed simulation more precisely, trial sets are also chosen for genetic algorithm and system parameters. The performance i.e. availability of the system is evaluated by using the designed values of the system parameters. A flowchart for working principal of GA is shown in fig. 5.1.

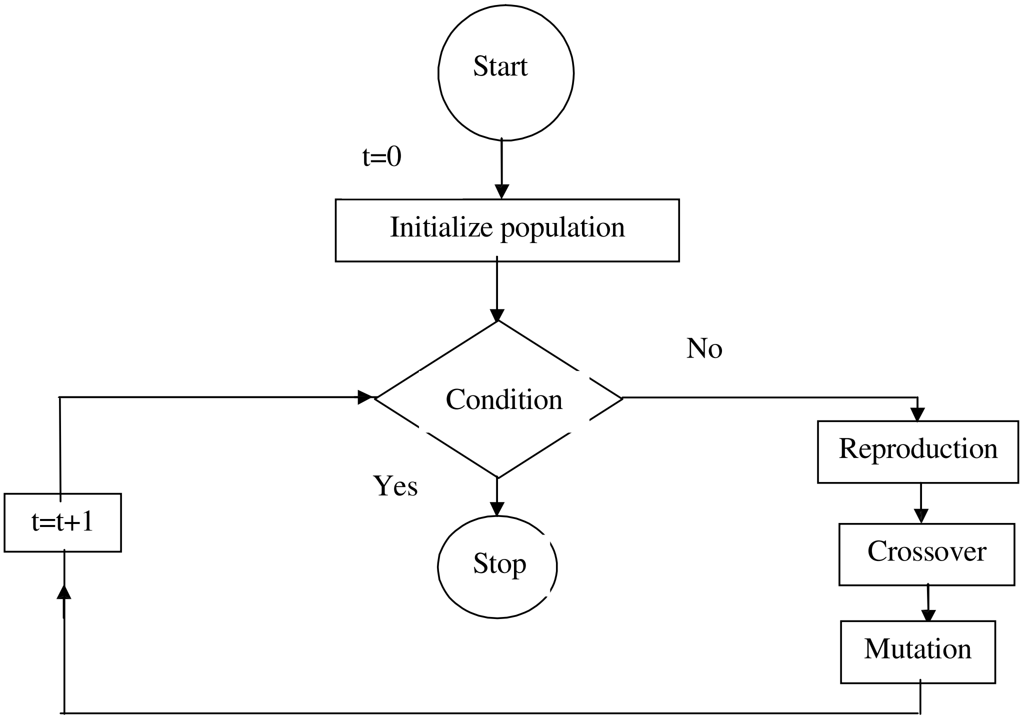


Fig. 5.1 Working Principle of Genetic Algorithm

The GA parameters used for the performance optimization are as follows:

Coding System: Real- value coding system

Selection operator: Tournament selection

Crossover operator: Simulated binary crossover

Mutation operator: Polynomial mutation for all variables

Variable boundaries: Rigid

Real value coding system: If the variable of the parameter space of an optimization problem is continuous, a real coded GA is possibly indicated. Rea numbers have a floating-point representation on a computer and the decision space is always discretised.

Tournament selection: It is probably the most popular selection method in genetic algorithm due to its efficiency and simple implementation. In tournament selection, n individuals are selected randomly from the larger population, and the selected individuals compete against each other. The individual with the highest fitness wins and will be included as one of the next generation population.

Binary crossover: Two points crossover operator performs the exchange of genes between two individuals using two points of intersection.

5.2 PERFORMANCE OPTIMIZATION OF THE SYSTEMS OF DAIRY AND SUGAR PLANTS

In this section, the performance optimization of the systems of dairy plant (i.e. Skim milk powder production, Butter oil production, Steam generation and Refrigeration system) and the performance optimization of systems of sugar plant (i.e. Feeding system, Crushing system, Refining system, Evaporation system and Crystallization system) is carried out by using Genetic Algorithm (GA) technique to get optimal values of the availability of the systems.

5.2.1 Performance optimization for the Skim milk powder production system

The performance optimization of the Skim milk powder production system is carried out using GA. The GA is computerised search and optimization algorithm based on the mechanics of natural genetics and selection. GA is chosen become because it is found to be potential search and optimization technique foe complex optimization problems. GA mimics the principles of genetics and natural selection to constitute search and optimization procedures. The MATLAB software has been used in GA.

The performance of the Skim milk powder production system is highly influenced by the failure rate (λ) and repair rate (μ) parameters of each subsystem of the system. Genetic algorithm is hereby proposed to coordinate the failure and repair rates parameters of each subsystem for stable system performance i.e. high availability. Here, the number of parameters are ten i.e. five failure rates and five repair rates with ($\lambda_4=\lambda_5$, $\mu_4= \mu_5$) and ($\lambda_6=\lambda_7$, $\mu_6=\mu_7$). The failure and repair rate parameter constraints i.e. variables are; (λ_1, μ_1), (λ_2, μ_2), (λ_3, μ_3), (λ_4, μ_4) and (λ_6, μ_6). The range of parameter constraints i.e. (λ_1, μ_1), (λ_2, μ_2), (λ_3, μ_3), (λ_4, μ_4), (λ_6, μ_6) are

$\lambda_1\in[0.0023,0.0082]$, $\lambda_2\in[0.0011,0.0075]$, $\lambda_3\in[0.0031,0.0091]$, $\lambda_4=\lambda_5\in[0.0038, 0.0092]$, $\lambda_6=\lambda_7\in[0.00251,0.00821]$, $\mu_1\in[0.31,0.89]$, $\mu_2\in[0.021,0.095]$, $\mu_3\in[0.23,0.72]$, $\mu_4=\mu_5\in[0.032, 0.097]$, $\mu_6= \mu_7\in[0.049, 0.092]$

Here, real-coded structures are used and simulation is performed in four ways i.e. simulation is done based on number of generations, crossover probability, mutation probability and population size. The results are presented in table 5.1, 5.2, 5.3 and 5.4.

(a) The simulation is done to maximum number of generations, which vary from 20 to 140. The effect of variation in number of generations on availability of the Skim milk powder production system is shown in Fig. 5.2. The table 5.1 reveals that the optimum value of system`s performance i.e. availability is 94.2% approx. when number of generation is equal to 80 and the corresponding best possible combination of failure and repair rates are; (λ_1=0.0025, μ_1=0.88), (λ_2=0.0015, μ_2=0.088), (λ_3=0.0035, μ_3=0.60), (λ_4=0.0050, μ_4=0.035), (λ_6=0.00363, μ_6=0.073).

(b) The simulation is done to crossover probability, which vary from 0.2 to 0.9. The effect of variation in crossover probability on availability of the Skim milk powder production system is shown in Fig. 5.3. The table 5.2 reveals that the optimum value of system`s performance is 94.73% approx. when the crossover probability is equal to 0.7 and the corresponding best possible combination of failure and repair rates are; (λ_1=0.0024, μ_1=0.88), (λ_2=0.0011, μ_2=0.092), (λ_3=0.0071, μ_3=0.69), (λ_4=0.0063, μ_4=0.075), (λ_6=0.00261, μ_6=0.088).

(c) The simulation is done to mutation probability, which vary from 0.010 to 0.018. The effect of variation in mutation probability on availability of the Skim milk powder production system is shown in Fig. 5.4. The table 5.3 reveals that the optimum value of system`s performance is 94% approx. when the mutation probability is equal to 0.012 and the corresponding best possible combination of failure and repair rates are; (λ_1=0.0023, μ_1=0.80), (λ_2=0.0013, μ_2=0.081), (λ_3=0.0040, μ_3=0.56), (λ_4=0.0090, μ_4=0.036), (λ_6=0.00749, μ_6=0.082).

(d) The simulation is done to the population size, which vary from 20 to 60. The effect of variation in population size on availability of the Skim milk powder production system is shown in Fig. 5.5. The table 5.4 reveals that the optimum value of system`s performance is 94.3% approx. when population size is equal to 50 and the corresponding best possible combination of failure and repair rates are; (λ_1=0.0024, μ_1=0.83), (λ_2=0.0013, μ_2=0.078), (λ_3=0.0057, μ_3=0.61), (λ_4=0.0057, μ_4=0.036), (λ_6=0.00393, μ_6=0.077).

5.2.2 Performance optimization for the Butter oil production system

The performance of the Butter oil production system is highly influenced by the failure rate (β) and repair rate (α) parameters of its subsystems. The number of parameters or variables is twelve i.e. six failure rate and six repair rates with (β_4=β_5, α_4=α_5). Failure and repair rate parameter constraints i.e. variables are; (β_1, α_1), (β_2, α_2), (β_3, α_3), (β_4, α_4) , (β_6, α_6) and (β_7, α_7).The range of parameter constraints are

$\beta_1 \in [0.0028, 0.0075]$, $\beta_2 \in [0.0047, 0.0094]$, $\beta_3 \in [0.0043, 0.0087]$, $\beta_4 = \beta_5 \in [0.0035, 0.0078]$, $\beta_6 \in [0.00231, 0.00621]$, $\beta_7 \in [0.00128, 0.00825]$, $\alpha_1 \in [0.221, 0.782]$, $\alpha_2 \in [0.043, 0.095]$, $\alpha_3 \in [0.181, 0.785]$, $\alpha_4 = \alpha_5 \in [0.027, 0.183]$, $\alpha_6 \in [0.046, 0.179]$ and $\alpha_7 \in [0.016, 0.085]$.

Here, real-coded structures are used and simulation is performed in four ways i.e. simulation is done based on number of generations, crossover probability, mutation probability and population size. The results are presented in table 5.5, 5.6, 5.7 and 5.8.

(a) The simulation is done to maximum number of generations, which varies from 20 to 160. The effect of number of generation on availability of the Butter oil production system is shown in Fig. 5.6. The table 5.5 reveals that the optimum value of system`s performance is 85.83% when number of generation is equal to 100 and the corresponding best possible combination of failure and repair rates are; (β_1=0.0059, α_1=0.641), (β_2=0.0047, α_2=0.091), (β_3=0.0049, α_3=0.453), (β_4=0.0046, α_4=0.080), (β_6=0.00246, α_6=0.056), (β_7=0.00162, α_7=0.078).

(b) The simulation is done to crossover probability, which vary from 0.2 to 0.9. The effect of crossover probability on availability of the Butter oil production system is shown in Fig. 5.7. The table 5.6 reveals that the optimum value of system`s performance is 86.7% when crossover probability is 0.7 and the corresponding best possible combination of failure and repair rates are; (β_1=0.003, α_1=0.703), (β_2=0.0055, α_2=0.087), (β_3=0.0069, α_3=0.652), (β_4=0.0038, α_4=0.078), (β_6=0.00246, α_6=0.076), (β_7=0.00129, α_7=0.082).

(c) The simulation is done to mutation probability, which vary from 0.010 to 0.020. The effect of mutation probability on availability of the Butter oil production system is shown in Fig. 5.8. The table 5.7 reveals that the optimum value of system`s performance is 85.43% when mutation probability is equal to 0.016 and the corresponding best possible combination of failure and repair rates are; (β_1=0.004, α_1=0.448), (β_2=0.0047, α_2=0.092), (β_3=0.0068, α_3=0.379), (β_4=0.0039, α_4=0.069), (β_6=0.00245, α_6=0.076), (β_7=0.00218, α_7=0.068).

(d) The simulation is done to population size, which vary from 20 to 120. The effect of population size on availability of the Butter oil production system is shown in Fig. 5.9. The table 5.8 reveals that the optimum value of system`s performance is 85.4 % when population size is equal to 60 and the corresponding best possible combination of failure and repair rates are; (β_1=0.039, α_1=0.447), (β_2=0.0045,

α_2=0.095), (β_3=0.0067, α_3=0.381), (β_4=0.0041, α_4=0.067), (β_6=0.00243, α_6=0.075), (β_7=0.00219, α_7=0.071).

5.2.3 Performance optimization for the Steam generation system

The performance of the Steam generation system is highly influenced by the failure rate (θ) and repair rate (ω) parameters of its subsystems. The number of parameters or variables are ten i.e. five failure rates and five repair rates with ($\theta_3=\theta_4$, $\omega_3=\omega_4$) and ($\theta_6=\theta_7$, $\omega_6=\omega_7$). The failure and repair rate parameter constraints i.e. variables are; (θ_1, ω_1), (θ_2, ω_2), (θ_3, ω_3), (θ_5, ω_5) and (θ_6, ω_6). The range of parameter constraints are $\theta_1 \in [0.0028, 0.0087]$, $\theta_2 \in [0.012, 0.073]$, $\theta_3 = \theta_4 \in [0.0018, 0.0087]$, $\theta_5 \in [0.0023, 0.0083]$, $\theta_6 = \theta_7 \in [0.0018, 0.0093]$, $\omega_1 \in [0.13, 0.78]$, $\omega_2 \in [0.08, 0.45]$, $\omega_3 = \omega_4 \in [0.012, 0.097]$, $\omega_5 \in [0.16, 0.83]$, and $\omega_6 = \omega_7 \in [0.17, 0.76]$.

Here, the simulation is performed in four ways i.e. simulation is done based on number of generation, crossover probability, mutation probability and population size. The results are presented in table 5.9, 5.10, 5.11 and 5.12.

(a) The simulation is done to maximum number of generations, which varies from 20 to 160. The effect of number of generation on availability of the Steam generation system is shown in Fig. 5.10. The table 5.9 reveals that the optimum value of system`s performance is 96.2% when number of generation is equal to 60 and the corresponding best possible combination of failure and repair rates are; (θ_1=0.00300, ω_1=0.663), (θ_2=0.0120, ω_2=0.411), (θ_3=0.00228, ω_3=0.0767), (θ_5 = 0.00237, ω_5=0.644) and (θ_6=0.00836, ω_6=0.321).

(b) The simulation is done to crossover probability, which vary from 0.2 to 0.6. The effect of crossover probability on availability of the Steam generation system is shown in Fig. 5.11. The table 5.10 reveals that the optimum value of system`s performance is 95.73% when crossover probability is 0.2 and the corresponding best possible combination of failure and repair rates are; (θ_1=0.00337, ω_1=0.755), (θ_2=0.0147, ω_2=0.434), (θ_3=0.00209, ω_3=0.0890), (θ_5=0.00273, ω_5=0.500) and (θ_6=0.00195, ω_6=0.306).

(c) The simulation is done to mutation probability, which vary from 0.010 to 0.020. The effect of mutation probability on availability of the Steam generation system is shown in Fig. 5.12. The table 5.11 reveals that the optimum value of system`s performance is 96.17% when mutation probability is equal to 0.016 and the corresponding best possible combination of failure and repair rates are; (θ_1=0.00351, ω_1=0.664), (θ_2=0.0123, ω_2=0.443), (θ_3=0.00288, ω_3=0.0771), (θ_5=0.00287, ω_5=0.632) and (θ_6=0.00842, ω_6=0.359).

(d) The simulation is done to population size, which vary from 20 to 120. The effect of population size on availability of the Steam generation system is shown in Fig. 5.13. The table 5.12 reveals that the optimum value of system`s performance is 95.96% when population size is equal to 60 and the corresponding best possible combination of failure and repair rates are; (θ_1=0.00412, ω_1=0.626), (θ_2=0.0124, ω_2=0.421), (θ_3=0.00317, ω_3=0.072), (θ_5=0.00255, ω_5=0.634) and (θ_6=0.00842, ω_6=0.701).

5.2.4 Performance optimization for the Refrigeration system

The performance of the Refrigeration system is highly influenced by the failure rate (ϕ) parameters and repair rate (τ) parameters of its subsystems. The number of parameters or variables are ten i.e. five failure rates and five repair rates with (ϕ_1= ϕ_2, τ_1= τ_2), (ϕ_3= ϕ_4 and, τ_3= τ_4). The failure and repair rate parameter constraints i.e. variables are; (ϕ_1, τ_1), (ϕ_3,τ_3), (ϕ_5, τ_5), (ϕ_6, τ_6) and (ϕ_7,τ_7). The range of parameter constraints are

$\phi_1=\phi_2\in[0.025,0.078]$, $\phi_3=\phi_4\in[0.015\ ,0.078]$, $\phi_5\in[0.0021,0.0093]$, $\phi_6\in[0.01,\ 0.085]$, $\phi_7\in[0.016,0.092]$, $\tau_1=\tau_2\in[0.13,\ 0.78]$, $\tau_3=\tau_4\in[0.15,\ 0.78]$, $\tau_5\in[0.13,\ 0.78]$, $\tau_6\in[0.18,\ 0.85]$, $\tau_7\in[0.1,\ 0.69]$

Here, real-coded structures are used and simulation is performed in four ways i.e. simulation is done based on number of generations, crossover probability, mutation probability and population size. The results are presented in table 5.13, 5.14, 5.15 and 5.16.

(a) The simulation is done to maximum number of generations, which varies from 20 to 160. The effect of number of generation on availability of Refrigeration system is shown in Fig. 5.14. The table 5.13 reveals that the optimum value of system`s performance is 95.2% when number of generation is equal to 40 and the corresponding best possible combination of failure and repair rates are; (ϕ_1=0.0342, τ_1=0.748), (ϕ_3=0.0245, τ_3=0.711), (ϕ_5=0.0027, τ_5=0.730), (ϕ_6=0.0105, τ_6=0.765), (ϕ_7=0.0184, τ_7=0.612).

(b) The simulation is done to crossover probability, which vary from 0.2 to 0.6. The effect of crossover probability on availability of the Refrigeration system is shown in Fig. 5.15. The table 5.14 reveals that the optimum value of system`s performance is

95.2% when crossover probability is 0.3 and the corresponding best possible combination of failure and repair rates are; (ϕ_1=0.03119, τ_1=0.746), (ϕ_3=0.02445, τ_3=0.767), (ϕ_5=0.00278, τ_5=0.730), (ϕ_6=0.01027, τ_6=0.749), (ϕ_7=0.01853, τ_7=0.610).

(c) The simulation is done to mutation probability, which vary from 0.010 to 0.020. The effect of mutation probability on availability of the Refrigeration system is shown in Fig. 5.16. The table 5.15 reveals that the optimum value of system`s performance is 95.12% when mutation probability is equal to 0.018 and the corresponding best possible combination of failure and repair rates are; (ϕ_1=0.06803, τ_1=0.744), (ϕ_3=0.01669, τ_3=0.766), (ϕ_5=0.00253, τ_5=0.726), (ϕ_6=0.01004, τ_6=0.797), (ϕ_7=0.01635, τ_7=0.608).

(d) The simulation is done to population size, which vary from 20 to 120. The effect of population size on availability of the Refrigeration system is shown in Fig. 5.17. The table 5.16 reveals that the optimum value of system`s performance is 95.3% when population size is equal to 120 and the corresponding best possible combination of failure and repair rates are; (ϕ_1=0.03325, τ_1=0.744), (ϕ_3=0.02344, τ_3=0.710), (ϕ_5=0.00262, τ_5=0.668), (ϕ_6=0.01026, τ_6=0.738), (ϕ_7=0.01731, τ_7=0.610).

5.2.5 Performance optimization for the Feeding system

The performance of the Feeding system is highly influenced by the failure rate (ε) and repair rate (Δ) parameters of its subsystems. The number of parameters or variables are eight i.e. four failure and four repair rates with ($\varepsilon_1 = \varepsilon_2$, $\Delta_1 = \Delta_2$), ($\varepsilon_4 = \varepsilon_5$, $\Delta_4 = \Delta_5$) and ($\varepsilon_6 = \varepsilon_7$, $\Delta_6 = \Delta_7$). The failure and repair rate parameter constraints i.e. variables are; (ε_1, Δ_1), (ε_3, Δ_3), (ε_4, Δ_4) and (ε_6, Δ_6).The range of parameter constraints are

$\varepsilon_1=\varepsilon_2 \in [0.0025, 0.0092]$, $\varepsilon_3 \in [0.0031, 0.0087]$, $\varepsilon_4=\varepsilon_5 \in [0.0042, 0.0095]$, $\varepsilon_6=\varepsilon_7 = \in [0.0018, 0.0085]$, $\Delta_1= \Delta_2 \in [0.03, 0.18]$, $\Delta_3 \in [0.091, 0.19]$, $\Delta_4= \Delta_5 \in [0.03, 0.22]$, $\Delta_6=\Delta_7 = \in [0.01, 0.18]$.

Here, real-coded structures are used and simulation is performed in four ways i.e. simulation is done based on number of generations, crossover probability, mutation probability and population size. The results are presented in table 5.17, 5.18, 5.19 and 5.20.

(a) The simulation is done to maximum number of generations, which varies from 20 to 160. The effect of number of generation on availability of Feeding system is shown in Fig. 5.18. The table 5.17 reveals that the optimum value of system`s performance is 98.11% when number of generation is equal to 160 and the corresponding best possible combination of failure and repair rates are; ($\boldsymbol{\varepsilon}_1$=0.0028, $\boldsymbol{\Delta}_1$=0.1726), ($\boldsymbol{\varepsilon}_3$=0.0032, $\boldsymbol{\Delta}_3$=0.1804), ($\boldsymbol{\varepsilon}_4$ = 0.0056, $\boldsymbol{\Delta}_4$=0.1913), ($\boldsymbol{\varepsilon}_6$=0.0030, $\boldsymbol{\Delta}_6$=0.1392).

(b) The simulation is done to crossover probability, which vary from 0.2 to 0.7. The effect of crossover probability on availability of the Feeding system is shown in Fig. 5.19. The table 5.18 reveals that the optimum value of system`s performance is 98% when crossover probability is 0.5 and the corresponding best possible combination of failure and repair rates are; ($\boldsymbol{\varepsilon}_1$=0.0037, $\boldsymbol{\Delta}_1$=0.1172), ($\boldsymbol{\varepsilon}_3$=0.0032, $\boldsymbol{\Delta}_3$=0.1836), ($\boldsymbol{\varepsilon}_4$ = 0.0054, $\boldsymbol{\Delta}_4$=0.1960), ($\boldsymbol{\varepsilon}_6$=0.0038, $\boldsymbol{\Delta}_6$=0.1643).

(c) The simulation is done to mutation probability, which vary from 0.010 to 0.020. The effect of mutation probability on availability of the Feeding system is shown in Fig. 5.20. The table 5.19 reveals that the optimum value of system`s performance is 98.1% when mutation probability is equal to 0.014 and the corresponding best possible combination of failure and repair rates are; ($\boldsymbol{\varepsilon}_1$=0.0041, $\boldsymbol{\Delta}_1$=0.1682), ($\boldsymbol{\varepsilon}_3$=0.0031, $\boldsymbol{\Delta}_3$=0.1814), ($\boldsymbol{\varepsilon}_4$ = 0.0045, $\boldsymbol{\Delta}_4$=0.2188), ($\boldsymbol{\varepsilon}_6$=0.0050, $\boldsymbol{\Delta}_6$=0.1506).

(d) The simulation is done to population size, which vary from 20 to 120. The effect of population size on availability of the Feeding system is shown in Fig. 5.21. The table 5.20 reveals that the optimum value of system`s performance is 98% when population size is equal to 120 and the corresponding best possible combination of failure and repair rates are; ($\boldsymbol{\varepsilon}_1$=0.0041, $\boldsymbol{\Delta}_1$=0.1653), ($\boldsymbol{\varepsilon}_3$=0.0031, Δ_3=0.1826), ($\boldsymbol{\varepsilon}_4$=0.0051, $\boldsymbol{\Delta}_4$=0.1758), ($\boldsymbol{\varepsilon}_6$=0.0045, $\boldsymbol{\tau}_6$=0.0829).

5.2.6 Performance optimization for the Crushing system

The performance of the Crushing system is highly influenced by the failure rate (σ) and repair rate (ρ) parameters of its subsystems. The number of parameters or variables are six i.e. three failure rate and three repair rates with (σ_3= σ_4, ρ_3= ρ_4). The failure and repair rates parameter constraints i.e. variables are; (σ_1, ρ_1), (σ_2, ρ_2) and (σ_3, ρ_3). The range of parameter constraints are

$\sigma_1 \in [0.0042,0.0086]$, $\sigma_2 \in [0.0063 ,0.0096]$, $\sigma_3 = \sigma_4 \in [0.0058,0.0092]$, $\rho_1 \in [0.012, 0.021]$, $\rho_2 \in [0.014, 0.027]$, $\rho_3 = \rho_4 \in [0.024, 0.046]$.

Here, real-coded structures are used and simulation is performed in four ways i.e. simulation is done based on number of generations, crossover probability, mutation probability and population size. The results are presented in table 5.21, 5.22, 5.23 and 5.24.

(a) The simulation is done to maximum number of generations, which varies from 20 to 160. The effect of number of generation on availability of Crushing system is shown in Fig. 5.22. The table 5.21 reveals that the optimum value of system`s performance is 86.7% when number of generation is equal to 120 and the corresponding best possible combination of failure and repair rates are; (σ_1=0.004257, ρ_1=0.090133), (σ_2=0.006944, ρ_2=0.094216), (σ_3 = 0.006101, ρ_3=0.094216).

(b) The simulation is done to crossover probability, which vary from 0.2 to 0.6. The effect of crossover probability on availability of the Crushing system is shown in Fig. 5.23. The table 5.22 reveals that the optimum value of system`s performance is 86.5% when crossover probability is 0.6 and the corresponding best possible combination of failure and repair rates are; (σ_1=0.005002, ρ_1=0.090685), (σ_2=0.006547, ρ_2=0.092585), (σ_3 = 0.005852, ρ_3=0.095363).

(c) The simulation is done to mutation probability, which vary from 0.010 to 0.020. The effect of mutation probability on availability of the Crushing system is shown in Fig. 5.24. The table 5.23 reveals that the optimum value of system`s performance is 86.5% when mutation probability is equal to 0.014 and the corresponding best possible combination of failure and repair rates are; σ_1=0.005213, ρ_1=0.094757, σ_2=0.006383, ρ_2=0.094262, σ_3 = 0.006164, ρ_3=0.092657.

(d) The simulation is done to population size, which vary from 20 to 120. The effect of population size on availability of the Crushing system is shown in Fig. 5.25. The table 5.24 reveals that the optimum value of system`s performance is 86% when population size is equal to 80 and the corresponding best possible combination of failure and repair rates are; (σ_1=0.004594, ρ_1=0.097348), (σ_2=0.006324, ρ_2=0.082298), (σ_3 = 0.006518, ρ_3=0.085437).

5.2.7 Performance optimization for the Refining system

The performance of the Refining system is highly influenced by the failure rate (η) and repair rate (ξ) parameters of its subsystems. The number of parameters or variables are eight with (η_2=η_1, ξ_2= ξ_1), (η_3=η_1, ξ_3= ξ_1) and (η_6=η_5, ξ_6=ξ_5). The failure and repair rate parameter constraints i.e. variables are; (η_1, ξ_1), (η_4, ξ_4), (η_5, ξ_5) and (η_7, ξ_7). The range of parameter constraints are

η_1= η_2= $\eta_3$$\in$[0.002, 0.009], $\eta_4$$\in$[0.0022, 0.0087], η_5= $\eta_6$$\in$[0.0012, 0.0073], $\eta_7$$\in$[0.031, 0.0095], ξ_1= ξ_2= $\xi_3$$\in$[0.08, 0.148], $\xi_4$$\in$[0.21, 0.68], ξ_5= $\xi_6$$\in$[0.032, 0.092], $\xi_7$$\in$[0.026, 0.084].

Here, the simulation is performed in three ways i.e. simulation is done based on number of generation, crossover probability, mutation probability and population size. The results are presented in table 5.25, 5.26, 5.27 and 5.28.

(a) The simulation is done to maximum number of generations, which varies from 20 to 160. The effect of number of generation on availability of the Refining system is shown in Fig. 5.26. The table 5.25 reveals that the optimum value of system`s performance is 95% when number of generation is equal to 120 and the corresponding best possible combination of failure and repair rates are; (η_1=0.0023, ξ_1=0.1139), (η_4=0.0046, ξ_4=0.5636), (η_5=0.0024, ξ_5=0.0779), (η_7=0.0033, ξ_7=0.0821).

(b) The simulation is done to crossover probability, which vary from 0.2 to 0.9. The effect of crossover probability on availability of the Refining system is shown in Fig. 5.27. The table 5.26 reveals that the optimum value of system`s performance is 95% when crossover probability is 0.9 and the corresponding best possible combination of failure and repair rates are; (η_1=0.0027, ξ_1=0.1084), (η_4=0.0044, ξ_4=0.4075), (η_5=0.0018, ξ_5=0.0721), (η_7=0.0031, ξ_7=0.0813).

(c) The simulation is done to mutation probability, which vary from 0.010 to 0.020. The effect of mutation probability on availability of the Refining system is shown in Fig. 5.28. The table 5.27 reveals that the optimum value of system`s performance is 94.6% when mutation probability is equal to 0.016 and the corresponding best possible combination of failure and repair rates are; (η_1=0.0020, ξ_1=0.0949), (η_4=0.0042, ξ_4=0.4439), (η_5=0.0015, ξ_5=0.0561), (η_7=0.0033, ξ_7=0.0759).

(d) The simulation is done to population size, which vary from 20 to 60. The effect of population size on availability of the Refining system is shown in Fig. 5.29. The table 5.28 reveals that the optimum value of system`s performance is 95.4% when population size is equal to 50 and the corresponding best possible combination of failure and repair rates are; (η_1=0.0023, ξ_1=0.1301), (η_4=0.0025, ξ_4=0.5144), (η_5=0.0018, ξ_5=0.0830), (η_7=0.0034, ξ_7=0.0822).

5.2.8 Performance optimization for the Evaporation system

The performance of the Evaporation system is highly influenced by the failure rate (ψ) and repair rate (γ) parameters of its subsystems. The number of parameters or variables are six i.e. three failure rates and three repair rates with (ψ_2= ψ_1, γ_2= γ_1) and (ψ_5= ψ_4, γ_5=

γ_4). The failure and repair rate parameter constraints i.e. variables are; (ψ_1, γ_1), (ψ_3, γ_3) and (ψ_4, γ_4). The range of parameter constraints are

$\psi_1 = \psi_2 \in [0.0009, 0.0026]$, $\psi_3 \in [0.0063, 0.0096]$, $\psi_4 = \psi_5 \in [0.0021, 0.0046]$, $\gamma_1 = \gamma_2 \in [0.016, 0.027]$, $\gamma_3 \in [0.010, 0.12]$, $\gamma_4 = \gamma_5 \in [0.024, 0.12]$.

Here, the simulation is performed in four ways i.e. simulation is done based on number of generation, crossover probability, mutation probability and population size. The results are presented in table 5.29, 5.30, 5.31 and 5.32.

(a) The simulation is done to maximum number of generations, which varies from 20 to 160. The effect of number of generation on availability of the Evaporation system is shown in Fig. 5.30. The table 5.29 reveals that the optimum value of system`s performance is 93% when number of generation is equal to 80 and the corresponding best possible combination of failure and repair rates are; (ψ_1=0.000982, γ_1=0.016854), (ψ_3=0.006366, γ_3=0.109264), (ψ_4=0.002408, γ_4=0.11969).

(b) The simulation is done to crossover probability, which vary from 0.2 to 0.6. The effect of crossover probability on availability of the Evaporation system is shown in Fig. 5.31. The table 5.30 reveals that the optimum value of system`s performance is 93% when crossover probability is 0.2 and the corresponding best possible combination of failure and repair rates are; (ψ_1=0.001215, γ_1=0.023182), (ψ_3=0.006467, γ_3=0.118381), (ψ_4=0.00251, γ_4=0.115457).

(c) The simulation is done to mutation probability, which vary from 0.010 to 0.020. The effect of mutation probability on availability of the Evaporation system is shown in Fig. 5.32. The table 5.31 reveals that the optimum value of system`s performance is 93.21% when mutation probability is equal to 0.010 and the corresponding best possible combination of failure and repair rates are; (ψ_1=0.001310, γ_1=0.024986), (ψ_3=0.006356, γ_3=0.119119), (ψ_4=0.002181, γ_4=0.108608).

(d) The simulation is done to population size, which vary from 20 to 120. The effect of population size on availability of the Refining system is shown in Fig. 5.33. The table 5.32 reveals that the optimum value of system`s performance is 93.2% when population size is equal to 120 and the corresponding best possible combination of failure and repair rates are; (ψ_1=0.001503, γ_1=0.01708), (ψ_3=0.006351, γ_3=0.113098), (ψ_4=0.002215, γ_4=0.116628).

5.2.9 Performance optimization for the Crystallization system

The performance of the Crystallization system is highly influenced by the failure rate (δ) and repair rate ($\emptyset$) parameters of its subsystems. The number of parameters or variables are six i.e. three failure rates and three repair rate with ($\delta_2= \delta_1$, $\emptyset_2= \emptyset_1$) and ($\delta_3=\delta_4=\delta_5$, $\emptyset_3= \emptyset_4= \emptyset_5$). The failure and repair rate parameter constraints i.e. variables are; (δ_1, $\emptyset_1$), (δ_3, $\emptyset_3$) and (δ_6, $\emptyset_6$). The range of parameter constraints are

$\delta_1=\delta_2\in[0.001 \text{ to } 0.0075\ ]$, $\delta_3= \delta_4= \delta_5 \in[0.0016, 0.0085]$, $\delta_6 \in[0.0062, 0.0098]$, $\emptyset_1= \emptyset_2 \in[0.010, 0.287]$, $\emptyset_3= \emptyset_4= \emptyset_5 \in[0.028, 0.95]$, $\emptyset_6 \in[0.0085, 0.087]$.

Here, simulation is done based on no. of generations, crossover & mutation probability and population size. The results are presented in table 5.33, 5.34, 5.35 and 5.36.

(a) The simulation is done to max. of generations, which varies from 20 to 160. The effect of number of generation on availability of the Crystallization system is shown in Fig. 5.34. The table 5.33 reveals that the optimum value of system`s performance is 96.5% when number of generation is equal to 120 and the corresponding best possible combination of failure and repair rates are; (δ_1=0.006738, $\emptyset_1$=0.03212), (δ_3=0.002191, $\emptyset_3$=0.947856), (δ_6=0.009619, $\emptyset_6$=0.08690).

(b) The simulation is done to crossover probability, which vary from 0.2 to 0.6. The effect of crossover probability on availability of the Evaporation system is shown in Fig. 5.35. The table 5.34 reveals that the optimum value of system`s performance is 96.95% when crossover probability is 0.3 and the corresponding best possible combination of failure and repair rates are; (δ_1=0.004935, $\emptyset_1$=0.02305), (δ_3=0.001619, $\emptyset_3$=0.885348), (δ_6=0.009780, $\emptyset_6$=0.08625).

(c) The simulation is done to mutation probability, which vary from 0.010 to 0.020. The effect of mutation probability on availability of the Evaporation system is shown in Fig. 5.36. The table 5.35 reveals that the optimum value of system`s performance is 95.25% when mutation probability is equal to 0.012 and the corresponding best possible combination of failure and repair rates are; (δ_1=0.007217, $\emptyset_1$=0.02237), (δ_3=0.003642, $\emptyset_3$=0.927002), (δ_6=0.009554, $\emptyset_6$=0.08620).

(d) The simulation is done to population size, which vary from 20 to 120. The effect of population size on availability of the Refining system is shown in Fig. 5.37. The table 5.36 reveals that the optimum value of system`s performance is 94% when population size is equal to 120 and the corresponding best possible combination of failure and repair rates are; (δ_1=0.006658, $\emptyset_1$=0.010847), (δ_3=0.007503, $\emptyset_3$=0.328142), (δ_6=0.009247, $\emptyset_6$=0.08602).

Table 5.1 Effect of number of generations on the availability of the Skim milk powder production system
(Population size=80, crossover probability=0.85, mutation probability=0.015)

S.N.	**No. of gen.**	**Av.**	λ_1	λ_2	λ_3	λ_4	λ_6	μ_1	μ_2	μ_3	μ_4	μ_6
1	20	0.93028591	0.0023	0.0015	0.0033	0.0069	0.00425	0.75	0.064	0.30	0.076	0.088
2	40	0.93524235	0.0028	0.0016	0.0053	0.0055	0.00299	0.83	0.078	0.67	0.055	0.068
3	60	0.93568364	0.0032	0.0011	0.0048	0.0045	0.00314	0.77	0.088	0.70	0.076	0.084
4	**80**	**0.94190548**	**0.0025**	**0.0015**	**0.0035**	**0.0050**	**0.00363**	**0.88**	**0.088**	**0.60**	**0.035**	**0.073**
5	100	0.93572570	0.0024	0.0012	0.0063	0.0075	0.00650	0.67	0.088	0.70	0.042	0.089
6	120	0.93665663	0.0028	0.0014	0.0045	0.0055	0.00504	0.89	0.073	0.53	0.043	0.081
7	140	0.93630233	0.0024	0.0011	0.0049	0.0048	0.00383	0.89	0.069	0.33	0.079	0.081

Table 5.2 Effect of crossover probability on the availability of the Skim milk powder production system
(Number of generation=80, population size=80, mutation probability=0.015)

S.N.	P_c	**Av.**	λ_1	λ_2	λ_3	λ_4	λ_6	μ_1	μ_2	μ_3	μ_4	μ_6
1	0.2	0.93541152	0.0028	0.0011	0.0033	0.0089	0.00665	0.83	0.090	0.38	0.060	0.084
2	0.3	0.93608730	0.0027	0.0017	0.0045	0.0055	0.00278	0.84	0.081	0.60	0.064	0.066
3	0.4	0.94158996	0.0026	0.0016	0.0054	0.0059	0.00309	0.89	0.093	0.57	0.045	0.069
4	0.5	0.93978038	0.0023	0.0012	0.0051	0.0064	0.000293	0.72	0.072	0.68	0.086	0.085
5	0.6	0.94400296	0.0026	0.0011	0.0063	0.0061	0.00252	0.85	0.091	0.51	0.033	0.062
6	**0.7**	**0.94727808**	**0.0024**	**0.0011**	**0.0071**	**0.0063**	**0.00261**	**0.88**	**0.092**	**0.69**	**0.075**	**0.088**
7	0.8	0.93986313	0.0023	0.0016	0.0035	0.0086	0.00475	0.78	0.080	0.68	0.054	0.083
8	0.9	0.93940655	0.0028	0.0017	0.0049	0.0062	0.00259	0.88	0.085	0.62	0.049	0.079

Table 5.3 Effect of mutation probability on the availability of the Skim milk powder production system

(Number of generation=80, population size=80, crossover probability=0.85)

S.N.	**P_m**	**Av.**	**λ_1**	**λ_2**	**λ_3**	**λ_4**	**λ_5**	**μ_1**	**μ_2**	**μ_3**	**μ_4**	**μ_5**
1	0.010	0.92829257	0.0034	0.0018	0.0044	0.0074	0.00475	0.89	0.081	0.62	0.039	0.062
2	**0.012**	**0.94031170**	**0.0023**	**0.0013**	**0.0040**	**0.0090**	**0.00749**	**0.80**	**0.081**	**0.56**	**0.036**	**0.082**
3	0.014	0.93761740	0.0026	0.0014	0.0047	0.0053	0.00422	0.83	0.094	0.51	0.073	0.078
4	0.016	0.93925683	0.0030	0.0011	0.0043	0.0041	0.00346	0.86	0.089	0.42	0.036	0.055
5	0.018	0.93352085	0.0030	0.0019	0.0050	0.0046	0.00355	0.86	0.089	0.65	0.062	0.087

Table 5.4 Effect of population size on the availability of the Skim milk powder production system

(Number of generation=80, crossover probability=0.85, mutation probability=0.015)

S.N.	**P. Size**	**Av.**	**λ_1**	**λ_2**	**λ_3**	**λ_4**	**λ_6**	**μ_1**	**μ_2**	**μ_3**	**μ_4**	**μ_6**
1	20	0.92846057	0.0032	0.0011	0.0040	0.0072	0.0027	0.73	0.086	0.26	0.045	0.073
2	30	0.93538455	0.0029	0.0016	0.0053	0.0040	0.00373	0.79	0.089	0.65	0.046	0.084
3	40	0.93440341	0.0025	0.0012	0.0035	0.0038	0.00662	0.87	0.063	0.30	0.036	0.075
4	**50**	**0.94262014**	**0.0024**	**0.0013**	**0.0057**	**0.0057**	**0.00393**	**0.83**	**0.078**	**0.61**	**0.036**	**0.077**
5	60	0.93623686	0.0024	0.0011	0.0088	0.0080	0.00303	0.79	0.064	0.66	0.073	0.086

Table 5.5 Effect of number of generations on the availability of the Butter oil production system
(Population size=80, crossover probability=0.85, mutation probability=0.015)

S. N.	**No. of gen.**	**Av.**	**β_1**	**β_2**	**β_3**	**β_4**	**β_6**	**β_7**	**α_1**	**α_2**	**α_3**	**α_4**	**α_6**	**α_7**
1	20	0.830096	0.0032	0.0067	0.0052	0.0037	0.00256	0.00261	0.775	0.087	0.705	0.051	0.069	0.061
2	40	0.835708	0.0040	0.0048	0.0069	0.0038	0.00424	0.00188	0.710	0.067	0.753	0.071	0.075	0.070
3	60	0.840354	0.0037	0.0048	0.0059	0.0046	0.00276	0.00241	0.4780	0.079	0.486	0.056	0.071	0.082
4	80	0.843559	0.0060	0.0055	0.0080	0.0058	0.00256	0.00151	0.753	0.076	0.528	0.083	0.078	0.068
5	**100**	**0.858283**	**0.0059**	**0.0047**	**0.0049**	**0.0046**	**0.00246**	**0.00162**	**0.641**	**0.091**	**0.453**	**0.080**	**0.056**	**0.078**
6	120	0.854483	0.0031	0.0049	0.0050	0.0041	0.00282	0.00139	0.318	0.091	0.348	0.068	0.073	0.059
7	140	0.848666	0.0052	0.0053	0.0079	0.0048	0.00287	0.00161	0.753	0.095	0.554	0.064	0.066	0.079
8	160	0.845266	0.0051	0.0047	0.0059	0.0043	0.00283	0.00229	0.579	0.093	0.477	0.066	0.065	0.065

Table 5.6 Effect of crossover probability on the availability of the Butter oil production system
(Number of generation=80, population size=80, mutation probability=0.015)

S.N.	**P_c**	**Av.**	**β_1**	**β_2**	**β_3**	**β_4**	**β_6**	**β_7**	**α_1**	**α_2**	**α_3**	**α_4**	**α_6**	**α_7**
1	0.2	0.840124	0.0029	0.0051	0.0078	0.0041	0.00263	0.00134	0.239	0.088	0.296	0.068	0.073	0.059
2	0.3	0.842157	0.0062	0.0051	0.0043	0.006	0.00249	0.00153	0.378	0.089	0.327	0.074	0.074	0.061
3	0.4	0.843737	0.0036	0.005	0.0046	0.0042	0.00283	0.00369	0.515	0.092	0.543	0.081	0.075	0.070
4	0.5	0.851576	0.0039	0.0055	0.0052	0.0039	0.00234	0.00145	0.549	0.092	0.376	0.067	0.069	0.061
5	0.6	0.854152	0.0056	0.005	0.007	0.0048	0.00289	0.00137	0.669	0.094	0.595	0.069	0.078	0.068
5	**0.7**	**0.867057**	**0.003**	**0.0055**	**0.0069**	**0.0038**	**0.00246**	**0.00129**	**0.703**	**0.087**	**0.652**	**0.078**	**0.076**	**0.082**
6	0.8	0.858118	0.0042	0.0048	0.0049	0.0043	0.00265	0.00143	0.771	0.09	0.375	0.055	0.070	0.065
7	0.9	0.854654	0.0046	0.005	0.0068	0.0043	0.0035	0.00143	0.761	0.091	0.632	0.065	0.056	0.061

Table 5.7 Effect of mutation probability on the availability of the Butter oil production system

(Number of generation=80, population size=80, crossover probability=0.85)

S.N.	**P_m**	**Av.**	**β_1**	**β_2**	**β_3**	**β_4**	**β_6**	**β_7**	**α_1**	**α_2**	**α_3**	**α_4**	**α_6**	**α_7**
1	0.010	0.843629	0.0057	0.0049	0.0072	0.0049	0.00244	0.00156	0.35	0.094	0.34	0.078	0.058	0.07
2	0.012	0.847574	0.0047	0.0058	0.0075	0.0045	0.00262	0.00138	0.757	0.078	0.693	0.082	0.067	0.063
3	0.014	0.84929	0.004	0.0056	0.0068	0.0051	0.00267	0.00166	0.715	0.085	0.64	0.082	0.076	0.057
4	**0.016**	**0.854326**	**0.004**	**0.0047**	**0.0068**	**0.0039**	**0.00245**	**0.00218**	**0.448**	**0.092**	**0.379**	**0.069**	**0.076**	**0.068**
5	0.018	0.852411	0.0066	0.0052	0.0076	0.0035	0.00327	0.00135	0.591	0.087	0.665	0.08	0.073	0.056
6	0.020	0.849976	0.0032	0.0048	0.0045	0.0064	0.00313	0.00136	0.693	0.083	0.453	0.079	0.066	0.084

Table 5.8 Effect of population size on the availability of the Butter oil production system

(Number of generations=80, crossover probability=0.85, mutation probability=0.015)

S.N.	**P. size**	**Av.**	**β_1**	**β_2**	**β_3**	**β_4**	**β_6**	**β_7**	**α_1**	**α_2**	**α_3**	**α_4**	**α_6**	**α_7**
1	20	0.842938	0.0056	0.0051	0.0071	0.0048	0.00242	0.00154	0.34	0.092	0.35	0.076	0.057	0.07
2	40	0.846672	0.0049	0.0056	0.0074	0.0043	0.00261	0.00136	0.748	0.077	0.691	0.081	0.069	0.062
3	**60**	**0.854321**	**0.039**	**0.0045**	**0.0067**	**0.0041**	**0.00243**	**0.00219**	**0.447**	**0.095**	**0.381**	**0.067**	**0.075**	**0.071**
4	80	0.852409	0.0065	0.0051	0.0079	0.0033	0.00327	0.00139	0.593	0.087	0.667	0.080	0.071	0.058
5	100	0.849969	0.0031	0.0046	0.0043	0.0067	0.00321	0.00137	0.691	0.085	0.451	0.081	0.065	0.083
6	120	0.849291	0.0039	0.0055	0.0066	0.0053	0.00263	0.00163	0.713	0.081	0.65	0.085	0.073	0.055

Table 5.9 Effect of number of generations on the availability of the Steam generation system

(Population size=80, crossover probability=0.85, mutation probability=0.015)

S.N.	**No. of gen.**	**Av.**	**θ_1**	**θ_2**	**θ_3**	**θ_5**	**θ_6**	**ω_1**	**ω_2**	**ω_3**	**ω_5**	**ω_6**
1	20	0.961441	0.00440	0.0126	0.00219	0.00241	0.00867	0.688	0.449	0.0712	0.651	0.315
2	40	0.955711	0.00383	0.0149	0.00262	0.00267	0.00817	0.646	0.426	0.0743	0.673	0.651
3	**60**	**0.962258**	**0.00300**	**0.0120**	**0.00228**	**0.00237**	**0.00836**	**0.663**	**0.411**	**0.0767**	**0.644**	**0.321**
4	80	0.960033	0.00423	0.0131	0.00331	0.00278	0.00780	0.672	0.449	0.0796	0.656	0.725
5	100	0.959065	0.00327	0.0126	0.00195	0.00261	0.00776	0.607	0.390	0.0775	0.637	0.609
6	120	0.941328	0.00419	0.0136	0.00328	0.00262	0.00387	0.331	0.435	0.0331	0.289	0.723
7	140	0.950374	0.00360	0.0193	0.00235	0.00241	0.00183	0.757	0.449	0.0805	0.724	0.329
8	160	0.958386	0.00363	0.0147	0.00298	0.00298	0.00873	0.754	0.449	0.0884	0.658	0.685

Table 5.10 Effect of crossover probability on the availability of the Steam generation system

(Number of gen. = 80, Population size=80, mutation probability=0.015)

S.N.	**P_c**	**Av.**	**θ_1**	**θ_2**	**θ_3**	**θ_5**	**θ_6**	**ω_1**	**ω_2**	**ω_3**	**ω_5**	**ω_6**
1	**0.2**	**0.957375**	**0.00337**	**0.0147**	**0.00209**	**0.00273**	**0.00195**	**0.755**	**0.434**	**0.0890**	**0.500**	**0.306**
2	0.3	0.953638	0.00369	0.0131	0.00246	0.00264	0.00873	0.693	0.392	0.0882	0.299	0.652
3	0.4	0.944342	0.00389	0.0197	0.00288	0.00291	0.00255	0.702	0.406	0.0868	0.774	0.675
4	0.5	0.955456	0.00592	0.0135	0.00224	0.00233	0.00786	0.676	0.409	0.0787	0.645	0.486
5	0.6	0.957254	0.00760	0.0132	0.00224	0.00288	0.00217	0.738	0.443	0.0915	0.746	0.362

Table 5.11 Effect of mutation probability on the availability of the Steam generation system

(Number of gen. = 80, Population size=80, crossover probability=0.85)

S.N.	**P_c**	**Av.**	**θ_1**	**θ_2**	**θ_3**	**θ_5**	**θ_6**	**ω_1**	**ω_2**	**ω_3**	**ω_5**	**ω_6**
1	0.010	0.960318	0.00362	0.0138	0.00186	0.00236	0.00199	0.760	0.419	0.0892	0.768	0.697
2	0.012	0.955427	0.00324	0.0127	0.00256	0.00259	0.00186	0.747	0.389	0.0875	0.294	0.647
3	0.014	0.955695	0.00342	0.0167	0.00233	0.00243	0.00900	0.776	0.448	0.0832	0.680	0.628
4	**0.016**	**0.961711**	**0.00351**	**0.0123**	**0.00288**	**0.00287**	**0.00842**	**0.664**	**0.443**	**0.0771**	**0.632**	**0.359**
5	0.018	0.946947	0.0044	0.0192	0.00351	0.00356	0.00871	0.692	0.448	0.0881	0.721	0.708
6	0.020	0.960552	0.00411	0.0121	0.00228	0.00290	0.00912	0.726	0.406	0.0767	0.629	0.677

Table 5.12 Effect of population size on the availability of the Steam generation system

(Number of generations=80, crossover probability=0.85, mutation probability=0.015)

S.N.	**P. Size**	**Av.**	**θ_1**	**θ_2**	**θ_3**	**θ_5**	**θ_6**	**ω_1**	**ω_2**	**ω_3**	**ω_5**	**ω_6**
1	20	0.914245	0.00721	0.0155	0.00449	0.00612	0.00411	0.354	0.411	0.036	0.310	0.201
2	40	0.934079	0.00775	0.0133	0.00257	0.00262	0.00429	0.330	0.402	0.033	0.325	0.668
3	**60**	**0.959599**	**0.00412**	**0.0124**	**0.00317**	**0.00255**	**0.00842**	**0.626**	**0.421**	**0.072**	**0.634**	**0.701**
4	80	0.947863	0.00393	0.0143	0.00298	0.00249	0.00189	0.750	0.419	0.034	0.297	0.696
5	100	0.953701	0.00360	0.0152	0.00235	0.00296	0.00198	0.759	0.449	0.091	0.322	0.369
6	120	0.959485	0.00340	0.0134	0.00208	0.00276	0.00859	0.613	0.434	0.078	0.643	0.306

Table 5.13 Effect of number of generations on the availability of the Refrigeration system

(Population size=80, crossover probability=0.85, mutation probability=0.015)

S.N.	**No. of gen.**	**Av.**	ϕ_1	ϕ_3	ϕ_5	ϕ_6	ϕ_7	τ_1	τ_3	τ_5	τ_6	τ_7
1	20	0.945948	0.0548	0.0168	0.0025	0.0172	0.0162	0.739	0.759	0.723	0.796	0.615
2	**40**	**0.951774**	**0.0342**	**0.0245**	**0.0027**	**0.0105**	**0.0184**	**0.748**	**0.711**	**0.730**	**0.765**	**0.612**
3	60	0.950713	0.0377	0.0300	0.0034	0.0121	0.0173	0.773	0.738	0.697	0.806	0.615
4	80	0.943339	0.0661	0.0600	0.0023	0.0119	0.0179	0.759	0.721	0.742	0.811	0.620
5	100	0.941236	0.0669	0.0630	0.0022	0.0103	0.0195	0.746	0.710	0.668	0.818	0.610
6	120	0.942455	0.0721	0.0252	0.0028	0.0105	0.0196	0.744	0.710	0.668	0.717	0.608
7	140	0.939756	0.0338	0.0203	0.0027	0.0114	0.0179	0.752	0.774	0.738	0.389	0.629
8	160	0.949543	0.0349	0.0252	0.0028	0.0113	0.0197	0.766	0.730	0.692	0.774	0.628

Table 5.14 Effect of crossover probability on the availability of the Refrigeration system

(Number of gen. = 80, Population size=80, mutation probability=0.015)

S.N.	P_c	**Av.**	ϕ_1	ϕ_3	ϕ_5	ϕ_6	ϕ_7	τ_1	τ_3	τ_5	τ_6	τ_7
1	0.2	0.913967	0.03339	0.0232	0.00264	0.01793	0.02168	0.220	0.203	0.729	0.776	0.611
2	**0.3**	**0.951882**	**0.03119**	**0.02445**	**0.00278**	**0.01027**	**0.01853**	**0.746**	**0.767**	**0.730**	**0.749**	**0.610**
3	0.4	0.947610	0.06815	0.01753	0.00211	0.01014	0.0161	0.745	0.765	0.727	0.690	0.550
4	0.5	0.941624	0.0699	0.0213	0.00304	0.01216	0.0217	0.761	0.726	0.744	0.844	0.625
5	0.6	0.950076	0.04176	0.0239	0.00336	0.01106	0.01874	0.751	0.717	0.690	0.795	0.630

Table 5.15 Effect of mutation probability on the availability of the Refrigeration system

(Number of gen. = 80, Population size=80, crossover probability=0.85)

S.N.	**P_m**	**Av.**	**ϕ_1**	**ϕ_3**	**ϕ_5**	**ϕ_6**	**ϕ_7**	**τ_1**	**τ_3**	**τ_5**	**τ_6**	**τ_7**
1	0.010	0.935368	0.03821	0.02299	0.00257	0.01345	0.01676	0.774	0.735	0.696	0.376	0.635
2	0.012	0.946821	0.04051	0.03184	0.0036	0.01309	0.02000	0.769	0.731	0.753	0.829	0.642
3	0.014	0.936918	0.07044	0.06377	0.00725	0.01075	0.01763	0.750	0.713	0.732	0.808	0.614
4	0.016	0.939767	0.03739	0.04626	0.00523	0.01147	0.01732	0.650	0.653	0.613	0.808	0.516
5	**0.018**	**0.951199**	**0.06803**	**0.01669**	**0.00253**	**0.01004**	**0.01635**	**0.744**	**0.766**	**0.726**	**0.797**	**0.608**
6	0.020	0.950191	0.06553	0.01741	0.00262	0.01075	0.01677	0.750	0.714	0.673	0.801	0.614

Table 5.16 Effect of population size on the availability of the Refrigeration system

(Number of generations=80, crossover probability=0.85, mutation probability=0.015)

S. N.	**P. Size**	**Av.**	**ϕ_1**	**ϕ_3**	**ϕ_5**	**ϕ_6**	**ϕ_7**	**τ_1**	**τ_3**	**τ_5**	**τ_6**	**τ_7**
1	20	0.896764	0.07105	0.02462	0.00292	0.03814	0.02025	0.576	0.602	0.558	0.764	0.456
2	40	0.940643	0.03325	0.02307	0.00262	0.01106	0.01685	0.751	0.717	0.735	0.377	0.616
3	60	0.876706	0.03676	0.02738	0.00312	0.02842	0.02228	0.490	0.464	0.474	0.426	0.379
4	80	0.916519	0.04015	0.02775	0.00256	0.03536	0.01637	0.310	0.714	0.674	0.799	0.612
5	100	0.951242	0.04214	0.02436	0.00343	0.01093	0.01773	0.763	0.727	0.749	0.763	0.625
6	**120**	**0.953133**	**0.03325**	**0.02344**	**0.00262**	**0.01026**	**0.01731**	**0.744**	**0.710**	**0.668**	**0.738**	**0.610**

Table 5.17 Effect of number of generations on the availability of the Feeding system
(Population size=80, crossover probability=0.85, mutation probability=0.015)

S. N.	**No. of gen.**	**Av.**	**ε_1**	**ε_3**	**ε_4**	**ε_6**	**Δ_1**	**Δ_3**	**Δ_4**	**Δ_6**
1	20	0.980448	0.0050	0.0068	0.0092	0.0021	0.0310	0.1377	0.1953	0.0103
2	40	0.978234	0.0026	0.0033	0.0054	0.0032	0.0818	0.1681	0.1654	0.1558
3	60	0.979975	0.0029	0.0031	0.0050	0.0069	0.1379	0.1783	0.1790	0.1573
4	80	0.979353	0.0050	0.0031	0.0051	0.0051	0.1420	0.1679	0.2174	0.1753
5	100	0.979540	0.0027	0.0031	0.0055	0.0050	0.1779	0.1890	0.1962	0.0849
6	120	0.977307	0.0036	0.0037	0.0047	0.0047	0.1228	0.1812	0.2168	0.1160
7	140	0.981059	0.0028	0.0032	0.0056	0.0030	0.1726	0.1804	0.1913	0.1392
8	**160**	**0.981149**	**0.0028**	**0.0032**	**0.0056**	**0.0030**	**0.1726**	**0.1804**	**0.1913**	**0.1392**

Table 5.18 Effect of crossover probability on the availability of the Feeding system
(Number of generation=80, population size=80, mutation probability=0.015)

S. N.	**P_c**	**Av.**	**ε_1**	**ε_3**	**ε_4**	**ε_6**	**Δ_1**	**Δ_3**	**Δ_4**	**Δ_6**
1	0.2	0.979105	0.0043	0.0033	0.0072	0.0077	0.1400	0.1895	0.2089	0.1756
2	0.3	0.975971	0.0043	0.0033	0.0072	0.0077	0.1400	0.1895	0.2089	0.1756
3	0.4	0.978297	0.0031	0.0033	0.0043	0.0046	0.1411	0.1735	0.1946	0.1014
4	**0.5**	**0.980689**	**0.0037**	**0.0032**	**0.0054**	**0.0038**	**0.1172**	**0.1836**	**0.1960**	**0.1643**
5	0.6	0.978608	0.0028	0.0034	0.0050	0.0036	0.1621	0.1675	0.1996	0.1785
6	0.7	0.977640	0.0028	0.0031	0.0045	0.0033	0.1402	0.1452	0.2147	0.1332

Table 5.19 Effect of mutation probability on the availability of the Feeding system

(Number of generation=80, population size=80, crossover probability=0.85)

S.N.	**P_m**	**Av.**	**ε_1**	**ε_3**	**ε_4**	**ε_6**	**Δ_1**	**Δ_3**	**Δ_4**	**Δ_6**
1	0.010	0.979043	0.0042	0.0033	0.0061	0.0033	0.1756	0.1748	0.1635	0.1402
2	0.012	0.978215	0.0033	0.0036	0.0048	0.0031	0.1152	0.1800	0.1841	0.1271
3	**0.014**	**0.981094**	**0.0041**	**0.0031**	**0.0045**	**0.0050**	**0.1682**	**0.1814**	**0.2188**	**0.1506**
4	0.016	0.979634	0.0038	0.0032	0.0049	0.0040	0.1650	0.1806	0.1754	0.0899
5	0.018	0.978472	0.0045	0.0038	0.0048	0.0050	0.1551	0.1898	0.2012	0.1732
6	0.020	0.976018	0.0038	0.0041	0.0044	0.0052	0.1329	0.1898	0.1907	0.1287

Table 5.20 Effect of population size on the availability of the Feeding system

(Number of generations=80, crossover probability=0.85, mutation probability=0.015)

S. N.	**P. Size**	**Av.**	**ε_1**	**ε_3**	**ε_4**	**ε_6**	**Δ_1**	**Δ_3**	**Δ_4**	**Δ_6**
1	20	0.977307	0.0034	0.0042	0.0048	0.00517	0.1282	0.1823	0.2153	0.1149
2	40	0.977540	0.0029	0.0034	0.0055	0.0042	0.1301	0.1431	0.2151	0.1326
3	60	0.979540	0.0032	0.0033	0.0064	0.0043	0.1782	0.1870	0.1942	0.0832
4	80	0.979043	0.0045	0.0037	0.0068	0.0032	0.1759	0.1751	0.1665	0.1404
5	100	0.978297	0.0035	0.0035	0.0053	0.0048	0.1423	0.1745	0.1951	0.1015
6	**120**	**0.979634**	**0.0041**	**0.0031**	**0.0051**	**0.0045**	**0.1653**	**0.1826**	**0.1758**	**0.0829**

Table 5.21 Effect of number of generations on the availability of the Crushing system

(Population size=80, crossover probability=0.85, mutation probability=0.015)

S. N.	**No. of gen.**	**Av.**	σ_1	σ_2	σ_3	ρ_1	ρ_2	ρ_3
1	20	0.858904	0.004239	0.006462	0.007616	0.077926	0.092154	0.095793
2	40	0.842942	0.005520	0.006739	0.006127	0.082303	0.082646	0.081237
3	60	0.855307	0.004203	0.006503	0.007276	0.073892	0.088143	0.094454
4	80	0.849666	0.004342	0.007028	0.006051	0.078745	0.091517	0.067245
5	100	0.864883	0.004444	0.006451	0.006171	0.091104	0.093095	0.080868
6	**120**	**0.86705**	**0.004257**	**0.006944**	**0.006101**	**0.090133**	**0.094176**	**0.094216**
7	140	0.86179	0.004299	0.006344	0.007083	0.090199	0.094955	0.077144
8	160	0.852355	0.004839	0.006356	0.006215	0.089183	0.080224	0.078205

Table 5.22 Effect of crossover probability on the availability of the Crushing system

(Number of gen. = 80, Population size=80, mutation probability=0.015)

S. N.	P_c	**Av.**	σ_1	σ_2	σ_3	ρ_1	ρ_2	ρ_3
1	0.2	0.858237	0.004403	0.006422	0.006353	0.076952	0.086127	0.095099
2	0.3	0.844501	0.005656	0.006550	0.007482	0.084341	0.091042	0.082894
3	0.4	0.850759	0.005773	0.006475	0.007724	0.097729	0.093131	0.082496
4	0.5	0.847623	0.004777	0.006576	0.005967	0.070042	0.082131	0.094688
5	**0.6**	**0.864638**	**0.005002**	**0.006547**	**0.005852**	**0.090685**	**0.092585**	**0.095363**

Table 5.23 Effect of mutation probability on the availability of the Crushing system

(Number of gen. = 80, Population size=80, crossover probability=0.85)

S. N.	**P_m**	**Av.**	**σ_1**	**σ_2**	**σ_3**	**ρ_1**	**ρ_2**	**ρ_3**
1	0.010	0.864041	0.004390	0.006518	0.006486	0.088307	0.093890	0.084867
2	0.012	0.859906	0.004738	0.006472	0.007978	0.095628	0.093928	0.089701
3	**0.014**	**0.86505**	**0.005213**	**0.006383**	**0.006164**	**0.094757**	**0.094262**	**0.092657**
4	0.016	0.852495	0.005432	0.006353	0.006771	0.092738	0.090196	0.076923
5	0.018	0.853843	0.005063	0.006589	0.007322	0.096067	0.084073	0.091292
6	0.020	0.856291	0.004516	0.006938	0.006087	0.082616	0.094600	0.076414

Table 5.24 Effect of population size on the availability of the Crushing system

(Number of generations=80, crossover probability=0.85, mutation probability=0.015)

S. N.	**P. Size**	**Av.**	**σ_1**	**σ_2**	**σ_3**	**ρ_1**	**ρ_2**	**ρ_3**
1	20	0.854328	0.004689	0.006436	0.007556	0.077145	0.092284	0.094463
2	40	0.857213	0.005173	0.006628	0.007160	0.093873	0.090750	0.093141
3	60	0.858272	0.004334	0.006753	0.007179	0.086141	0.087681	0.094938
4	**80**	**0.860453**	**0.004594**	**0.006324**	**0.006518**	**0.097348**	**0.082298**	**0.085437**
5	100	0.853134	0.006027	0.006751	0.006663	0.097780	0.089387	0.095208
6	120	0.849776	0.004415	0.006409	0.007178	0.067606	0.094765	0.081864

Table 5.25 Effect of number of generations on the availability of the Refining system
(Population size=80, crossover probability=0.85, mutation probability=0.015)

S. N.	**No. of gen.**	**Av.**	η_1	η_4	η_5	η_7	ξ_1	ξ_4	ξ_5	ξ_7
1	20	0.947190	0.0024	0.0042	0.0014	0.0032	0.1070	0.4931	0.0785	0.0724
2	40	0.947850	0.0037	0.0033	0.0030	0.0032	0.1429	0.5763	0.0738	0.0729
3	60	0.947185	0.0030	0.0041	0.0019	0.0031	0.1411	0.2788	0.0892	0.0805
4	80	0.945659	0.0026	0.0035	0.0019	0.0032	0.1398	0.2842	0.0789	0.0747
5	100	0.939998	0.0028	0.0025	0.0021	0.0033	0.1314	0.2989	0.0681	0.0628
6	**120**	**0.950913**	**0.0023**	**0.0046**	**0.0024**	**0.0033**	**0.1139**	**0.5636**	**0.0779**	**0.0821**
7	140	0.947915	0.0021	0.0022	0.0015	0.0032	0.0893	0.5586	0.0916	0.0662
8	160	0.943120	0.0024	0.0053	0.0013	0.0038	0.1216	0.5702	0.0912	0.0779

Table 5.26 Effect of crossover probability on the availability of the Refining system
(Number of generation=80, population size=80, mutation probability=0.015)

S. N.	P_c	**Av.**	η_1	η_4	η_5	η_7	ξ_1	ξ_4	ξ_5	ξ_7
1	0.2	0.942722	0.0042	0.0035	0.0016	0.0036	0.1277	0.2507	0.0758	0.0838
2	0.3	0.936429	0.0024	0.0045	0.0019	0.0034	0.0992	0.4209	0.0807	0.0637
3	0.4	0.946498	0.0031	0.0039	0.0022	0.0037	0.1099	0.5732	0.0892	0.0802
4	0.5	0.943462	0.0036	0.0063	0.0020	0.0034	0.1287	0.5585	0.0669	0.0776
5	0.6	0.949394	0.0022	0.0057	0.0022	0.0034	0.1453	0.6519	0.0744	0.0826
5	0.7	0.940521	0.0026	0.0074	0.0016	0.0032	0.1260	0.3459	0.0856	0.0813
6	0.8	0.944033	0.0020	0.0024	0.0019	0.0037	0.0815	0.4308	0.0806	0.0746
7	**0.9**	**0.949927**	**0.0027**	**0.0044**	**0.0018**	**0.0031**	**0.1084**	**0.4075**	**0.0721**	**0.0813**

Table 5.27 Effect of mutation probability on the availability of the Refining system

(Number of generation=80, population size=80, crossover probability=0.85)

S. N.	**P_m**	**Av.**	**η_1**	**η_4**	**η_5**	**η_7**	**ξ_1**	**ξ_4**	**ξ_5**	**ξ_7**
5	0.010	0.945249	0.0040	0.0023	0.0013	0.0037	0.1298	0.4015	0.0876	0.0756
4	0.012	0.941895	0.0037	0.0077	0.0015	0.0040	0.1456	0.6579	0.0862	0.0837
1	0.014	0.946222	0.0035	0.0023	0.0016	0.0032	0.1025	0.3851	0.0776	0.0684
6	**0.016**	**0.946441**	**0.0020**	**0.0042**	**0.0015**	**0.0033**	**0.0949**	**0.4439**	**0.0561**	**0.0759**
8	0.018	0.940003	0.0022	0.0031	0.0024	0.0039	0.1302	0.5553	0.0592	0.0732
2	0.020	0.944683	0.0020	0.0041	0.0013	0.0036	0.0994	0.5677	0.0588	0.0740

Table 5.28 Effect of population size on the availability of the Refining system

(Number of generation=80, crossover probability=0.85, mutation probability=0.015)

S. N.	**P. Size**	**Av.**	**η_1**	**η_4**	**η_5**	**η_7**	**ξ_1**	**ξ_4**	**ξ_5**	**ξ_7**
1	20	0.949865	0.0025	0.0036	0.0025	0.0033	0.1434	0.6731	0.0892	0.0738
2	30	0.952364	0.0024	0.0036	0.0027	0.0032	0.1095	0.5477	0.0720	0.0825
3	40	0.949531	0.0031	0.0061	0.0013	0.0032	0.1165	0.5217	0.0706	0.0838
4	**50**	**0.954268**	**0.0023**	**0.0025**	**0.0018**	**0.0034**	**0.1301**	**0.5144**	**0.0830**	**0.0822**
5	60	0.937138	0.0032	0.0034	0.0027	0.0034	0.0981	0.3033	0.0911	0.0671

Table 5.29 Effect of number of generations on the availability of the Evaporation system

(Population size=80, crossover probability=0.85, mutation probability=0.015)

S. N.	**No. of gen.**	**Av.**	**ψ_1**	**ψ_3**	**ψ_4**	**γ_1**	**γ_3**	**γ_4**
1	20	0.92563	0.00181125	0.006407	0.002224	0.018766	0.111474	0.095097
2	40	0.929279	0.001508461	0.006415	0.00222	0.016519	0.108306	0.115764
3	60	0.916769	0.002492301	0.006975	0.002164	0.024738	0.099486	0.115489
4	**80**	**0.929681**	**0.000982000**	**0.006366**	**0.002408**	**0.016854**	**0.109264**	**0.11969**
5	100	0.928973	0.001402000	0.006602	0.002442	0.025963	0.116862	0.117712
6	120	0.921667	0.000946000	0.007078	0.002331	0.020353	0.113897	0.09731
7	140	0.92563	0.001811250	0.006407	0.002224	0.018766	0.111474	0.095097
8	160	0.929279	0.001508461	0.006415	0.00222	0.016519	0.108306	0.115764

Table 5.30 Effect of crossover probability on the availability of the Evaporation system

(Number of gen. = 80, Population size=80, mutation probability=0.015)

S. N.	**P_c**	**Av.**	**ψ_1**	**ψ_3**	**ψ_4**	**γ_1**	**γ_3**	**γ_4**
1	**0.2**	**0.930074**	**0.001215**	**0.006467**	**0.00251**	**0.023182**	**0.118381**	**0.115457**
2	0.3	0.926485	0.001254	0.006422	0.002386	0.023196	0.107203	0.116188
3	0.4	0.928933	0.002348	0.006318	0.002279	0.017016	0.116393	0.10937
4	0.5	0.929371	0.001301	0.006893	0.002236	0.019856	0.119554	0.112777
5	0.6	0.929263	0.001362	0.00685	0.002199	0.024278	0.11816	0.116437

Table 5.31 Effect of mutation probability on the availability of the Evaporation system

(Number of gen. =80, Population size=80, crossover probability=0.85)

S. N.	**P_m**	**Av.**	**ψ_1**	**ψ_3**	**ψ_4**	**γ_1**	**γ_3**	**γ_4**
1	**0.010**	**0.932115**	**0.001310**	**0.006356**	**0.002181**	**0.024986**	**0.119119**	**0.108608**
2	0.012	0.921137	0.001066	0.007372	0.002354	0.02177	0.114936	0.104294
3	0.014	0.926253	0.002370	0.006508	0.002302	0.026125	0.11228	0.111957
4	0.016	0.925598	0.001960	0.006524	0.002475	0.020435	0.110082	0.112787
5	0.018	0.925877	0.001610	0.006825	0.002607	0.025042	0.117982	0.11281
6	0.020	0.930159	0.001097	0.006611	0.002163	0.024144	0.116858	0.112323

Table 5.32 Effect of population size on the availability of the Evaporation system

(Number of gen. =80, crossover probability=0.85, mutation probability=0.015)

S. N.	**P. Size**	**Av.**	**ψ_1**	**ψ_3**	**ψ_4**	**γ_1**	**γ_3**	**γ_4**
1	20	0.924900	0.001625	0.006699	0.00237	0.016136	0.112839	0.097714
2	40	0.927333	0.002091	0.006371	0.002111	0.026314	0.110197	0.1066
3	60	0.922988	0.002263	0.007322	0.002243	0.021087	0.116769	0.113894
4	80	0.923922	0.002438	0.007101	0.002229	0.016646	0.118162	0.111818
5	100	0.927056	0.002411	0.006569	0.002247	0.019871	0.11953	0.102851
6	**120**	**0.931899**	**0.001503**	**0.006351**	**0.002215**	**0.017108**	**0.113098**	**0.116628**

Table 5.33 Effect of number of generations on the availability of the Crystallization system

(Population size=80, crossover probability=0.85, mutation probability=0.015)

S. N.	**No. of gen.**	**Av.**	**δ_1**	**δ_3**	**δ_6**	**$ø_1$**	**$ø_3$**	**$ø_6$**
1	20	0.918945	0.006894	0.007173	0.009341	0.13696	0.49917	0.08649
2	40	0.957698	0.007044	0.001914	0.009223	0.09308	0.85004	0.08517
3	60	0.930729	0.007086	0.006764	0.009499	0.14944	0.36079	0.08516
4	80	0.910404	0.006138	0.005957	0.009384	0.32363	0.32135	0.08639
5	100	0.940257	0.007145	0.007711	0.009628	0.03114	0.41923	0.08690
6	**120**	**0.964956**	**0.006738**	**0.002191**	**0.009619**	**0.03212**	**0.94785**	**0.08690**
7	140	0.936807	0.005865	0.008481	0.009384	0.01574	0.50713	0.08697
8	160	0.896937	0.005725	0.007656	0.009485	0.10794	0.78291	0.08568

Table 5.34 Effect of crossover probability on the availability of the Crystallization system

(Number of gen. = 80, Population size=80, mutation probability=0.015)

S. N.	**P_c**	**Av.**	**δ_1**	**δ_3**	**δ_6**	**$ø_1$**	**$ø_3$**	**$ø_6$**
1	0.2	0.953678	0.006772	0.001652	0.009225	0.14937	0.909814	0.08638
2	**0.3**	**0.969572**	**0.004935**	**0.001619**	**0.009780**	**0.02305**	**0.885348**	**0.08625**
3	0.4	0.960499	0.007091	0.002118	0.009488	0.07310	0.940481	0.08533
4	0.5	0.936503	0.005810	0.007153	0.009787	0.05216	0.039733	0.08543
5	0.6	0.924514	0.007077	0.006650	0.009224	0.08318	0.045617	0.08674

Table 5.35 Effect of mutation probability on the availability of the Evaporation system

(Number of gen. = 80, Population size=80, crossover probability=0.85)

S. N.	**P_m**	**Av.**	**δ_1**	**δ_3**	**δ_6**	**$ø_1$**	**$ø_3$**	**$ø_6$**
1	0.010	0.928500	0.005014	0.008473	0.009553	0.18784	0.035353	0.08598
2	**0.012**	**0.952531**	**0.007217**	**0.003642**	**0.009554**	**0.02237**	**0.927002**	**0.08620**
3	0.014	0.934049	0.006161	0.007993	0.009753	0.20090	0.031768	0.08559
4	0.016	0.930953	0.005923	0.005662	0.009687	0.11113	0.030925	0.08501
5	0.018	0.931625	0.007447	0.005215	0.009392	0.08875	0.937601	0.08644
6	0.020	0.919275	0.007197	0.007343	0.009730	0.05274	0.944741	0.08662

Table 5.36 Effect of population size on the availability of the Crystallization system

(Number of generations=80, crossover probability=0.85, mutation probability=0.015)

S.N.	**P. Size**	**Av.**	**δ_1**	**δ_3**	**δ_6**	**$ø_1$**	**$ø_3$**	**$ø_6$**
1	20	0.928703	0.006321	0.001762	0.009232	0.032515	0.905499	0.08508
2	40	0.931474	0.004963	0.005373	0.009407	0.005415	0.944365	0.08675
3	60	0.924243	0.007246	0.004343	0.009759	0.019651	0.880000	0.08681
4	80	0.906515	0.005389	0.007518	0.009712	0.007817	0.069011	0.08578
5	100	0.926983	0.007475	0.002043	0.009467	0.035486	0.808137	0.08689
6	**120**	**0.940985**	**0.006658**	**0.007503**	**0.009247**	**0.010847**	**0.328142**	**0.08602**

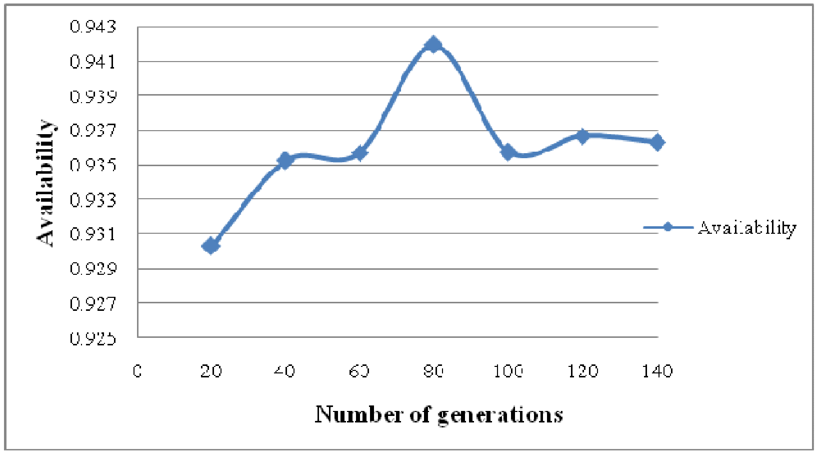


Fig. 5.2 Effect of number of generations on the availability of the Skim milk powder production system

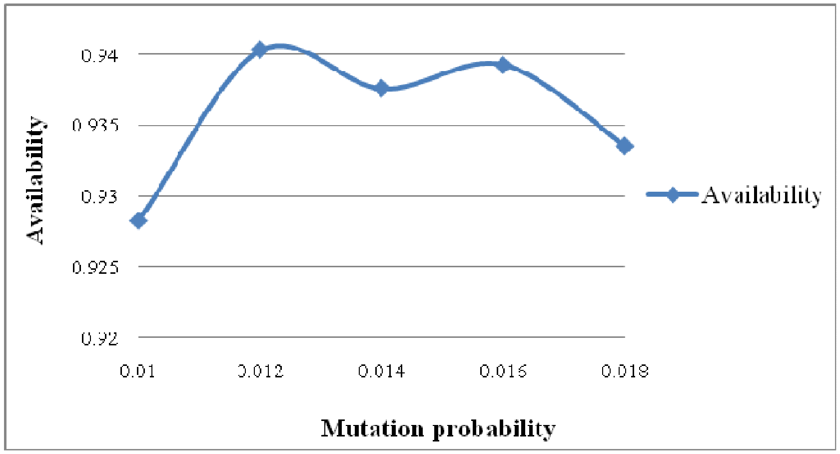


Fig. 5.4 Effect of mutation probability on the availability of the Skim milk powder production system

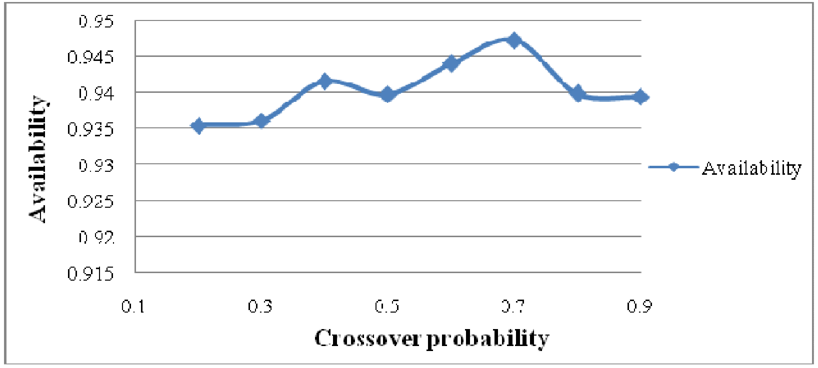


Fig.5.3 Effect of crossover probability on the availability of the Skim milk powder production system

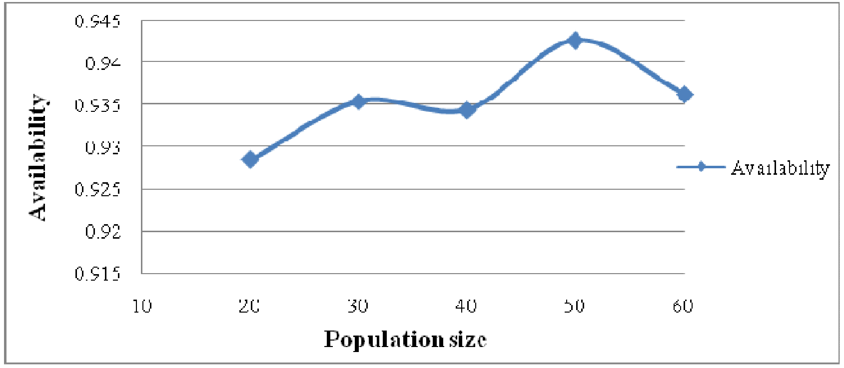


Fig. 5.5 Effect of population size on the availability of the Skim milk powder production system

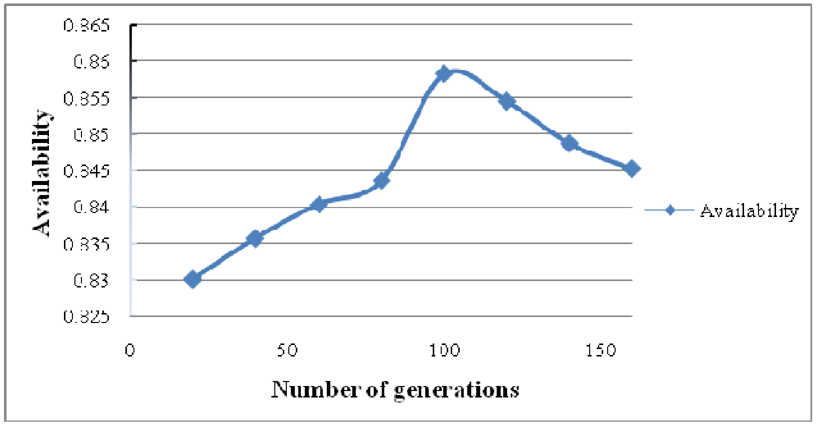


Fig. 5.6 Effect of number of generations on the availability of the Butter oil production system

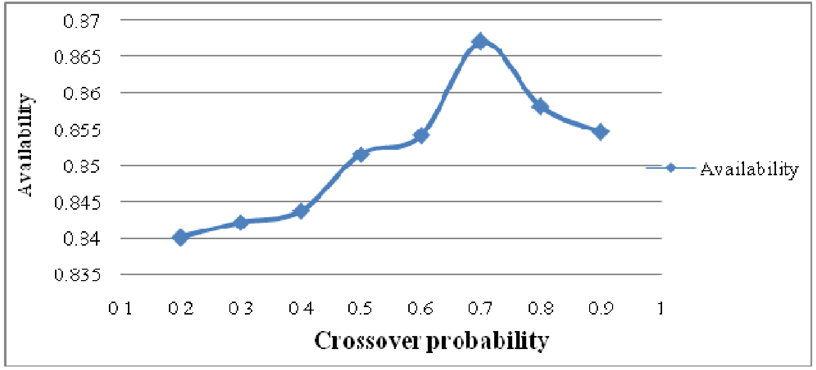


Fig. 5.7 Effect of crossover probability on the availability of the Butter oil production system

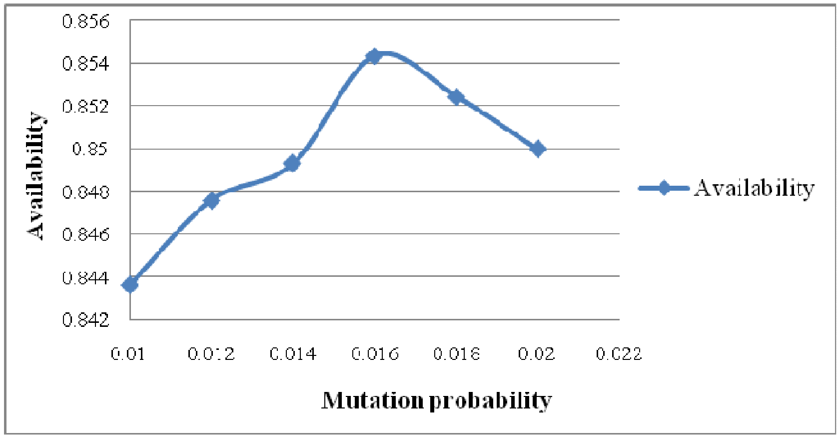


Fig. 5.8 Effect of mutation probability on the availability of the Butter oil production system

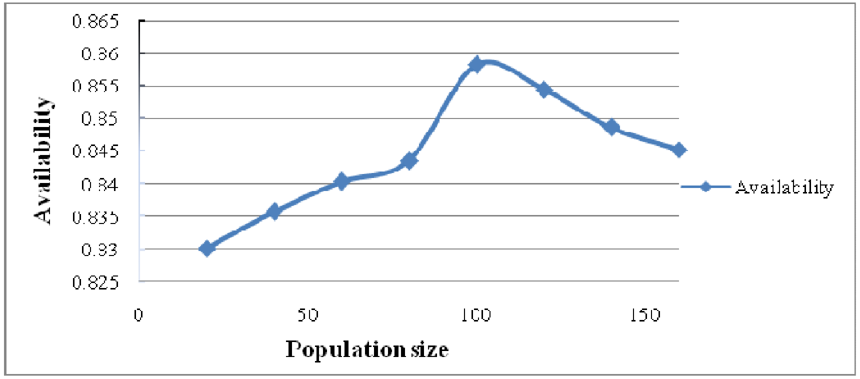


Fig. 5.9 Effect of population size on the availability of the Butter oil production system

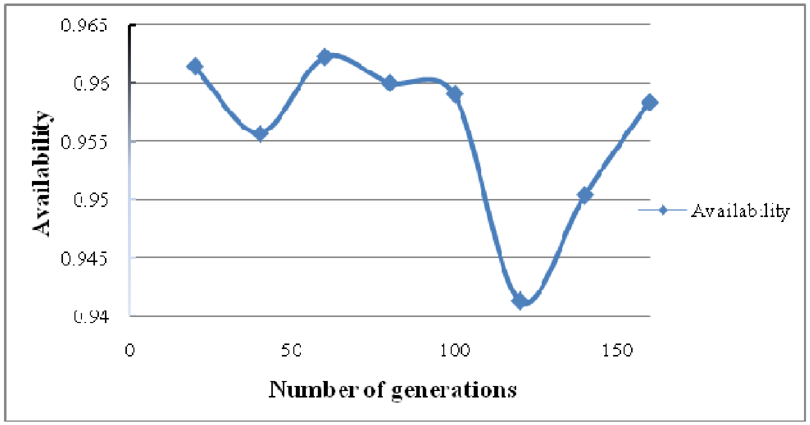


Fig. 5.10 Effect of number of generations on the availability of the Steam generation system

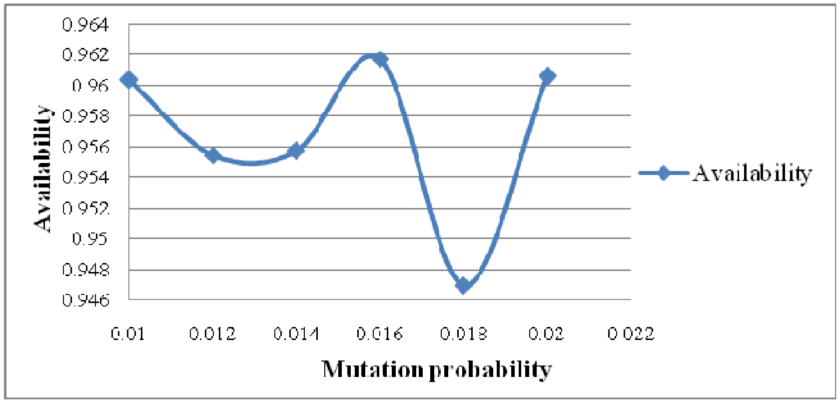


Fig. 5.12 Effect of mutation probability on the availability of the Steam generation system

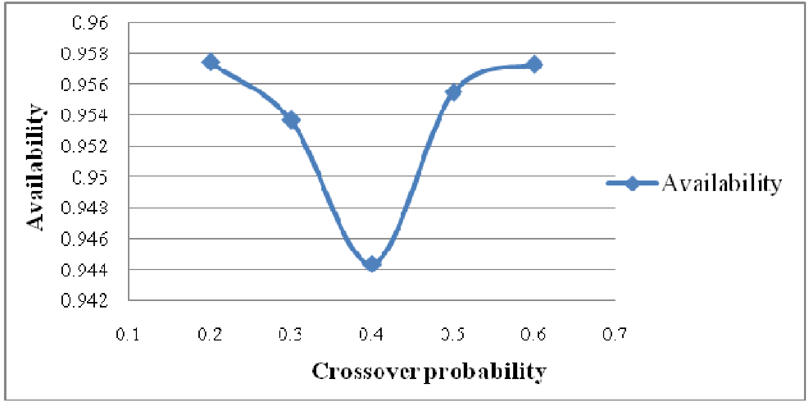


Fig. 5.11 Effect of crossover probability on the availability of the Steam generation system

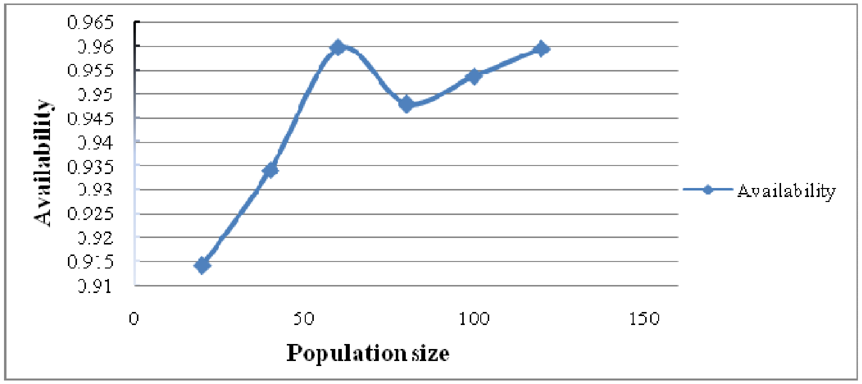


Fig. 5.13 Effect of population size on the availability of the Steam generation system

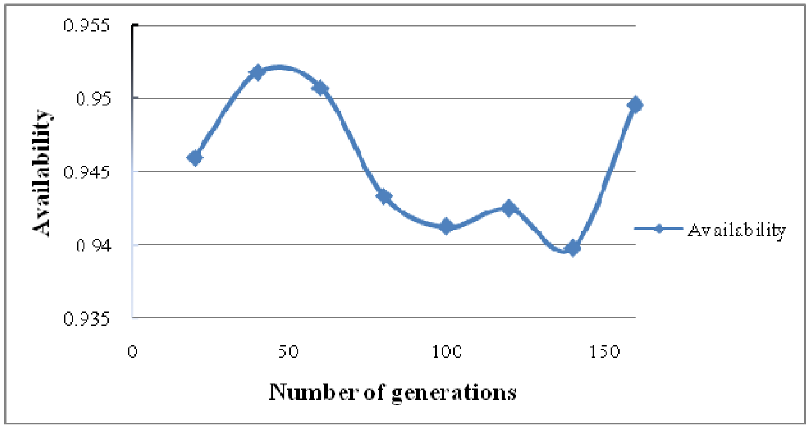


Fig. 5.14 Effect of number of generations on the availability of the Refrigeration system

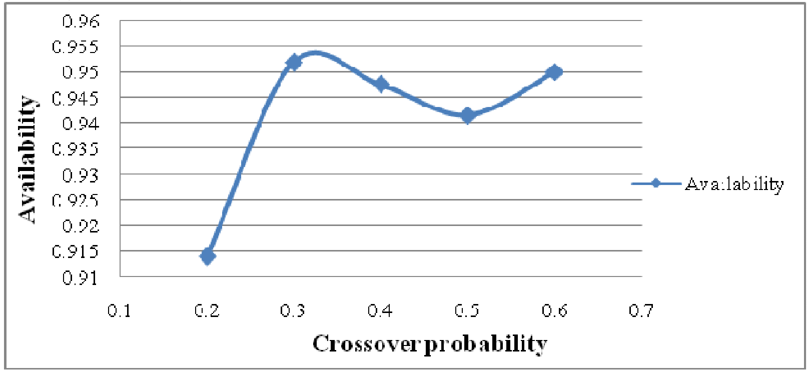


Fig. 5.15 Effect of crossover probability on the availability of the Refrigeration system

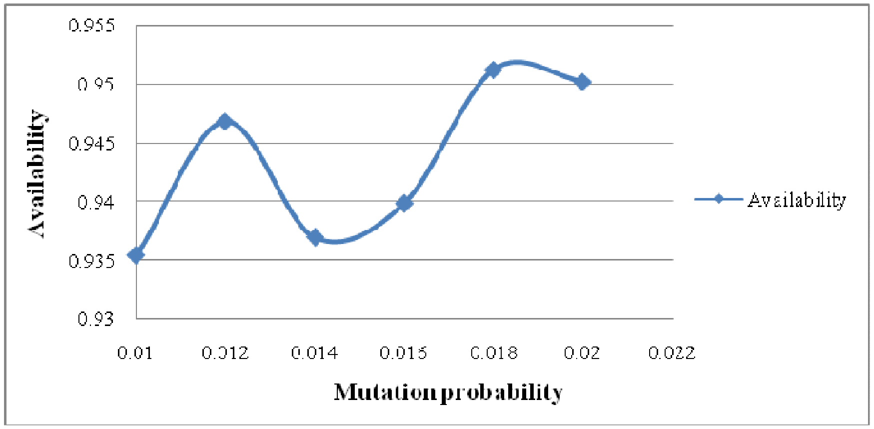


Fig. 5.16 Effect of mutation probability on the availability of the Refrigeration system

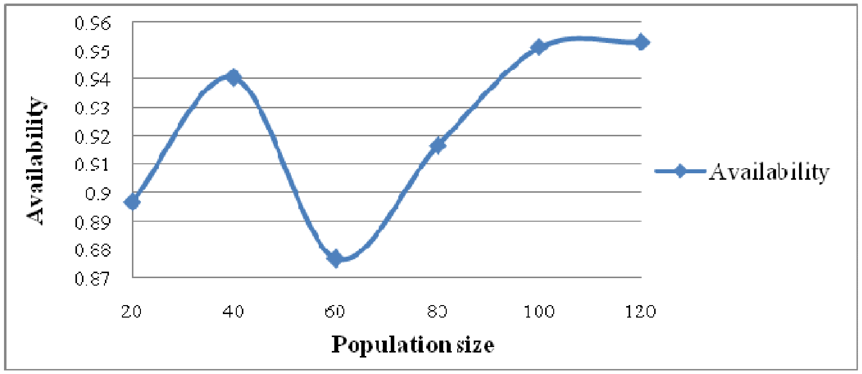


Fig. 5.17 Effect of population size on the availability of the Refrigeration system

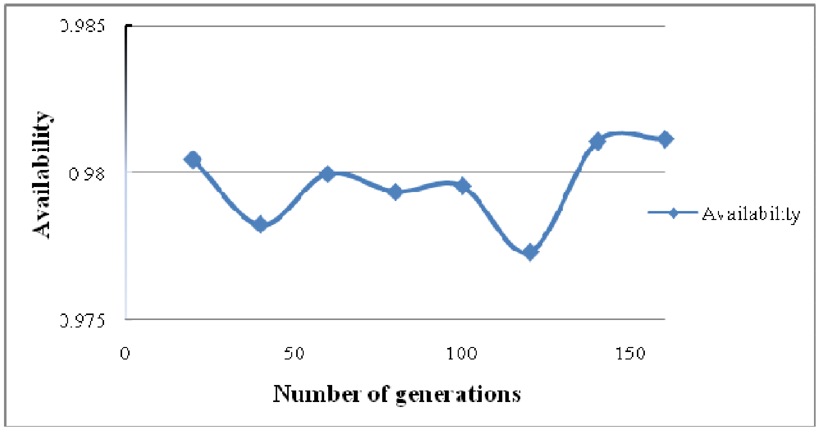


Fig. 5.18 Effect of number of generations on the availability of the Feeding system

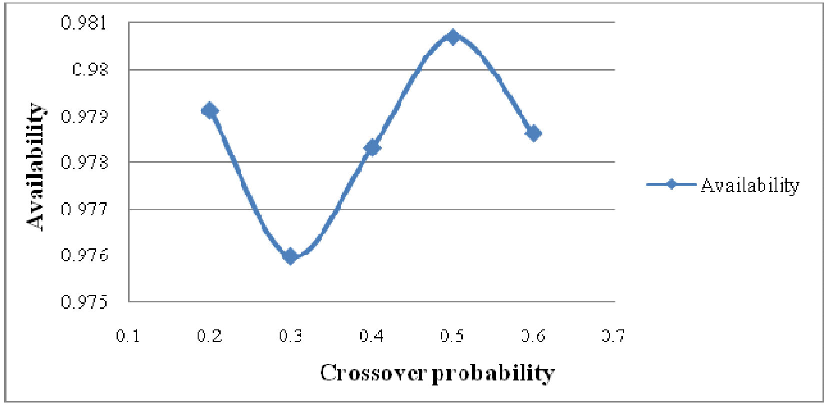


Fig. 5.19 Effect of crossover probability on the availability of the Feeding system

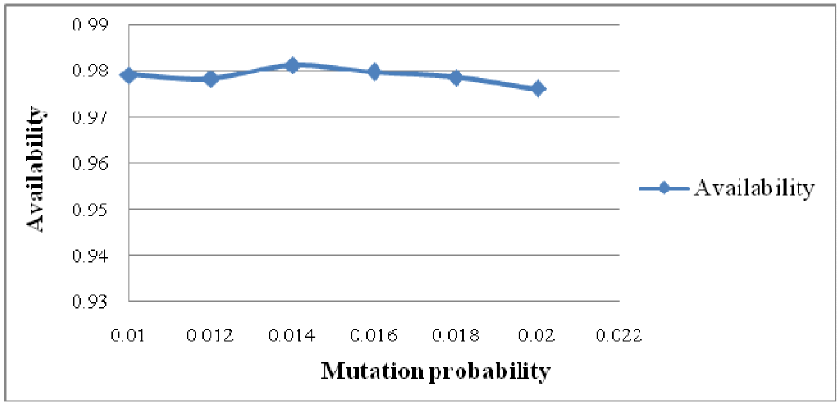


Fig. 5.20 Effect of mutation probability on the availability of the Feeding system

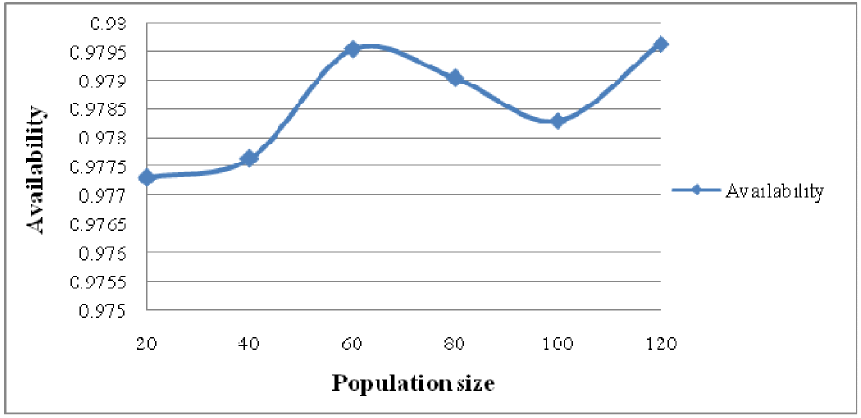


Fig. 5.21 Effect of population size on the availability of the Feeding system

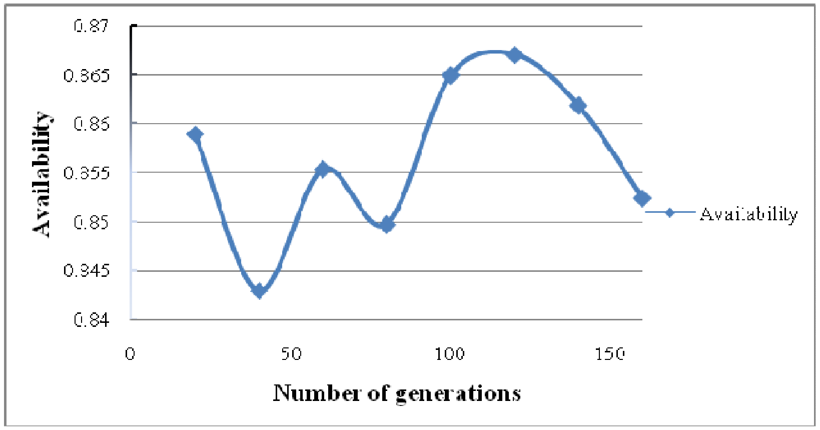


Fig. 5.22 Effect of number of generations on the availability of the Crushing system

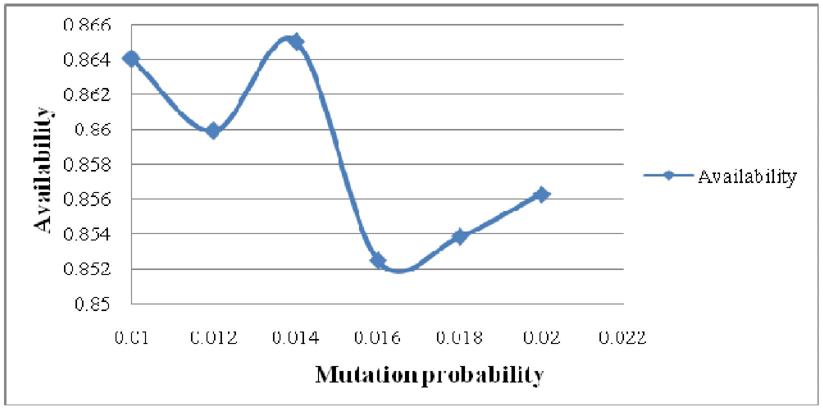


Fig. 5.24 Effect of mutation probability on the availability of the Crushing system

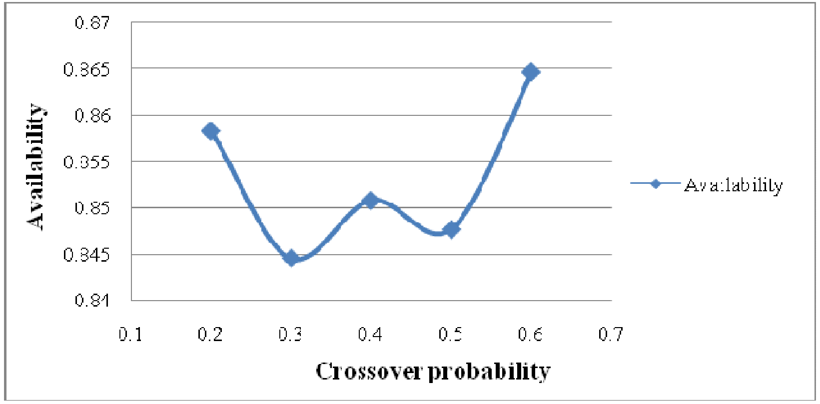


Fig. 5.23 Effect of crossover probability on the availability of the Crushing system

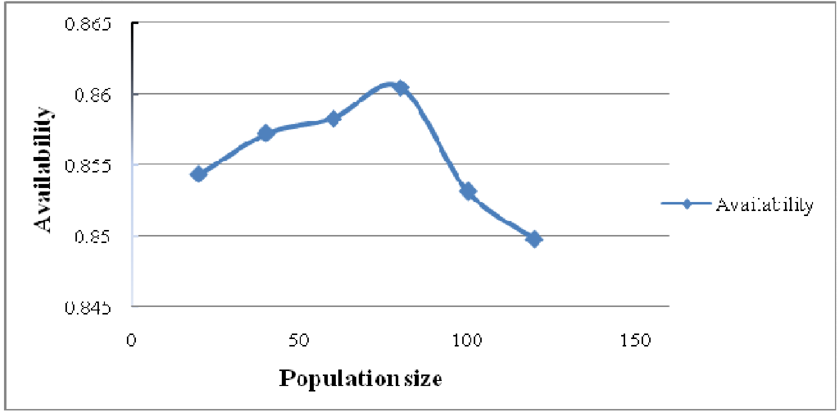


Fig. 5.25 Effect of population size on the availability of the Crushing system

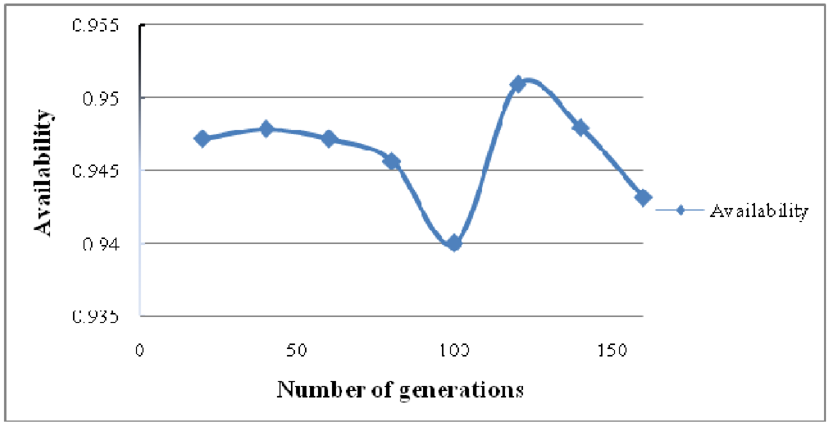


Fig. 5.26 Effect of number of generations on the availability of the Refining system

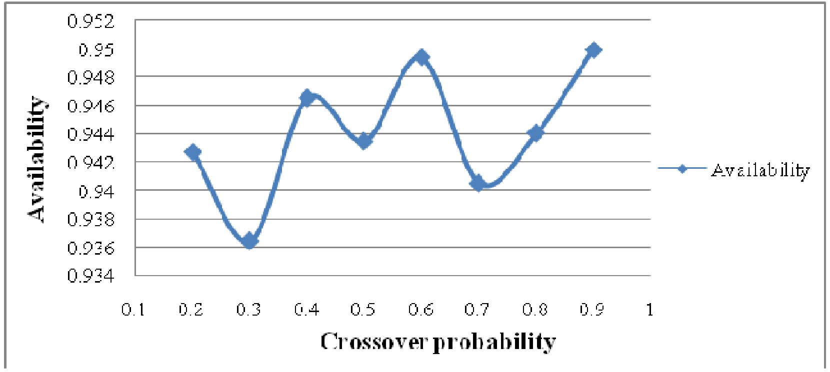


Fig. 5.27 Effect of crossover probability on the availability of the Refining system

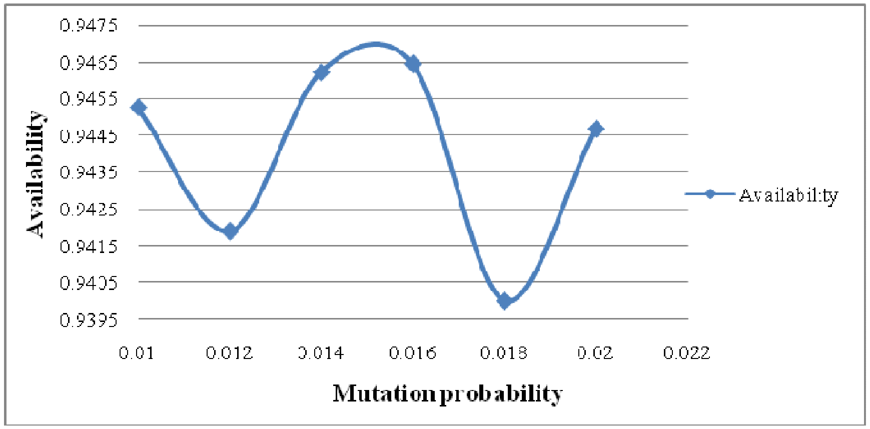


Fig. 5.28 Effect of mutation probability on the availability of the Refining system

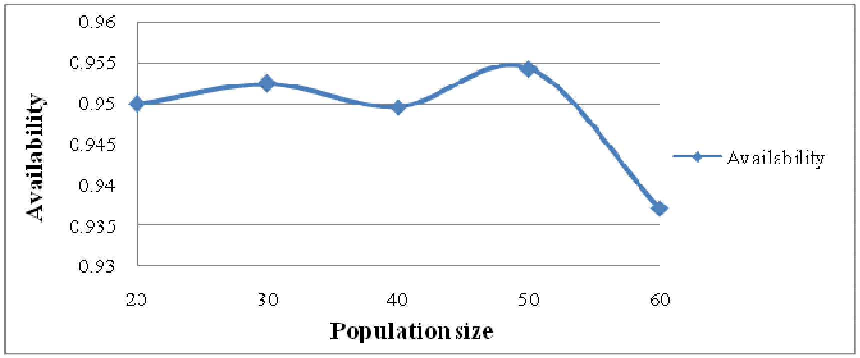


Fig. 5.29 Effect of population size on the availability of the Refining system

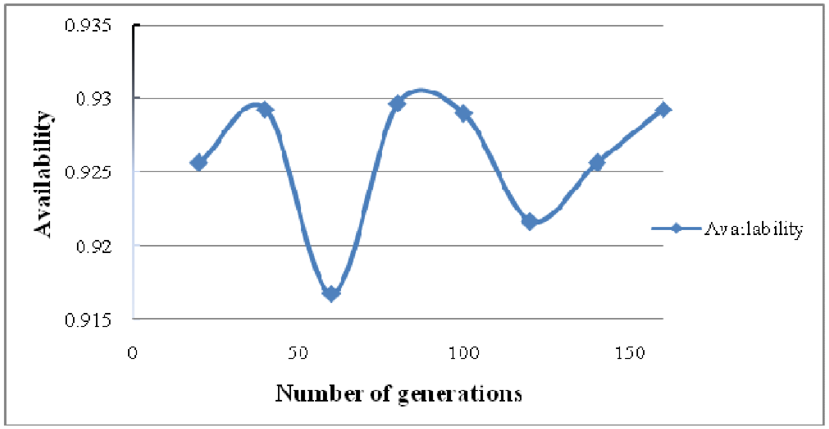


Fig. 5.30 Effect of number of generations on the availability of the Evaporation system

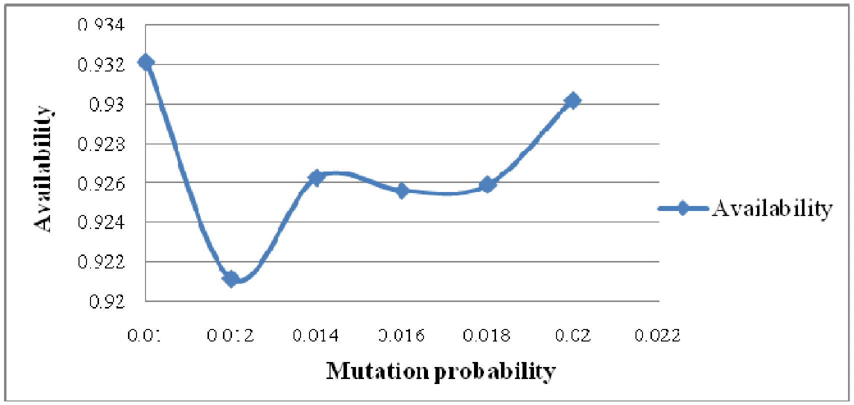


Fig. 5.32 Effect of mutation probability on the availability of the Evaporation system

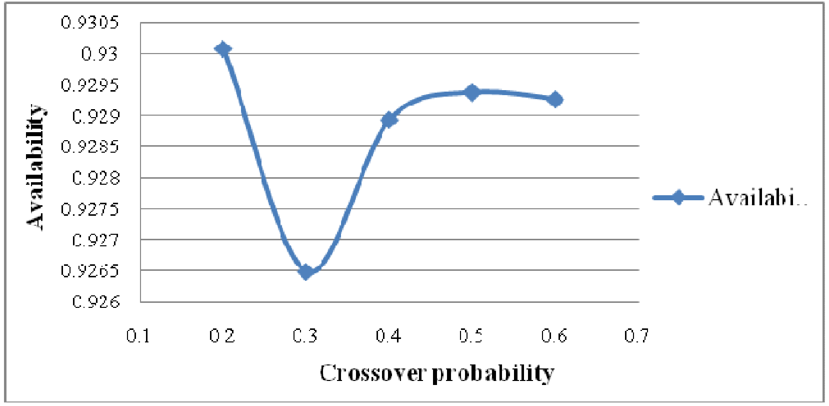


Fig. 5.31 Effect of crossover probability on the availability of the Evaporation system

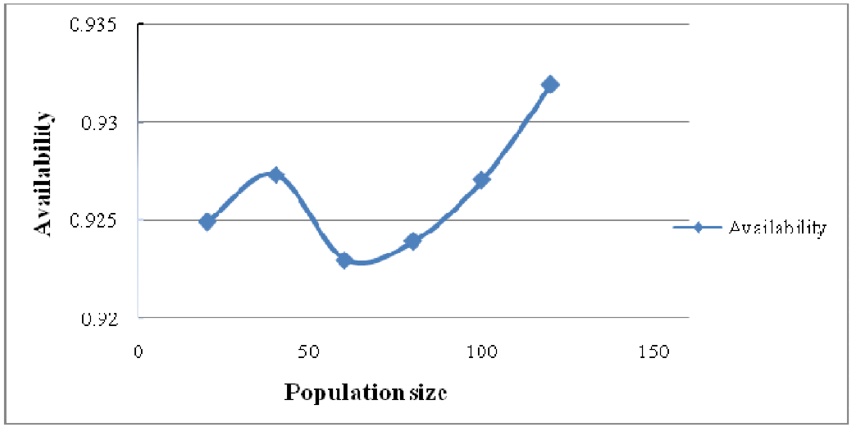


Fig. 5.33 Effect of population size on the availability of the Evaporation system

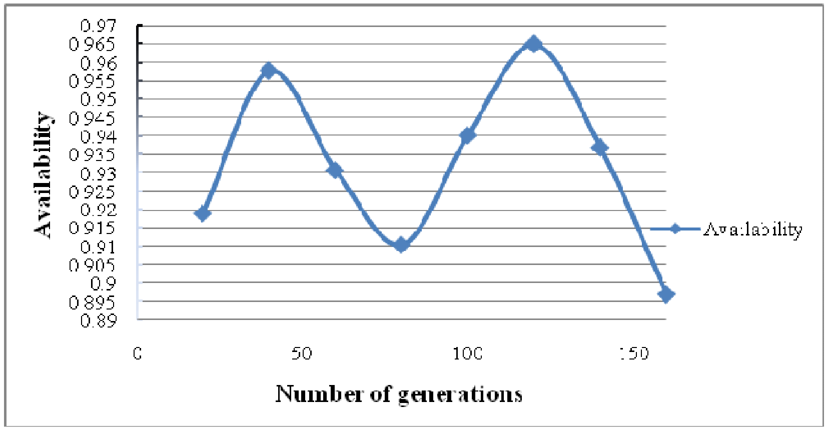


Fig. 5.34 Effect of number of generations on the availability of the Crystallization system

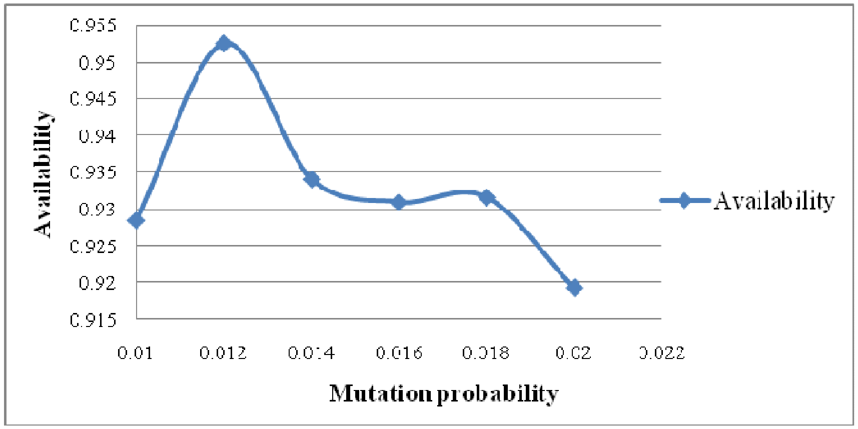


Fig. 5.36 Effect of mutation probability on the availability of the Crystallization system

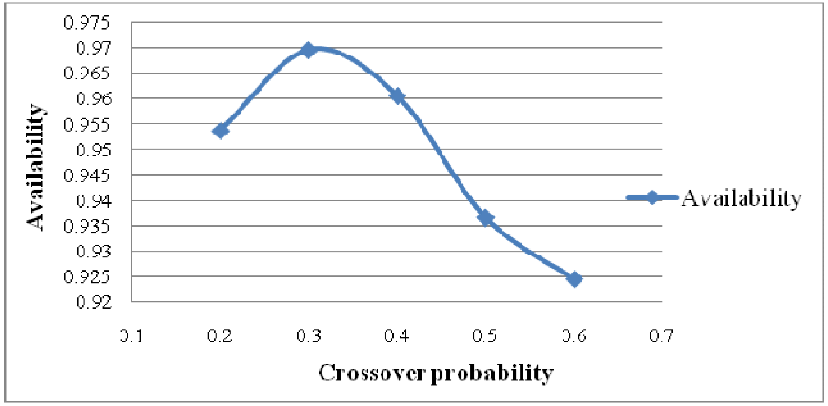


Fig. 5.35 Effect of crossover probability on the availability of the Crystallization system

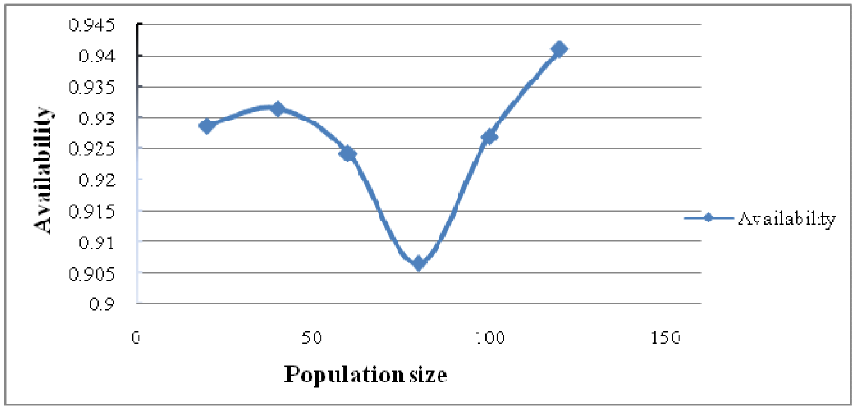


Fig. 5.37 Effect of population size on the availability of the Crystallization system

CHAPTER 6: PERFORMANCE ANALYSIS OF THE DAIRY AND SUGAR PLANTS

The performance analysis for Skim milk powder production system, Butter oil production system, Steam generation system, Refrigeration system of dairy plant and Feeding system, Crushing system, Refining system, Evaporation system and Crystallization system of the sugar plant are analyzed to plan and adopt suitable maintenance strategies for the performance improvement of the systems.

6.1 PERFORMANCE ANALYSIS FOR THE SKIM MILK POWDER PRODUCTION SYSTEM

The performance analysis for the Skim milk powder production system is analyzed by developing Decision Support System (DSS), RAMD analysis and fuzzy-reliability analysis of the system.

The Decision Support System (DSS) deals with the quantitative analysis of all the factors viz. maintenance strategies and states of nature which influence the maintenance decisions associated with the industrial system. These decision models are developed to take decision under uncertainty (probabilistic model) for the purpose of performance analysis. Such models are used to implement the proper maintenance decisions for the industrial system. On the basis of decision support system developed, we may select possible combination of failure and repair rates i.e. optimal maintenance strategy.

6.1.1 Performance analysis for Decision Support Systems of the Skim milk powder production system

The Decision Support System of each subsystem for the reliability of the Skim milk powder system are developed for one year (i.e. time, *t* =30-360 days) by solving the equation (4.1.10) with Runge-Kutta method and shown in table 6.1.1, 6.1.2, 6.1.3, 6.1.4, 6.1.5 and 6.1.6. While, the Decision Support System of each subsystem for the availability of the Skim milk powder system are developed by solving the equation (4.1.23) with various combinations of failure and repair rate parameters of subsystems of the system and shown in tables 6.1.7, 6.1.8, 6.1.9, 6.1.10, 6.1.11. The table 6.1.12 reveals the optimal values of failure and repair rates of subsystems for maximum availability of the system.

(a) Effect of the failure and repair rates of the Chiller subsystem on the reliability of the system

The effect of the failure rate of the Chiller subsystem on the reliability of the system is studied by varying their values as: λ_1=0.0035, 0.0038, 0.0041 and 0.0045. The failure and repair rates of other subsystems were taken as: λ_2=0.0057, λ_3=0.0073, λ_4=0.0048, λ_6=0.0451, μ_1=0.321, μ_2=0.073, μ_3=0.281, μ_4=0.092, μ_6=0.089. The reliability of the system is calculated using these values and the results are shown in table 6.1.1. This table reveals that the reliability of the system decreases by 0.795% approximately with the increase of time. However, it decreases by 0.278% approximately with the increase in the failure rate of the Chiller subsystem from 0.0035 to 0.0045 and MTBF decreases by 0.278% approximately.

The effect of the repair rate of the Chiller subsystem on the reliability of the system is studied by varying their values as: μ_1=0.318, 0.321, 0.325 and 0.328. The failure and repair rates of other subsystems were taken as: λ_1=0.0038, λ_2=0.0057, λ_3=0.0073, λ_4=0.0048, λ_6=0.0451, μ_2=0.073, μ_3=0.281, μ_4=0.092, μ_6=0.089.The reliability of the system is calculated using these values and the results are shown in table 6.1.1. This table reveals that the reliability of the system decreases by 0.795% approximately with the increase of time. However, it increases by 0.033% approximately with the increase in the repair rate of the Chiller subsystem from 0.318 to 0.328 and MTBF increases by 0.033% approximately.

(b) Effect of the failure and repair rates of the Cream separator subsystem on the reliability of the system

The effect of the failure rate of the Cream separator subsystem on the reliability of the system is studied by varying their values as: λ_2=0.0054, 0.0057, 0.0060 and 0.0063.The failure and repair rates of other subsystems were taken as: λ_1=0.0038, λ_3=0.0073, λ_4=0.0048, λ_6=0.00451, μ_1=0.321, μ_2=0.073, μ_3=0.281, μ_4=0.092, μ_6=0.089. The reliability of the system is calculated using these values and the results are shown in table 6.1.2. This table reveals that the reliability of the system decreases from 0.851 to 0.764% approximately with the increase of time. However, it decreases by 1.092% approximately with the increase in the failure rate of the Cream separator subsystem from 0.0054 to 0.0063 and MTBF decreases by 1.084% approximately.

The effect of the repair rate of Cream separator subsystem on the reliability of the system is studied by varying their values as: μ_2=0.070, 0.073, 0.076 and 0.079. The failure and repair rates of other subsystems were taken as: λ_1=0.0038, λ_2=0.0057, λ_3=0.0073, λ_4=0.0048, λ_6=0.00451, μ_1=0.321, μ_3=0.281, μ_4=0.092, μ_6=0.089. The reliability of the system is calculated using these values and the results are shown in table 6.1.2. This table reveals that the reliability of the system decreases from 0.890 to 0.638% approximately with the increase of time. However, it increases by 0.832% approximately with the increase in the repair rate of the Cream separator subsystem from 0.070 to 0.079 and MTBF increases by 0.807% approximately.

(c) Effect of the failure and repair rates of the Pasteurizer subsystem on the reliability of the system

The effect of the failure rate of the Pasteurizer subsystem on the reliability of the system is studied by varying their values as: λ_3=0.0070, 0.0073, 0.0076 and 0.0079.The failure and repair rates of other subsystems were taken as: λ_1=0.0038, λ_2=0.0057, λ_4=0.0048, λ_6=0.00451, μ_1=0.321, μ_2=0.073, μ_3=0.281, μ_4=0.092, μ_6=0.089. The reliability of the system is calculated using these values and the results are shown in table 6.1.3. This table reveals that the reliability of the system decreases by 0.795% approximately with the increase of time. However, it decreases by 0.285% approximately with the increase in the failure rate of the Pasteurizer subsystem from 0.0070 to 0.0079 and MTBF decreases by 0.286% approximately.

The effect of the repair rate of the Pasteurizer subsystem on the reliability of the system is studied by varying their values as: μ_3=0.278, 0.281, 0.284 and 0.287. The failure and repair rates of other subsystems were taken as: λ_1=0.0038, λ_2=0.0057, λ_3=0.0073, λ_4=0.0048, λ_6=0.00451, μ_1=0.321, μ_2=0.073, μ_4=0.092, μ_6=0.089.The reliability of the system is calculated using these values and the results are shown in table 6.1.3. This table reveals that the reliability of the system decreases by 0.794% approximately with the increase of time. However, it increases by 0.074% approximately with the increase in the repair rate of the Pasteurizer subsystem from 0.278 to 0.287 and MTBF increases by 0.074% approximately.

(d) Effect of the failure and repair rates of the Evaporator subsystem on reliability of the system

The effect of the failure rate of the Evaporator subsystem on reliability of the system is studied by varying their values as: λ_4=0.0045, 0.0048, 0.0051 and 0.0054.The failure and repair rates of other subsystems were taken as: λ_1=0.0038, λ_2=0.0057, λ_3=0.0073, λ_6=0.00451, μ_1=0.321, μ_2=0.073, μ_3=0.281, μ_4=0.092, μ_6=0.089. The reliability of the system is calculated using these values and the results are shown in table 6.1.4. This table reveals that the reliability of the system decreases from 0.805 to 0.788% approximately with the increase of time. However, it decreases from 0.080 to 0.063% approximately with the increase in the failure rate of the Evaporator subsystem from 0.0045 to 0.0054 and MTBF decreases by 0.078% approximately.

The effect of the repair rate of Evaporator on the reliability of the system is studied by varying their values as: μ_4=0.089, 0.092, 0.095 and 0.098. The failure and repair rates of other subsystems were taken as: λ_1=0.0038, λ_2=0.0057, λ_3=0.0073, λ_4=0.0048, λ_6=0.00451, μ_1=0.321, μ_2=0.073, μ_3=0.281, μ_6=0.089.The reliability of the system is calculated using these values and the results are shown in table 6.1.4. This table reveals that the reliability of the system decreases from 0.801 to 0.782% approximately with the increase of time. However, it increases from 0.022 to 0.041% approximately with the increase in the repair rate of the Evaporator subsystem from 0.089 to 0.098 and MTBF increases by 0.039% approximately.

(e) Effect of the failure and repair rates of the Drying chamber subsystem on the reliability of the system

The effect of the failure rate of the Drying chamber subsystem on the reliability of the system is studied by varying their values as: λ_6=0.00448, 0.00451, 0.00454 and 0.00457.The failure and repair rates of other subsystems were taken as: λ_1=0.0038, λ_2=0.0057, λ_3=0.0073, λ_4=0.0048, μ_1=0.321, μ_2=0.073, μ_3=0.281, μ_4=0.092, μ_6=0.059. The reliability of the system is calculated using these values and the results are shown in table 6.1.5. This table reveals that the reliability of the system decreases by 0.794% approximately with the increase of time. However, it decreases by 0.009% approximately with the increase in the failure rate of the Drying chamber subsystem from 0.00448 to 0.00457 and MTBF decreases by 0.009% approximately.

The effect of the repair rate of the Drying chamber subsystem on the reliability of the system is studied by varying their values as: μ_6=0.086, 0.089, 0.092 and 0.095. The failure and repair rates of other subsystems were taken as: λ_1=0.0038, λ_2=0.0057, λ_3=0.0073, λ_4=0.0048, λ_6=0.0451, μ_1=0.321, μ_2=0.073, μ_3=0.281, μ_4=0.092.The reliability of the system is calculated using these values and the results are shown in table 6.1.5. This table reveals that the reliability of the system decreases from 0.801 to 0.781% approximately with the increase of time. However, it increases from 0.023 to 0.044% approximately with the increase in repair rate of the Drying chamber subsystem from 0.086 to 0.095 and MTBF increases by 0.042% approximately.

(f) Effect of the failure and repair rates of the Chiller subsystem on the availability of the system

The effect of the failure and repair rates of the Chiller subsystem on the availability of the system is studied by varying their values as: λ_1=0.0035, 0.0038, 0.0041, 0.0045 and μ_1=0.318, 0.321, 0.325, and 0.328. The failure and repair rates of other subsystems were taken as: λ_2=0.0057: λ_3=0.0073: λ_4=0.0048: λ_6=0.0451, μ_2=0.073: μ_3=0.281: μ_4=0.092: μ_6=0.089. The availability of the system is calculated using these values and the results are shown in table 6.1.7. This table reveals that the increase in failure rate of the Chiller subsystem has approximately 0.288% negative impacts on the availability of the system while increase in repair rate of the Chiller subsystem has approximately 0.034% impacts on the availability of the system.

(g) Effect of the failure and repair rates of the Cream separator subsystem on the availability of the system

The effect of the failure and repair rates of the Cream separator subsystem on the availability of the system is studied by varying their values as: λ_2=0.0054, 0.0057, 0.0060, 0.0063 and μ_2=0.070, 0.073, 0.076, and 0.079. The failure and repair rates of other subsystems were taken as: λ_1=0.0038, λ_3=0.0073, λ_4=0.0048, λ_6=0.00451, μ_1=0.321, μ_3=0.281, μ_4=0.092, μ_6=0.089. The availability of the system is calculated using these values and the results are shown in table 6.1.8. This table reveals that the increase in the failure rate of the Cream separator subsystem has approximately 1.134% negative impacts on the availability of the system while increase in the repair rate of the Cream separator subsystem has approximately 0.905% impacts on the availability of the system.

(h) Effect of the failure and repair rates of the Pasteurizer subsystem on the availability of the system

The effect of the failure and repair rates of the Pasteurizer subsystem on the availability of the system is studied by varying their values as: λ_3=0.0070, 0.0073, 0.0076, 0.0079 and μ_3=0.278, 0.281, 0.284, and 0.287. The failure and repair rates of other subsystems were taken as: λ_1=0.0038, λ_2=0.0057, λ_4=0.0048, λ_6=0.00451, μ_1=0.321, μ_2=0.073, μ_4=0.092, μ_6=0.089. The availability of the system is calculated using these values and the results are shown in Table 6.1.9. This table reveals that the increase in the failure rate of the Pasteurizer subsystem has approximately 0.295% negative impacts on the availability of the system while increase in the repair rate of the Pasteurizer subsystem has approximately 0.0786% impacts on the availability of the system.

(i) Effect of the failure and repair rates of the Evaporator subsystem on the availability of the system

The effect of the failure and repair rates of the Evaporator subsystem on the availability of the system is studied by varying their values as: λ_4=0.0045, 0.0048, 0.0051, 0.0054 and μ_4=0.089, 0.092, 0.095, and 0.098. The failure and repair rates of other subsystems were taken as: λ_1=0.0038, λ_2=0.0057, λ_3=0.0073, λ_6=0.00451: μ_1=0.321, μ_2=0.073, μ_3=0.281, μ_6=0.089. The availability of the system is calculated using these values and the results are shown in table 6.1.10. This table reveals that the increase in the failure rate of the Evaporator subsystem has approximately 0.0122% negative impacts on the availability of the system while increase in the repair rate of the Evaporator subsystem has approximately 0.0762% negative impacts on the availability of the system.

(j) Effect of the failure and repair rates of the Drying chamber subsystem on availability of the system

The effect of the failure and repair rates of the Drying chamber subsystem on the availability of the system is studied by varying their values as: λ_6=0.00448, 0.00451, 0.00454, 0.00457 and μ_6=0.086, 0.089, 0.092, and 0.095. The failure and repair rates of other subsystems were taken as: λ_1=0.0038, λ_2=0.0057, λ_3=0.0073, λ_4=0.0048: μ_1=0.321, μ_2=0.073, μ_3=0.281, μ_4=0.092. The availability of the system is calculated using these values and the results are shown in table 6.1.11. This table reveals that the increase in the failure rate of the Drying chamber subsystem has approximately 0.0286% negative impacts on the availability of the system while increase in the repair rate of the Drying chamber subsystem has approximately 0.134% impacts on the availability of the system.

Table 6.1.1 Decision matrix for the Chiller subsystem on the reliability of the Skim milk powder production system

Time	**Failure rate of Chiller (λ_1)**				**Repair rate of Chiller (μ_1)**			
(Days)	**0.0035**	**0.0038**	**0.0041**	**0.0045**	**0.318**	**0.321**	**0.325**	**0.328**
30	0.900018	0.899260	0.898503	0.897495	0.899168	0.899260	0.899379	0.899467
60	0.893576	0.892830	0.892086	0.891095	0.892741	0.892830	0.892947	0.893032
90	0.892930	0.892185	0.891442	0.890452	0.892096	0.892185	0.892303	0.892391
120	0.892872	0.892127	0.891384	0.890395	0.892038	0.892127	0.892244	0.892331
150	0.892866	0.892121	0.891378	0.890389	0.892033	0.892121	0.892238	0.892324
180	0.892866	0.892118	0.891374	0.890388	0.892033	0.892118	0.892236	0.892322
210	0.892863	0.892121	0.891377	0.890387	0.892032	0.892121	0.892235	0.892322
240	0.892865	0.892120	0.891377	0.890389	0.892033	0.892120	0.892237	0.892323
270	0.892864	0.892121	0.891378	0.890388	0.892032	0.892121	0.892237	0.892323
300	0.892865	0.892121	0.891378	0.890389	0.892032	0.892121	0.892237	0.892322
330	0.892865	0.892121	0.891378	0.890389	0.892032	0.892121	0.892237	0.892323
360	0.892865	0.892121	0.891378	0.890389	0.892032	0.892121	0.892237	0.892322
MTBF	321.67	321.40	321.13	320.78	321.37	321.40	321.44	321.47

Table 6.1.2 Decision matrix for the Cream separator subsystem on the reliability of the Skim milk powder production system

Days	**Failure rate of cream separator (λ_2)**				**Repair rate of cream separator (μ_2)**			
	0.0054	**0.0057**	**0.0060**	**0.0063**	**0.070**	**0.073**	**0.076**	**0.079**
30	0.902299	0.899260	0.896238	0.893232	0.897457	0.899260	0.900980	0.902621
60	0.896095	0.892830	0.889588	0.886369	0.890316	0.892830	0.895177	0.897372
90	0.895467	0.892185	0.888928	0.885694	0.889550	0.892185	0.894631	0.896905
120	0.895410	0.892127	0.888869	0.885634	0.889475	0.892127	0.894585	0.896869
150	0.895404	0.892121	0.888862	0.885627	0.889466	0.892121	0.894581	0.896866
180	0.895400	0.892118	0.888859	0.885624	0.889462	0.892118	0.894577	0.896863
210	0.895403	0.892121	0.888862	0.885627	0.889465	0.892121	0.894580	0.896865
240	0.895403	0.892120	0.888861	0.885626	0.889465	0.892120	0.894580	0.896865

270	0.895404	0.892121	0.888862	0.885627	0.889465	0.892121	0.894581	0.896866
300	0.895404	0.892121	0.888862	0.885627	0.889465	0.892121	0.894581	0.896866
330	0.895404	0.892121	0.888862	0.885627	0.889465	0.892121	0.894581	0.896866
360	0.895404	0.892121	0.888862	0.885627	0.889465	0.892121	0.894581	0.896866
MTBF	322.57	321.40	320.24	319.08	320.48	321.40	322.26	323.06

Table 6.1.3 Decision matrix for the Pasteurizer subsystem on the reliability of the Skim milk powder production system

Days	**Failure rate of pasteurizer (λ_3)**				**Repair rate of pasteurizer (μ_3)**			
	0.007	**0.0073**	**0.0076**	**0.0079**	**0.278**	**0.281**	**0.284**	**0.287**
30	0.900127	0.89926	0.898395	0.897531	0.899031	0.89926	0.899484	0.899703
60	0.893682	0.89283	0.89198	0.891131	0.892606	0.89283	0.893049	0.893263
90	0.893036	0.892185	0.891337	0.89049	0.891962	0.892185	0.892404	0.892618
120	0.892978	0.892127	0.891279	0.890432	0.891904	0.892127	0.892346	0.89256
150	0.892972	0.892121	0.891272	0.890415	0.891898	0.892121	0.892339	0.892553
180	0.892969	0.892118	0.891268	0.890425	0.891895	0.892118	0.892336	0.89255
210	0.892971	0.892121	0.891272	0.890424	0.891897	0.892121	0.892339	0.892553
240	0.892971	0.89212	0.891271	0.890424	0.891897	0.89212	0.892339	0.892553
270	0.892971	0.892121	0.891272	0.890425	0.891898	0.892121	0.892339	0.892553
300	0.892971	0.892121	0.891272	0.890424	0.891898	0.892121	0.892339	0.892553
330	0.892971	0.892121	0.891272	0.890425	0.891898	0.892121	0.892339	0.892553
360	0.892971	0.892121	0.891272	0.890425	0.891898	0.892121	0.892339	0.892553
MTBF	321.71	321.40	321.09	320.79	321.32	321.40	321.48	321.56

Table 6.1.4 Decision matrix for the Evaporator subsystem on the reliability of the Skim milk powder production system

Days	**Failure rate of evaporator (λ_4)**				**Repair rate of evaporator (μ_4)**			
	0.0045	**0.0048**	**0.0051**	**0.0054**	**0.089**	**0.092**	**0.095**	**0.098**
30	0.899448	0.899260	0.899072	0.898885	0.899193	0.899260	0.899324	0.899387
60	0.893062	0.892830	0.892599	0.892369	0.892716	0.892830	0.892938	0.893041
90	0.892423	0.892185	0.891950	0.891715	0.892060	0.892185	0.892303	0.892415
120	0.892366	0.892127	0.891891	0.891656	0.892000	0.892127	0.892247	0.892360
150	0.892359	0.892121	0.891884	0.891649	0.891993	0.892121	0.892241	0.892355
180	0.892360	0.892118	0.891881	0.891645	0.891994	0.892118	0.892238	0.892352
210	0.892357	0.892121	0.891884	0.891649	0.891990	0.892121	0.892241	0.892354

240	0.892359	0.892120	0.891883	0.891648	0.891992	0.892120	0.892241	0.892354
270	0.892359	0.892121	0.891884	0.891649	0.891993	0.892121	0.892241	0.892354
300	0.892359	0.892121	0.891884	0.891649	0.891993	0.892121	0.892241	0.892354
330	0.892359	0.892121	0.891884	0.891649	0.891993	0.892121	0.892241	0.892354
360	0.892359	0.892121	0.891884	0.891649	0.891993	0.892121	0.892241	0.892354
MTBF	321.49	321.40	321.32	321.23	321.36	321.40	321.44	321.48

Table 6.1.5 Decision matrix for the Drying chamber subsystem on the reliability of the Skim milk powder production system

Days	**Failure rate of Drying chamber (λ_6)**				**Repair rate of Drying chamber (μ_6)**			
	0.00448	**0.00451**	**0.00454**	**0.00457**	**0.086**	**0.089**	**0.092**	**0.095**
30	0.899280	0.899260	0.899239	0.899219	0.899187	0.899260	0.899330	0.899397
60	0.892856	0.892830	0.892804	0.892779	0.892704	0.892830	0.892948	0.893060
90	0.892212	0.892185	0.892159	0.892132	0.892048	0.892185	0.892314	0.892434
120	0.892154	0.892127	0.892101	0.892074	0.891988	0.892127	0.892257	0.892379
150	0.892148	0.892121	0.892094	0.892068	0.891982	0.892121	0.892251	0.892374
180	0.892144	0.892118	0.892091	0.892064	0.891978	0.892118	0.892248	0.892370
210	0.892147	0.892121	0.892094	0.892067	0.891981	0.892121	0.892251	0.892373
240	0.892147	0.892120	0.892094	0.892067	0.891981	0.892120	0.892251	0.892373
270	0.892147	0.892121	0.892094	0.892068	0.891981	0.892121	0.892251	0.892373
300	0.892147	0.892121	0.892094	0.892068	0.891981	0.892121	0.892251	0.892374
330	0.892147	0.892121	0.892094	0.892067	0.891981	0.892121	0.892251	0.892373
360	0.892147	0.892121	0.892094	0.892068	0.891981	0.892121	0.892251	0.892374
MTBF	321.41	321.40	321.39	321.38	321.35	321.4	321.45	321.49

Table 6.1.6 Decision matrix for the subsystems on the reliability of the Skim milk powder production system

Days	Change in reliability of the system with failure rate of Subsystems (% negative)					Change in reliability of the system with repair rate of Subsystems (% positive)				
	Chiller (λ_1)	**Cream separator (λ_2)**	**Pasteurizer (λ_3)**	**Evaporator (λ_4)**	**Drying chamber (λ_6)**	**Chiller (μ_1)**	**Cream separator (μ_2)**	**Pasteurizer (μ_3)**	**Evaporator (μ_4)**	**Drying chamber (μ_6)**
30	0.002803	0.010048	0.002883	0.000627	0.000068	0.000332	0.005755	0.000748	0.000215	0.000234
60	0.002776	0.010853	0.002854	0.000776	0.000086	0.000327	0.007925	0.000736	0.000365	0.000399
90	0.002775	0.010913	0.002851	0.000793	0.000089	0.000331	0.008269	0.000735	0.000398	0.000433
120	0.002774	0.010918	0.002851	0.000795	0.000089	0.000328	0.008314	0.000735	0.000404	0.000439
150	0.002773	0.010919	0.002863	0.000796	0.000089	0.000326	0.008319	0.000735	0.000405	0.000440
180	0.002775	0.010919	0.002850	0.000801	0.000089	0.000325	0.008320	0.000735	0.000401	0.000440
210	0.002772	0.010919	0.002852	0.000794	0.000089	0.000326	0.008320	0.000735	0.000409	0.000440
240	0.002774	0.010919	0.002853	0.000797	0.000089	0.000325	0.008320	0.000735	0.000405	0.000440
270	0.002773	0.010919	0.002852	0.000796	0.000089	0.000327	0.008320	0.000735	0.000405	0.000440
300	0.002774	0.010919	0.002852	0.000796	0.000089	0.000325	0.008320	0.000735	0.000406	0.000440
330	0.002773	0.010919	0.002851	0.000796	0.000090	0.000326	0.008320	0.000735	0.000405	0.000439
360	0.002774	0.010919	0.002852	0.000796	0.000089	0.000325	0.008320	0.000735	0.000405	0.000440

Table 6.1.7 Decision matrix for the Chiller subsystem on the availability of the Skim milk powder production system

λ_1 μ_1	**0.0035**	**0.0038**	**0.0041**	**0.0045**
0.318	0.88471296	0.88394603	0.88318046	0.88216182
0.321	0.88479348	0.88403330	0.88327445	0.88226475
0.325	0.88489855	0.88414718	0.88339712	0.88239908
0.328	0.88497569	0.88423078	0.88348717	0.88249769

Table 6.1.8 Decision matrix for the Cream separator subsystem on the availability of the Skim milk powder production system

λ_2 μ_2	**0.0054**	**0.0057**	**0.0060**	**0.0063**
0.070	0.88479721	0.88142576	0.87807996	0.87475950
0.073	0.88728607	0.88403330	0.88080432	0.87759889
0.076	0.88959087	0.88644866	0.88332860	0.88023048
0.079	0.89173129	0.88869233	0.88567406	0.88267627

Table 6.1.9 Decision matrix for the Pasteurizer subsystem on the availability of the Skim milk powder production system

λ_3 μ_3	**0.0070**	**0.0073**	**0.0076**	**0.0079**
0.278	0.88513124	0.88366565	0.88220501	0.88074930
0.281	0.88547484	0.88403330	0.88259655	0.88116459
0.284	0.88580667	0.88438838	0.88297474	0.88156572
0.287	0.88612734	0.88473153	0.88334023	0.88195341

Table 6.1.10 Decision matrix for the Evaporator subsystem on the availability of the Skim milk powder production system

λ_4 μ_4	**0.0045**	**0.0048**	**0.0051**	**0.0054**
0.089	0.88362163	0.88358669	0.88355181	0.88351701
0.092	0.88384421	0.88380888	0.88377361	0.88373842
0.095	0.88406903	0.88403330	0.88399763	0.88396204
0.098	0.88429611	0.88425997	0.88422390	0.88418791

Table 6.1.11 Decision matrix for the Drying chamber subsystem on the availability of the Skim milk powder production system

λ_6 μ_6	**0.00448**	**0.00451**	**0.00454**	**0.00457**
0.086	0.88370137	0.88361692	0.88353245	0.88344797
0.089	0.88411498	0.88403330	0.88395160	0.88386989
0.092	0.88450196	0.88442287	0.88434377	0.88426465
0.095	0.88486481	0.88478816	0.88471149	0.88463480

Table 6.1.12 Optimal values of failure and repair rates of the subsystems for the maximum availability of the Skim milk powder production system

S. N.	Subsystem	Failure rate (λ)	Repair rate (μ)	Max. Availability
1	Cream separator	0.0054	0.070	0.89173129
2	Pasteurizer	0.0070	0.278	0.89173129
3	Chiller	0.0035	0.318	0.88497569
4	Drying chamber	0.00448	0.095	0.88486481
5	Evaporator	0.0045	0.089	0.88429611

The decision matrices for Skim milk powder production system as given in tables (6.1.1 to 6.1.11) indicates that the Cream separator is the most critical subsystem as for as maintenance is concerned. So, this subsystem should be given top priority as the effect of its repair rates on the system availability is much higher than other subsystems. On the basis of repair rates, the repair priorities from maintenance point of view for Skim milk powder production system as under.

Decision criteria for the repair priority of the Skim milk powder production system

S. N.	Subsystem	Increase in failure rate (λ)	Decrease in		Increase in Repair rate (μ)	Increase in		Repair Priority
			Reliabiity	Availability		Reliabiity	Availability	
1	Cream separator	0.0054-0.0063	0.01084	0.9535	0.070-0.079	0.00807	0.7428	I
2	Pasteurizer	0.0070-0.0079	0.00286	0.4277	0.278-0.287	0.00074	0.0354	II
3	Drying chamber	0.00448-0.00457	0.00009	0.0241	0.086-0.095	0.00042	0.0367	III
4	Evaporator	0.0045-0.0054	0.0008	0.0106	0.089-0.098	0.00039	0.0226	IV
5	Chiller	0.0035-0.0045	0.00278	0.2514	0.318-0.328	0.00033	0.0087	V

6.1.2 Performance analysis for RAMD of the Skim milk powder production system

The RAMD indices for all the subsystems of the Skim milk powder system are computed and tabulated in table 6.1.13.

Table 6.1.13 RAMD indices for the subsystems of the Skim milk powder production system

RAMD indices of subsystems	Subsystem (S1)	Subsystem (S2)	Subsystem (S3)	Subsystem (S4)
Reliability	$e^{-0.0095t}$	$e^{-0.0073t}$	$e^{-0.0048t}$	$e^{-0.00451t}$
Availability	0.91749837	0.974679	0.9974195	0.997562
Maintainability	$1-e^{-0.10565t}$	$1-e^{-0.281t}$	$1-e^{-3.710667t}$	$1-e^{-3.690t}$
Dependability ($D_{min.}$)	0.9376508	0.981519	0.99810862	0.998212738
MTBF	105.26315 hr.	136.9863 hr.	104.1667 hr.	110.864745 hr.
MTTR	9.465284 hr.	3.558719 hr.	0.2694933 hr.	0.2709558 hr.
Dependability ratio (d)	11.120972	38.49315	386.528	409.16

6.1.3 Performance analysis for fuzzy-reliability of the Skim milk powder production system

The effect of the failure rate of the subsystems of the Skim milk powder production system on the fuzzy-reliability of the system is computed by using the equation (4.1.71) for one year (i.e. time, t=30-360 days) and by taking an average value of coverage factor (i.e. *c*

=0.5) as the value of system coverage factor (*c*) varies from 0 to 1. The table 6.1.14, 6.1.15, 6.1.16, 6.1.17 and 6.1.18 reveals the effect of the failure rate of each subsystem on fuzzy-reliability of the system while table 6.1.19 reveals the effect of coverage factor on fuzzy-reliability of the system.

(a) Effect of the failure rate of the Chiller subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Chiller subsystem on the fuzzy-reliability of the system is studied by varying its values as: λ_1=0.0034, 0.0038, 0.0042 at constant value of its repair rate i.e. μ_1=0.321.The failure and repair rates of other subsystems were taken as: λ_2=0.0057, λ_3=0.0073, λ_4=0.0048, λ_6=0.00451, μ_2=0.073, μ_3=0.281, μ_4=0.092, μ_6=0.089. The fuzzy-reliability of the system is calculated using these values and results are shown in the table 6.1.14.

(b) Effect of failure rate of the Cream separator subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Cream separator subsystem on the fuzzy-reliability of the system is studied by varying its values as: λ_2=0.0053, 0.0057, 0.0061 at constant value of its repair rate i.e. μ_2=0.073. The failure and repair rates of other subsystems were taken as: λ_1= 0.0038, λ_3=0.0073, λ_4=0.0048, λ_6=0.00451, μ_1=0.321, μ_3=0.281, μ_4=0.092, μ_6=0.089. The fuzzy-reliability of the system is calculated using these values and results are shown in the table 6.1.15.

(c) Effect of the failure rate of the Pasteurizer subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Pasteurizer on the fuzzy-reliability of the system is studied by varying its values as: λ_3=0.0069, 0.0073, 0.0077 at constant value of its repair rate i.e. μ_3=0.281. The failure and repair rates of other subsystems were taken as: λ_1= 0.0038, λ_2=0.0057, λ_4=0.0048, λ_6=0.00451, μ_1=0.321, μ_2=0.073, μ_4=0.092, μ_6=0.089. The fuzzy-reliability of the system is calculated using these values and results are shown in the table 6.1.16.

(d) Effect of the failure rate of the Evaporator subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Evaporator subsystem on the fuzzy-reliability of the system is studied by varying its values as: λ_4=0.0044, 0.0048, 0.0052 at constant value of its repair rate i.e. μ_4=0.092. The failure and repair rates of other subsystems were taken as: λ_1= 0.0038, λ_2=0.0057, λ_3=0.0073, λ_6=0.00451, μ_1=0.321, μ_2=0.073, μ_3=0.281, μ_6=0.089. The fuzzy-reliability of the system is calculated using these values and results are shown in the table 6.1.17.

(e) Effect of the failure rate of the Drying chamber subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Drying chamber subsystem on the fuzzy-reliability of the system is studied by varying its values as: λ_6=0.00447, 0.00451, 0.00455 at constant value of repair rate i.e. μ_6=0.089. The failure and repair rates of other subsystems were taken as: λ_1= 0.0038, λ_2=0.0057, λ_3=0.0073, λ_4=0.0048, μ_1=0.321, μ_2=0.073, μ_3=0.281: μ_4=0.092. The fuzzy-reliability of the system is calculated using these values and results are shown in the table 6.1.18.

Table 6.1.14 Effect of failure rate of the Chiller subsystem on the fuzzy-reliability of the Skim milk powder production system

Time (Days)	**Failure rate of the Chiller**		
	0.0034	**0.0038**	**0.0042**
30	0.92633495	0.92578936	0.92524442
60	0.92134282	0.92080122	0.92026027
90	0.92083138	0.92029000	0.91974928
120	0.92077534	0.92023391	0.91969312
150	0.92076777	0.92022623	0.91968536
180	0.92076674	0.92022517	0.91968428
210	0.92076617	0.92022449	0.91968348
240	0.92076520	0.92022342	0.91968230
270	0.92076628	0.92022453	0.91968342

300	0.92076527	0.92022326	0.91968187
330	0.92076676	0.92022496	0.91968379
360	0.92076881	0.92022724	0.91968630

Table 6.1.15 Effect of failure rate of the Cream separator subsystem on the fuzzy-reliability of the Skim milk powder production system

Time (Days)	**Failure rate of the Cream separator**		
	0.0053	**0.0057**	**0.0061**
30	0.92795230	0.92578936	0.92363477
60	0.92316437	0.92080122	0.91844973
90	0.92267373	0.92029000	0.91791850
120	0.92261992	0.92023391	0.91786020
150	0.92261249	0.92022623	0.91785229
180	0.92261150	0.92022517	0.91785116
210	0.92261080	0.92022449	0.91785050
240	0.92260977	0.92022342	0.91784938
270	0.92261086	0.92022453	0.91785050
300	0.92260961	0.92022326	0.91784921
330	0.92261133	0.92022496	0.91785090
360	0.92261358	0.92022724	0.91785322

Table 6.1.16 Effect of failure rate of the Pasteurizer subsystem on the fuzzy-reliability of the Skim milk powder production system

Time (Days)	**Failure rates of the Pasteurizer**		
	0.0069	**0.0073**	**0.0077**
30	0.92641329	0.92578936	0.92516625
60	0.92141982	0.92080122	0.92018312
90	0.92090783	0.92029000	0.91967272
120	0.92085215	0.92023391	0.91961649
150	0.92084387	0.92022623	0.91960918
180	0.92084378	0.92022517	0.91960749
210	0.92084255	0.92022449	0.91960728
240	0.92084252	0.92022342	0.91960517
270	0.92084349	0.92022453	0.91960680
300	0.92084240	0.92022326	0.91960502
330	0.92084460	0.92022496	0.91960668
360	0.92084577	0.92022724	0.91960957

Table 6.1.17 Effect of failure rate of the Evaporator subsystem on the fuzzy-reliability of the Skim milk powder production system

Time (Days)	**Failure rates of the Evaporator**		
	0.0044	**0.0048**	**0.0052**
30	0.92782905	0.92594937	0.92407810
60	0.92296720	0.92095982	0.91896303
90	0.92246805	0.92044848	0.91843980
120	0.92241338	0.92039235	0.91838227
150	0.92240576	0.92038460	0.91837438
180	0.92240493	0.92038368	0.91837339
210	0.92240401	0.92038280	0.91837254
240	0.92240323	0.92038195	0.91837161
270	0.92240416	0.92038288	0.91837257

300	0.92240291	0.92038161	0.91837126
330	0.92240473	0.92038340	0.91837302
360	0.92240681	0.92038553	0.91837521

Table 6.1.18 Effect of failure rate of the Drying chamber subsystem on the fuzzy-reliability of the Skim milk powder production system

Time (Days)	**Failure rates of the Drying chamber**		
	0.00447	**0.00451**	**0.00455**
30	0.92595576	0.92594937	0.92594298
60	0.92096912	0.92095982	0.92095053
90	0.92045831	0.92044848	0.92043865
120	0.92040226	0.92039235	0.92038243
150	0.92039452	0.92038460	0.92037467
180	0.92039361	0.92038368	0.92037375
210	0.92039273	0.92038280	0.92037287
240	0.92039188	0.92038195	0.92037202
270	0.92039282	0.92038288	0.92037295
300	0.92039154	0.92038161	0.92037168
330	0.92039333	0.92038340	0.92037347
360	0.92039546	0.92038553	0.92037560

(f) The effect of system coverage factor on the fuzzy-reliability of the system

It is obtained by varying the values of system coverage factor as: c=0, 0.2, 0.4, 0.6, 0.8, and 1.0. The failure and repair rates of other subsystems were taken as: λ_1= 0.0038, λ_2=0.0057, λ_3=0.0073, λ_4=0.0048, λ_6=0.00451, μ_1=0.321 μ_2=0.073, μ_3=0.281, μ_4=0.092, μ_6=0.089. The fuzzy-reliability of the system is calculated using these values and results are shown in table 6.1.19.

Table 6.1.19 Effect of the imperfect fault coverage on the fuzzy-reliability of the Skim milk powder production system

Time (Days)	***c*=0**	***c*=0.2**	***c*=0.4**	***c*=0.6**	***c*=0.8**	***c*=1.0**
30	0.902685	0.911495	0.920959	0.931117	0.942007	0.953680
60	0.897027	0.905914	0.915713	0.926465	0.938267	0.951175
90	0.896478	0.905331	0.915156	0.925999	0.937937	0.951034
120	0.896434	0.905276	0.915098	0.925951	0.937905	0.951029
150	0.896432	0.905273	0.915092	0.925943	0.937901	0.951028
180	0.896434	0.905277	0.915089	0.925945	0.937900	0.951028
210	0.896431	0.905272	0.915090	0.925945	0.937900	0.951028
240	0.896446	0.905272	0.915087	0.925945	0.937900	0.951028
270	0.896431	0.905273	0.915088	0.925949	0.937901	0.951028
300	0.896435	0.905271	0.915090	0.925945	0.937901	0.951028
330	0.896439	0.905268	0.915084	0.925948	0.937901	0.951028
360	0.896434	0.905270	0.915090	0.925946	0.937902	0.951028

6.2 PERFORMANCE ANALYSIS FOR BUTTER OIL PRODUCTION SYSTEM

The performance analysis for the Butter oil production system is analyzed by developing decision support systems, RAMD analysis and fuzzy-reliability analysis of the system.

6.2.1 Performance analysis for Decision Support Systems of the Butter oil production system

The Decision Support System of each subsystem for the reliability of the Butter oil production system are developed for one year (i.e. time, *t* =30-360 days) by solving the equation (4.2.7) with Runge-Kutta method and shown in table 6.2.1, 6.2.2, 6.2.3, 6.2.4, 6.2.5, 6.2.6 and 6.2.7. while, the Decision Support System of each subsystem for the availability of the Butter oil production system are developed by solving the equation (4.2.15) with various combinations of failure and repair rates parameters of subsystems of the system and shown in tables 6.2.8, 6.2.9, 6.2.10, 6.2.11, 6.2.12, 6,2,13. The table 6.2.14 reveals the optimal values of failure and repair rates of subsystems for maximum availability of the system.

(a) Effect of the failure and repair rates of the Chiller subsystem on the reliability of the system

The effect of the failure rate of the Chiller (β_1) subsystem on the reliability of the system is studied by varying their values as: β_1=0.0034, 0.0038, 0.0042 and 0.0046 at constant value of its repair rate i.e. α_1=0.321. The failure and repair rates of other subsystems were taken as: β_2=0.0057, β_3=0.0073, β_4=β_5=0.0045, β_6=0.00431, β_7=0.00328, α_2=0.083, α_3=0.281, α_4=α_5=0.105, α_6=0.096, α_7=0.026. The reliability of the system is calculated using these values and the results are shown in table 6.2.1. This table reveals that the reliability of the system decreases by 6.05% approximately with the increase of time. However, it decreases from 0.304 to 0.283% approximately with the increase in failure rate of the Chiller subsystem from 0.0034 to 0.0046 and MTBF decreases by 0.286% approximately.

The effect of the repair rate of Chiller (α_1) subsystem on the reliability of the system is studied by varying their values as: α_1=0.317, 0.321, 0.325 and 0.329 at constant value of its failure rate i.e. β_1=0.0038. The failure and repair rates of other subsystems were taken as: β_2=0.0057, β_3=0.0073, β_4=β_5=0.0045, β_6=0.00431, β_7=0.00328, α_2=0.083, α_3=0.281, α_4=α_5=0.105, α_6=0.096, α_7=0.026.The reliability of the system is calculated using these values and the results are shown in table 6.2.1. This table reveals that the reliability of the system decreases by 6.06% approximately with the increase of time. However, it increases by 0.034% approximately with the increase in repair rate of the Chiller subsystem from 0.317 to 0.329 and MTBF increases by 0.034% approximately.

(b) Effect of the failure and repair rates of the Cream separator subsystem on the reliability of the system

The effect of the failure rate of the Cream separator (β_2) subsystem on the reliability of the system is studied by varying their values as: β_2=0.0053, 0.0057, 0.0061 and 0.0065 at constant value of its repair rate i.e. α_2=0.073. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_3=0.0073, β_4=β_5=0.0045, β_6=0.00431, β_7=0.00328, α_1=0.321, α_3=0.281, α_4=α_5=0.105, α_6=0.096, α_7=0.026. The reliability of the system is calculated using these values and the results are shown in table 6.2.2. This table reveals that the reliability of the system decreases by 6.05% approximately with the increase of time. However, it decreases from 1.256 to 1.237% approximately with the increase in failure rate of the Cream separator subsystem from 0.0053 to 0.0065 and MTBF decreases by 1.246% approximately.

The effect of the repair rate of the Cream separator (α_2) subsystem on the reliability of the system is studied by varying their values as: α_2=0.069, 0.073, 0.077 and 0.081 at constant value of its failure rate i.e. β_2=0.0057. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_3=0.0073, β_4=β_5=0.0045, β_6=0.00431, β_7=0.00328, α_1=0.321, α_3=0.281, α_4=α_5=0.105, α_6=0.096, α_7=0.026. The reliability of the system is calculated using these values and the results are shown in table 6.2.2. This table reveals that the reliability of the system decreases from 6.14 to 5.96% approximately with the increase of time. However, it increases from 0.743 to 0.934% approximately with the increase in repair rate of the Cream separator subsystem from 0.069 to 0.081 and MTBF increases by 0.924% approximately.

(c) Effect of the failure and repair rates of Pasteurizer subsystem on reliability of the system

The effect of failure rate of Pasteurizer (β_3) on reliability of the system is studied by varying their values as: β_3=0.0069, 0.0073, 0.0077 and 0.0081 at constant value of its repair rate i.e. α_3=0.281. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_4=β_5=0.0045, β_6=0.00431, β_7=0.00328, α_1=0.321, α_2=0.073, α_4=α_5=0.105, α_6=0.096, α_7=0.026. The reliability of the system is calculated using these values and the results are shown in table 6.2.3. This table reveals that the reliability of the system decreases by 6.06% approximately with the increase of time. However, it decreases from 0.348 to 0.324% approximately with the increase in failure rate of the Pasteurizer subsystem from 0.0069 to 0.0081 and MTBF decreases by 0.327% approximately.

The effect of the repair rate of the Pasteurizer (α_3) subsystem on the reliability of the system is studied by varying their values as: α_3=0.277, 0.281, 0.285 and 0.289 at constant value of its failure rate i.e. β_3=0.0073. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_4=β_5=0.0045, β_6=0.00431, β_7=0.00328, α_1=0.321, α_2=0.073, α_4=α_5=0.105, α_6=0.096, α_7=0.026.The reliability of the system is calculated using these values and the results are shown in table 6.2.3. This table reveals that the reliability of the system decreases by 0.606% approximately with the increase of time. However, it increases from 0.084 to 0.091% approximately with the increase in repair rate of the Pasteurizer subsystem from 0.277 to 0.289 and MTBF increases by 0.084% approximately.

(d) Effect of the failure and repair rates of the Continuous butter making subsystem on the reliability of the system

The effect of the failure rate of the Continuous butter making (β_4) subsystem on the reliability of the system is studied by varying their values as: β_4=0.0041, 0.0045, 0.0049 and 0.0053 at constant value of its repair rate i.e. α_4=0.097. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_3=0.0073, β_6=0.00431, β_7=0.00328, α_1=0.321, α_2=0.073, α_3=0.281, α_6=0.096, α_7=0.026. The reliability of the system is calculated using these values and the results are shown in table 6.2.4. This table reveals that the reliability of the system decreases from 6.28 to 5.94% approximately with the increase of time. However, it decreases from 0.531 to 0.168% approximately with the increase in failure rate of the Continuous butter making subsystem from 0.0041 to 0.0053 and MTBF decreases by 0.456% approximately.

The effect of the repair rate of the Continuous butter making (α_4) subsystem on the reliability of the system is studied by varying their values as: α_4=0.093, 0.097, 0.101 and 0.105 at constant value of its failure rate i.e. β_4=0.0045. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_3=0.0073, β_6=0.00431, β_7=0.00328, α_1=0.321, α_2=0.073, α_3=0.281, α_6=0.096, α_7=0.026. The reliability of the system is calculated using these values and the results are shown in table 6.2.4. This table reveals that the reliability of the system decreases from 6.12 to 5.96% approximately with the increase of time. However, it increases from 0.025 to 0.137% approximately with the increase in repair rate of the Continuous butter making subsystem from 0.093 to 0.105 and MTBF increases by 0.137% approximately.

(e) Effect of the failure and repair rates of the Melting vats subsystem on the reliability of the system

The effect of the failure rate of the Melting vats (β_6) subsystem on the reliability of the system is studied by varying their values as: β_6=0.00427, 0.00431, 0.00435 and 0.00439 at constant value of its repair rate i.e. α_6=0.086. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_3=0.0073, β_4=β_5=0.0055, β_7=0.00328, α_1=0.321, α_2=0.083, α_3=0.281, α_4=α_5=0.105, α_7=0.026. The reliability of the system is calculated using these values and the results are shown in table 6.2.5. This table reveals that the reliability of the system decreases by 6.06% approximately with the increase of time. However, it decreases by 0.106% approximately with the increase in the failure rate of Melting vats subsystem from 0.00427 to 0.00439 and MTBF decreases by 0.107% approximately.

The effect of the repair rate of the Melting vats (α_6) subsystem on the reliability of the system is studied by varying their values as: α_6=0.082, 0.086, 0.090 and 0.094 at constant value of its failure rate i.e. β_6=0.00431. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_3=0.0073, β_4=β_5=0.0055, β_7=0.00328, α_1=0.321, α_2=0.083, α_3=0.281, α_4=α_5=0.105, α_7=0.026. The reliability of the system is calculated using these values and the results are shown in table 6.2.5. This table reveals that the reliability of the system decreases by 6.06% approximately with the increase of time. However, it increases from 0.454 to 0.511% approximately with the increase in repair rate of the Melting vats subsystem from 0.082 to 0.094 and MTBF increases by 0.510% approximately.

(f) Effect of the failure and repair rates of the Butter oil clarifier subsystem on the reliability of the system

The effect of the failure rate of the Butter oil clarifier (β_7) subsystem on the reliability of the system is studied by varying their values as: β_7=0.00324, 0.00328, 0.00332 and 0.00336 at constant value of its repair rate i.e. α_7=0.026. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_3=0.0073, β_4=β_5=0.0048, β_6=0.00441, α_1=0.321, α_2=0.073, α_3=0.281, α_4=α_5=0.092, α_6=0.096. The reliability of the system is calculated using these values and the results are shown in table 6.2.6. This table reveals that the reliability of the system decreases by 6.06% approximately with the increase of time. However, it decreases from 0.333 to 0.225% approximately with the increase in the failure rate of the Butter oil clarifier subsystem from 0.00324 to 0.00336 and MTBF decreases by 0.333% approximately.

The effect of the repair rate of the Butter oil clarifier (α_7) subsystem on the reliability of the system is studied by varying their values as: α_7=0.022, 0.026, 0.030 and 0.034 at constant value of its failure rate i.e. β_7=0.00328. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_3=0.0073, β_4=β_5=0.0048, β_6=0.00441, α_1=0.321, α_2=0.073, α_3=0.281, α_4=α_5=0.092, α_6=0.096. The reliability of the system is calculated using these values and the results are shown in table 6.2.6. This table reveals that the reliability of the system decreases from 7.34 to 4.50% approximately with the increase of time. However, it increases from 0.997 to 3.506% approximately with the increase in the repair rate of the Butter oil clarifier subsystem from 0.022 to 0.034 and MTBF increases by 3.5% approximately.

(g) Effect of the failure and repair rates of the subsystems on the reliability of the system

The reliability of the system decreases with the increase in failure rate of the subsystems, while reliability of the system increases with the increase in repair rates of the subsystems as mentioned in table 6.2.7.

(h) Effect of the failure and repair rates of the Chiller subsystem on the availability of the system

The effect of the failure and repair rates of the Chiller subsystem on the availability of the system is studied by varying their values as, β_1=0.0034, 0.0038, 0.0042, 0.0046 and α_1=0.317, 0.321, 0.325, 0.329. The failure and repair rates of other subsystems were taken as: β_2=0.0057, β_3=0.0073, β_4=β_5=0.0045, β_6=0.00431, β_7=0.00328, α_2=0.083, α_3=0.281, α_4=α_5=0.105, α_6=0.096, α_7=0.026. The availability of the system is calculated using these values and the results are shown in table 6.2.8. This table reveals that the increase in failure rate (β_1) of the Chiller subsystem has approximately 0.3438 to 1.6513% negative impacts on the availability of the system while increase in repair rate (α_1) of the Chiller subsystem has approximately 0.0360 to 0.0522% impacts on the availability of the system.

(i) Effect of the failure and repair rates of the Cream separator subsystem on the availability of the system

The effect of the failure and repair rates of the Cream separator subsystem on the availability of the system is studied by varying their values as, β_2=0.0053, 0.0057, 0.0061, 0.0065 and α_2=0.069, 0.073, 0.077, 0.081. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_3=0.0073, β_4=β_5=0.0045, β_6=0.00431, β_7=0.00328, α_1=0.321, α_3=0.281, α_4=α_5=0.105, α_6=0.096, α_7=0.026. The availability of the system is calculated using these values and the results are shown in table 6.2.9. This table reveals that the increase in the failure rate (β_2) of the Cream separator subsystem has approximately 1.3712 to

1.6512% negative impacts on availability of the system while increase in repair rate (α_2) of the Cream separator subsystem has approximately 1 to 1.35% impacts on the availability of the system.

(j) Effect of the failure and repair rates of the Pasteurizer subsystem on the availability of the system

The effect of the failure and repair rates of the Pasteurizer subsystem on the availability of the system is studied by varying their values as, β_3=0.0069, 0.0073, 0.0077, 0.0081 and α_3=0.277, 0.281, 0.285, 0.289. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_4=β_5=0.0045, β_6=0.00431, β_7=0.00328, α_1=0.321, α_2=0.083, α_4=α_5=0.105, α_6=0.096, α_7=0.026. The availability of the system is calculated using these values and the results are shown in Table 6.2.10. This table reveals that the increase in the failure rate (β_3) of the Pasteurizer subsystem has approximately 0.39 to 0.41% negative impacts on the availability of the system while increase in the repair rate (α_3) of the Pasteurizer subsystem has approximately 0.0965 to 0.11% impacts on the availability of the system.

(k) Effect of the failure and repair rates of the Continuous butter making subsystem on the availability of the system

The effect of the failure and repair rates of the Continuous butter making subsystem on the availability of the system is studied by varying their values as, β_4=0.0041, 0.0045, 0.0049, 0.0053 and α_4=0.093, 0.097, 0.101, 0.105. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_3=0.0073, β_6=0.00431, β_7=0.00328, α_1=0.321, α_2=0.083, α_3=0.281, α_6=0.096, α_7=0.026. The availability of the system is calculated using these values and the results are shown in table 6.2.11. This table reveals that the increase in the failure rate (β_4) of the Continuous butter making subsystem has approximately 0.54 to 0.61% negative impacts on the availability of the system while increase in the repair rate (α_4) of the Continuous butter making subsystem has approximately 0.2 to 0.28% negative impacts on the availability of the system.

(l) Effect of the failure and repair rates of the Melting vats subsystem on the availability of the system

The effect of the failure and repair rates of the Melting vats subsystem on the availability of the system is studied by varying their values as, β_6=0.00427, 0.00431, 0.00435, 0.00439 and α_6=0.082, 0.086, 0.090, 0.094. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_3=0.0073, β_4=β_5=0.0045, β_7=0.00328, α_1=0.321, α_2=0.083, α_3=0.281, α_4=α_5=0.105, α_7=0.026. The availability of the system is calculated using these values and the results are shown in table 6.2.12. This table reveals that the increase in failure rate (β_6) of the Butter oil clarifier subsystem has approximately 0.1187 to 0.1397% negative impacts on availability of the system while increase in repair rate (α_6) of the Butter oil clarifier subsystem has approximately 0.6248 to 0.6460% impacts on the availability of the system.

(m) Effect of the failure and repair rates of the Butter oil clarifier subsystem on the availability of the system

The effect of the failure and repair rates of the Butter oil clarifier subsystem on the availability of the system is studied by varying their values as: β_7=0.00324, 0.00328, 0.00332, 0.00336 and α_7=0.022, 0.026, 0.030, and 0.034. The failure and repair rates of other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_3=0.0073, β_4=β_5=0.0045, β_6=0.00431, α_1=0.321, α_2=0.083, α_3=0.281, α_4=α_5=0.105, α_6=0.096. The availability of the system is calculated using these values and the results are shown in table 6.2.13. This table reveals that the increase in the failure rate (β_7) of the Butter oil clarifier subsystem has approximately 0.0286% negative impacts on the availability of the system while increase in repair rate (α_7) of the Butter oil clarifier subsystem has approximately 0.134% impacts on the availability of the system.

Table 6.2.1 Decision matrix for the Chiller subsystem on the reliability of the Butter oil production system

Time (Days)	**Failure rate of the Chiller (β_1)**				**Repair rate of the Chiller (α_1)**			
	0.0034	**0.0038**	**0.0042**	**0.0046**	**0.317**	**0.321**	**0.325**	**0.329**
30	0.811307	0.810483	0.809662	0.808842	0.810382	0.810483	0.810582	0.810678
60	0.783467	0.782707	0.781949	0.781192	0.782615	0.782707	0.782797	0.782885
90	0.773588	0.772848	0.772109	0.771373	0.772758	0.772848	0.772937	0.773024
120	0.769005	0.768274	0.767545	0.766817	0.768186	0.768274	0.768360	0.768444
150	0.766573	0.765846	0.765120	0.764396	0.765761	0.765846	0.765933	0.766021
180	0.765147	0.764424	0.763701	0.762980	0.764337	0.764424	0.764509	0.764592
210	0.764206	0.763482	0.762760	0.762038	0.763404	0.763482	0.763564	0.763653
240	0.763539	0.762817	0.762097	0.761378	0.762732	0.762817	0.762903	0.762985
270	0.763039	0.762317	0.761597	0.760877	0.762233	0.762317	0.762395	0.762482
300	0.762640	0.761919	0.761199	0.760481	0.761834	0.761919	0.762004	0.762088
330	0.762327	0.761606	0.760887	0.760169	0.761521	0.761606	0.761690	0.761773
360	0.762077	0.761358	0.760641	0.759919	0.761267	0.761358	0.761438	0.761521
MTBF	277.41	277.14	276.88	276.61	277.11	277.14	277.17	277.20

Table 6.2.2 Decision matrix for the Cream separator subsystem on the reliability of the Butter oil production system

Time (Days)	**Failure rate of the Cream separator (β_2)**				**Repair rate of the Cream separator (α_2)**			
	0.0053	**0.0057**	**0.0061**	**0.0065**	**0.069**	**0.073**	**0.077**	**0.081**
30	0.813915	0.810483	0.807076	0.803694	0.808352	0.810483	0.812482	0.814357
60	0.786105	0.782707	0.779338	0.775998	0.779976	0.782707	0.785192	0.787460

90	0.776139	0.772848	0.769584	0.766349	0.770123	0.772848	0.775306	0.777535
120	0.771511	0.768274	0.765064	0.761880	0.765601	0.768274	0.770684	0.772867
150	0.769057	0.765846	0.762662	0.759504	0.763203	0.765846	0.768229	0.770388
180	0.767621	0.764424	0.761253	0.758108	0.761797	0.764424	0.766792	0.768939
210	0.766672	0.763482	0.760319	0.757182	0.760864	0.763482	0.765843	0.767983
240	0.766002	0.762817	0.759659	0.756527	0.760205	0.762817	0.765174	0.767310
270	0.765499	0.762317	0.759162	0.756032	0.759708	0.762317	0.764671	0.766805
300	0.765099	0.761919	0.758765	0.755638	0.759311	0.761919	0.764271	0.766403
330	0.764785	0.761606	0.758454	0.755328	0.759000	0.761606	0.763957	0.766088
360	0.764536	0.761358	0.758206	0.755081	0.758752	0.761358	0.763708	0.765839
MTBF	278.31	277.14	275.99	274.84	276.21	277.14	277.99	278.76

Table 6.2.3 Decision matrix for the Pasteurizer subsystem on the reliability of the Butter oil production system

Time	**Failure rate of the Pasteurizer (β_3)**				**Repair rate of the Pasteurizer (α_3)**			
(Days)	**0.0069**	**0.0073**	**0.0077**	**0.0081**	**0.277**	**0.281**	**0.285**	**0.289**
30	0.811426	0.810483	0.809543	0.808604	0.810230	0.810483	0.810730	0.810970
60	0.783576	0.782707	0.781841	0.780977	0.782477	0.782707	0.782931	0.783148
90	0.773692	0.772848	0.772005	0.771165	0.772625	0.772848	0.773064	0.773275
120	0.769109	0.768274	0.767441	0.766610	0.768054	0.768274	0.768488	0.768696
150	0.766676	0.765846	0.765018	0.764193	0.765628	0.765846	0.766058	0.766265
180	0.765251	0.764424	0.763598	0.762775	0.764206	0.764424	0.764635	0.764841
210	0.764312	0.763482	0.762657	0.761835	0.763265	0.763482	0.763693	0.763898
240	0.763639	0.762817	0.761995	0.761174	0.762600	0.762817	0.763028	0.763234
270	0.763137	0.762317	0.761494	0.760672	0.762101	0.762317	0.762528	0.762733

300	0.762749	0.761919	0.761097	0.760277	0.761702	0.761919	0.762130	0.762335
330	0.762428	0.761606	0.760790	0.759969	0.761390	0.761606	0.761817	0.762022
360	0.762180	0.761358	0.760532	0.759713	0.761141	0.761358	0.761569	0.761774
MTBF	277.45	277.14	276.84	276.54	277.06	277.14	277.22	277.30

Table 6.2.4 Decision matrix for the Continuous butter making subsystem on the reliability of the Butter oil production system

Time (Days)	**Failure rate of the Continuous butter making (β_4)**				**Repair rate of the Continuous butter making (α_4)**			
	0.0041	**0.0045**	**0.0049**	**0.0053**	**0.093**	**0.097**	**0.101**	**0.105**
30	0.810905	0.810483	0.810029	0.809543	0.810413	0.810483	0.810550	0.810615
60	0.783470	0.782707	0.781896	0.781041	0.782529	0.782707	0.782874	0.783030
90	0.773827	0.772848	0.771821	0.770751	0.772588	0.772848	0.773089	0.773313
120	0.769397	0.768274	0.767110	0.765910	0.767953	0.768274	0.768572	0.768848
150	0.767064	0.765846	0.764595	0.763318	0.765476	0.765846	0.766188	0.766505
180	0.765705	0.764424	0.763119	0.761798	0.764014	0.764424	0.764801	0.765151
210	0.764803	0.763482	0.762147	0.760804	0.763042	0.763482	0.763889	0.764265
240	0.764161	0.762817	0.761468	0.760118	0.762351	0.762817	0.763247	0.763646
270	0.763672	0.762317	0.760964	0.759617	0.761831	0.762317	0.762766	0.763182
300	0.763275	0.761919	0.760570	0.759231	0.761415	0.761919	0.762383	0.762813
330	0.762959	0.761606	0.760265	0.758939	0.761089	0.761606	0.762083	0.762525
360	0.762703	0.761358	0.760028	0.758714	0.760830	0.761358	0.761845	0.762296
MTBF	277.56	277.14	276.72	276.29	277.01	277.14	277.27	277.39

Table 6.2.5 Decision matrix for the Melting vats subsystem on the reliability of the Butter oil production system

Time	**Failure rate of the Melting vats (β_6)**				**Repair rate of the Melting vats (α_6)**			
(Days)	**0.00427**	**0.00431**	**0.00435**	**0.00439**	**0.082**	**0.086**	**0.090**	**0.094**
30	0.810783	0.810483	0.810184	0.809885	0.809182	0.810483	0.811706	0.812857
60	0.782995	0.782707	0.782420	0.782133	0.781195	0.782707	0.784095	0.785372
90	0.773126	0.772848	0.772570	0.772293	0.771374	0.772848	0.774194	0.775429
120	0.768548	0.768274	0.768001	0.767728	0.766831	0.768274	0.769592	0.770802
150	0.766117	0.765846	0.765575	0.765304	0.764419	0.765846	0.767151	0.768348
180	0.764694	0.764424	0.764153	0.763884	0.763004	0.764424	0.765721	0.766913
210	0.763752	0.763482	0.763213	0.762943	0.762067	0.763482	0.764776	0.765964
240	0.763087	0.762817	0.762548	0.762279	0.761404	0.762817	0.764109	0.765295
270	0.762587	0.762317	0.762049	0.761780	0.760906	0.762317	0.763608	0.764793
300	0.762188	0.761919	0.761650	0.761382	0.760508	0.761919	0.763208	0.764392
330	0.761875	0.761606	0.761338	0.761069	0.760197	0.761606	0.762896	0.764079
360	0.761626	0.761358	0.761089	0.760821	0.759948	0.761358	0.762647	0.763829
MTBF	277.24	277.14	277.04	276.95	276.63	277.14	277.61	278.04

Table 6.2.6 Decision matrix for the Butter oil clarifier subsystem on the reliability of the Butter oil production system

Time (Days)	**Failure rate of the Butter oil clarifier (β_7)**				**Repair rate of the Butter oil clarifier (α_7)**			
	0.00324	**0.00328**	**0.00332**	**0.00336**	**0.022**	**0.026**	**0.030**	**0.034**
30	0.811091	0.810483	0.809876	0.809270	0.807593	0.810483	0.813162	0.815647
60	0.783504	0.782707	0.781912	0.781118	0.775990	0.782707	0.788557	0.793669
90	0.773711	0.772848	0.771986	0.771127	0.763381	0.772848	0.780707	0.787287
120	0.769160	0.768274	0.767390	0.766508	0.757130	0.768274	0.777212	0.784483
150	0.766739	0.765846	0.764955	0.764067	0.753763	0.765846	0.775312	0.782877
180	0.765317	0.764424	0.763532	0.762642	0.751843	0.764424	0.774131	0.781808
210	0.764375	0.763482	0.762591	0.761702	0.750652	0.763482	0.773290	0.781004
240	0.763710	0.762817	0.761927	0.761039	0.749869	0.762817	0.772663	0.780384
270	0.763209	0.762317	0.761428	0.760541	0.749316	0.762317	0.772173	0.779891
300	0.762810	0.761919	0.761030	0.760144	0.748897	0.761919	0.771774	0.779486
330	0.762497	0.761606	0.760718	0.759832	0.748578	0.761606	0.771458	0.779166
360	0.762248	0.761358	0.760470	0.759584	0.748330	0.761358	0.771206	0.778909
MTBF	277.45	277.14	276.83	276.53	273.16	277.14	280.25	282.74

Table 6.2.7 Decision matrix for the subsystems on the reliability of the Butter oil production system

Time (Days)	**Change in reliability of the system with failure rate of the subsystems (% negative)**						**Change in reliability of the system with repair rate of the subsystems (% positive)**					
	Chiller (β_1)	**Cream separator (β_2)**	**Pasteurizer (β_3)**	**CBM (β_4)**	**Melting vats (β_6)**	**Butter oil clarifier (β_7)**	**Chiller (α_1)**	**Cream separator (α_2)**	**Pasteurizer (α_3)**	**CBM (α_4)**	**Melting vats (α_6)**	**Butter oil clarifier (α_7)**
30	0.304	1.256	0.348	0.168	0.111	0.225	0.037	0.743	0.091	0.025	0.454	0.122
60	0.290	1.286	0.332	0.310	0.110	0.304	0.034	0.960	0.086	0.064	0.535	0.139
90	0.286	1.261	0.327	0.397	0.108	0.334	0.034	0.962	0.084	0.094	0.526	0.135
120	0.284	1.248	0.325	0.453	0.107	0.345	0.034	0.949	0.084	0.117	0.518	0.132
150	0.284	1.242	0.324	0.488	0.106	0.348	0.034	0.941	0.083	0.134	0.514	0.131
180	0.283	1.239	0.324	0.510	0.106	0.350	0.033	0.938	0.083	0.149	0.512	0.130
210	0.284	1.238	0.324	0.523	0.106	0.350	0.033	0.936	0.083	0.160	0.511	0.129
240	0.283	1.237	0.323	0.529	0.106	0.350	0.033	0.935	0.083	0.170	0.511	0.129
270	0.283	1.237	0.323	0.531	0.106	0.350	0.033	0.934	0.083	0.177	0.511	0.129
300	0.283	1.237	0.324	0.530	0.106	0.349	0.033	0.934	0.083	0.184	0.511	0.129
330	0.283	1.237	0.323	0.527	0.106	0.349	0.033	0.934	0.083	0.189	0.511	0.129
360	0.283	1.237	0.324	0.523	0.106	0.349	0.033	0.934	0.083	0.193	0.511	0.129

Table 6.2.8 Decision matrix for the Chiller subsystem on the availability of the Butter oil production system

β_1 α_1	**0.0034**	**0.0038**	**0.0042**	**0.0046**
0.317	0.761042	0.760147	0.759234	0.758325
0.321	0.761142	0.760255	0.759356	0.758459
0.325	0.761238	0.760356	0.759468	0.758586
0.329	0.761337	0.760464	0.759583	0.758719

Table 6.2.9 Decision matrix for the Cream separator subsystem on the availability of the Butter oil production system

β_2 α_2	**0.0053**	**0.0057**	**0.0061**	**0.0065**
0.069	0.761178	0.756941	0.752751	0.748608
0.073	0.764226	0.760245	0.756317	0.752409
0.077	0.766921	0.763145	0.759436	0.755765
0.081	0.769273	0.765721	0.762216	0.758723

Table 6.2.10 Decision matrix for the Pasteurizer subsystem on the availability of the Butter oil production system

β_3 α_3	**0.0069**	**0.0073**	**0.0077**	**0.0081**
0.277	0.759497	0.758453	0.757421	0.756374
0.281	0.759758	0.758722	0.757697	0.756681
0.285	0.759991	0.758974	0.757998	0.756973
0.289	0.760238	0.759237	0.758248	0.757261

Table 6.2.11 Decision matrix for the Continuous butter making subsystem on the availability of the Butter oil production system

β_4 / α_4	**0.0041**	**0.0045**	**0.0049**	**0.0053**
0.093	0.759542	0.757997	0.756439	0.754889
0.097	0.760218	0.758725	0.757251	0.755767
0.101	0.760792	0.759387	0.757968	0.756571
0.105	0.761118	0.759743	0.758372	0.757012

Table 6.2.12 Decision matrix for the Melting vats subsystem on the availability of the Butter oil production system

β_6 / α_6	**0.00427**	**0.00431**	**0.00435**	**0.00439**
0.082	0.755596	0.755234	0.754882	0.754530
0.086	0.757346	0.757012	0.756768	0.756347
0.090	0.758901	0.758585	0.758267	0.757933
0.094	0.760317	0.761006	0.759721	0.759204

Table 6.2.13 Decision matrix for the Butter oil clarifier subsystem on the availability of the Butter oil production system

β_7 / α_7	**0.00324**	**0.00328**	**0.00332**	**0.00336**
0.022	0.743784	0.742469	0.741159	0.739853
0.026	0.760517	0.759414	0.758297	0.757195
0.030	0.772294	0.771324	0.770374	0.769418
0.034	0.781013	0.780166	0.779323	0.778489

Table 6.2.14 Optimal values of failure and repair rates of subsystems for maximum availability of the Butter oil production system

S. No.	Subsystem	Failure rate (β)	Repair rate (α)	Max. Availability
1	Butter oil clarifier	0.00324	0.034	0.781013
2	Cream separator	0.0053	0.081	0.769273
3	Chiller	0.0034	0.329	0.761337
4	Continuous butter making	0.0041	0.105	0.761118
5	Melting vats	0.00427	0.094	0.760317
6	Pasteurizer	0.0069	0.289	0.760238

The decision matrices for Butter oil production system as given in tables (6.2.1 to 6.2.13) indicate that the Butter oil clarifier is the most critical subsystem as for as maintenance is concerned. So, this subsystem should be given top priority as the effect of its repair rates on the system availability is much higher than other subsystems. On the basis of repair rates, the repair priorities from maintenance point of view for Butter oil production system as under.

Decision criteria for the repair priority of the Butter oil production system

S. N.	Subsystem	Increase in failure rate (β)	Decrease in		Increase in Repair rate (α)	Increase in		Repair Priority
			Reliabiity	Availability		Reliabiity	Availability	
1	Butter oil clarifier	0.00324-0.00336	0.33358	0.3163	0.022-0.034	0.13025	0.8895	I
2	Cream seperator	0.0053-0.0065	1.24625	1.1523	0.069-0.081	0.92500	0.2670	II
3	Melting vats	0.00427-0.00439	0.10700	0.1047	0.082-0.094	0.51042	0.1640	III
4	Continous butter making	0.0041-0.0053	0.45742	0.4367	0.093-0.105	0.13800	0.0383	IV
5	Pasteurizer	0.0069-0.0081	0.32675	0.3044	0.277-0.289	0.08408	0.0261	V
6	Chiller	0.0034-0.0046	0.28583	0.2678	0.317-0.329	0.03367	0.0109	VI

6.2.2 Performance analysis for RAMD of the Butter oil production system

The RAMD indices for all the subsystems of the Butter oil production system are computed and tabulated in table 6.2.15.

Table 6.2.15 RAMD indices for the subsystems of the Butter oil production system

RAMD indices of the subsystems	Subsystem (S1)	Subsystem (S2)	Subsystem (S3)	Subsystem (S4)
Reliability	$e^{-0.0038t}$	$e^{-0.013t}$	$e^{-0.0045t}$	$e^{-0.00759t}$
Availability	0.9883	0.8928	0.9979	0.9057
Maintainability	$1-e^{-0.321t}$	$1-e^{-0.125t}$	$1-e^{-4.3764t}$	$1-e^{-0.0632t}$
Dependability ($D_{min.}$)	0.9915	0.9169	0.9985	0.9280
MTBF	263.158 hr.	76.9231 hr.	111.1111 hr.	131.7523 hr.
MTTR	3.1153 hr.	8.0047 hr.	0.2285 hr.	15.8278 hr.
Dependability ratio (d)	84.4737	9.6098	486.1975	8.3241

6.2.3 Performance analysis for fuzzy-reliability of the Butter oil production system

The effect of the failure rate of the subsystems of the Butter oil production system on the fuzzy-reliability of the system is computed by using the equation (4.2.50) for one year (i.e. time, t=30-360 days) and by taking an average value of coverage factor (i.e. c =0.5) as the value of system coverage factor (c) varies from 0 to 1. The table The table 6.2.16, 6.2.17, 6.2.18, 6.2.19, 6.2.20 and table 6.2.21 reveals the effect of the failure rate of each subsystem on the fuzzy-reliability of the system while table 6.2.22 reveals the effect of the coverage factor on the fuzzy-reliability of the system.

(a) Effect of the failure rate of the Chiller subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Chiller (β_1) subsystem on the fuzzy-reliability of the system is studied by varying its values as: β_1=0.0033, 0.0038, 0.0043, 0.0048 at constant value of its repair rate i.e. α_1=0.316. The failure and repair rates of the other subsystems were taken as: β_2=0.0067, β_3=0.0073, β_4 = β_5=0.0055, β_6=0.00441, β_7=0.00328, α_2=0.083, α_3=0.281, α_4=α_5=0.105, α_6=0.096, α_7=0.026. The table 6.2.16 reveals that the fuzzy-reliability of the system decreases from 0.1111 to 0.0951% when the failure rate of the Chiller subsystem increases from 0.0033 to 0.0048.

(b) Effect of the failure rate of the Cream separator subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Cream separator (β_2) subsystem on the fuzzy-reliability of the system is studied by varying its values as: β_2=0.0052, 0.0057, 0.0062, 0.0067 at constant values of its repair rate i.e. α_2=0.068. The failure and repair rates of the other subsystem were taken as: β_1=0.0038, β_3=0.0073, $\beta_4=\beta_5$=0.0055, β_6=0.00441, β_7=0.00328, α_3=0.281, $\alpha_4=\alpha_5$=0.105, α_6=0.096, α_7=0.026. The table 6.2.17 reveals that the fuzzy-reliability of the system decreases from 0.7068 to 0.6280% when the failure rate of the Cream separator subsystem increases from 0.0052 to 0.0067.

(c) Effect of the failure rate of the Pasteurizer subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Pasteurizer (β_3) subsystem on the fuzzy-reliability of the system is studied as: β_3=0.0068, 0.0073, 0.0078, 0.0083 at constant values of its repair rates i.e. α_3=0.276. The failure and repair rates of the other subsystems were taken as:β_1=0.0038, β_2=0.0057, β_4 =β_5= 0.0055, β_6=0.00441, β_7=0.00328, α_1=0.321, α_2=0.073, $\alpha_4=\alpha_5$=0.105, α_6=0.096, α_7=0.026. The table 6.2.18 reveals that the fuzzy-reliability of the system decreases from 0.1907 to 0.1630% when the failure rate of the Pasteurizer subsystem increases from 0.0068 to 0.0083.

(d) Effect of the failure rate of the Continuous butter making subsystem on the fuzzy-reliability of the system

The effect of the failure rate of Continuous butter making (β_4) subsystem on the fuzzy-reliability of the system is studied as: β_4=0.004, 0.0045, 0.0050, 0.0055 at constant value of its repair rate i.e. α_4=0.092. The failure and repair rates of the other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_3=0.0073, β_6=0.00441, β_7=0.00328, α_1=0.321, α_2=0.083, α_3=0.281, α_6=0.096, α_7=0.026. The table 6.2.19 reveals that the fuzzy-reliability of the system decreases from 4.5856 to 1.2387% when the failure rate of the Continuous butter making subsystem increases from 0.004 to 0.0055.

(e) Effect of the failure rate of the Melting vats subsystem on the fuzzy-reliability of the system

The effect of the failure rate of Melting vats (β_6) subsystem on fuzzy-reliability of the system is studied as: β_6=0.00426, 0.00431, 0.00436, 0.00441 at constant value of its repair rate i.e. α_6=0.081. The failure and repair rates of the other subsystems were taken as: β_1=0.0038, β_2=0.0057, β_3=0.0073, β_4=β_5=0.0055, β_7=0.00328, α_1=0.321, α_2=0.083, α_3=0.281, α_4=α_5=0.105, α_7=0.026. The table 6.2.20 reveals that the fuzzy-reliability of the system decreases from 0.8824 to 0.6833% when the failure rate of the Melting vats subsystem increases from 0.00426 to 0.00441.

(f) Effect of the failure rate of the Butter oil clarifier subsystem on fuzzy-reliability of the system

The effect of the Butter oil clarifier (β_7) subsystem on the fuzzy-reliability of the system is studied as: β_7=0.00323, 0.00328, 0.00333, 0.00338 at constant value of its repair rate i.e. α_7=0.021. The failure and repair rates of the other subsystems were taken as: β_1=0.0038: β_2=0.0057, β_3=0.0073, β_4=β_5=0.0048, β_6=0.00441, α_1=0.321, α_2=0.073, α_3=0.281, α_4= α_5 =0.092, α_6=0.096. The table 6.2.21 reveals that the fuzzy-reliability of the system decreases from 0.1880 to 0.1191% when the failure rate of the Butter oil clarifier subsystem increases from 0.00323 to 0.00338.

(g) Effect of the system coverage factor (*c*) on fuzzy-reliability of the system

It is obtained by varying the values of the imperfect fault coverage as: *c*=0, 0.2, 0.4, 0.6, 0.8, and 1.0. The failure and repair rates of other subsystems were taken as: β_1=0.0038, α_1=0.316, β_2=0.0067, β_3=0.0073, β_4= β_5= 0.0055, β_6=0.00441, β_7=0.00328, α_2=0.083, α_3=0.281, α_4=α_5=0.105, α_6=0.096: α_7=0.026. The fuzzy-reliability of the system is calculated using these data and results are shown in table 6.2.22. The table 6.2.22 reveals that the fuzzy-reliability of the system increases with the increase in the imperfect fault coverage and it decreases with time.

Table 6.2.16 Effect of failure rate of the Chiller subsystem on the fuzzy-reliability of the Butter oil production system

Time (days)	**Failure rate of the Chiller**			
	0.0033	**0.0038**	**0.0043**	**0.0048**
30	0.858906	0.858211	0.857516	0.856822
60	0.822689	0.822055	0.821423	0.820792
90	0.801289	0.800686	0.800084	0.799483
120	0.785415	0.784833	0.784253	0.783673
150	0.772517	0.771951	0.771386	0.770822
180	0.761547	0.760993	0.760441	0.759889
210	0.751995	0.751451	0.750908	0.750365
240	0.743574	0.743037	0.742502	0.741967
270	0.736109	0.735579	0.735049	0.734521
300	0.729470	0.728945	0.728420	0.727896
330	0.723554	0.723032	0.722510	0.721990
360	0.718286	0.717767	0.717249	0.716732

Table 6.2.17 Effect of failure rate of the Cream separator subsystem on the fuzzy-reliability of the Butter oil production system

Time (days)	**Failure rate of the Cream separator**			
	0.0052	**0.0057**	**0.0062**	**0.0067**
30	0.861070	0.858211	0.855367	0.852540
60	0.824902	0.822055	0.819229	0.816422
90	0.803389	0.800686	0.798001	0.795335
120	0.787430	0.784833	0.782254	0.779692
150	0.774470	0.771951	0.769449	0.766963
180	0.763453	0.760993	0.758550	0.756122
210	0.753864	0.751451	0.749053	0.746671
240	0.745414	0.743037	0.740676	0.738330

270	0.737926	0.735579	0.733247	0.730930
300	0.731269	0.728945	0.726636	0.724342
330	0.725338	0.723032	0.720741	0.718465
360	0.720060	0.717767	0.715490	0.713229

Table 6.2.18 Effect of failure rate of the Pasteurizer subsystem on the fuzzy-reliability of the Butter oil production system

Time (days)	**Failure rate of the Pasteurizer**			
	0.0068	**0.0073**	**0.0078**	**0.0083**
30	0.859008	0.858211	0.857415	0.856621
60	0.822779	0.822055	0.821331	0.820606
90	0.801376	0.800686	0.799998	0.799310
120	0.785498	0.784833	0.784170	0.783507
150	0.772597	0.771951	0.771306	0.770661
180	0.761625	0.760993	0.760363	0.759733
210	0.752072	0.751451	0.750830	0.750211
240	0.743650	0.743037	0.742426	0.741815
270	0.736184	0.735579	0.734974	0.734371
300	0.729546	0.728945	0.728345	0.727747
330	0.723628	0.723032	0.722437	0.721843
360	0.718360	0.717767	0.717175	0.716585

Table 6.2.19 Effect of failure rate of the Continuous butter making subsystem on the fuzzy-reliability of the Butter oil production system

Time (days)	**Failure rate of the Continuous butter making**			
	0.004	**0.0045**	**0.005**	**0.0055**
30	0.860589	0.858211	0.855848	0.853501
60	0.826125	0.822055	0.818062	0.814141
90	0.806022	0.800686	0.795515	0.790502
120	0.791119	0.784833	0.778817	0.773056
150	0.778934	0.771951	0.765348	0.759102

180	0.768469	0.760993	0.754009	0.747482
210	0.759252	0.751451	0.744249	0.737598
240	0.751026	0.743037	0.735750	0.729097
270	0.743642	0.735579	0.728309	0.721747
300	0.736991	0.728945	0.721773	0.715371
330	0.730987	0.723032	0.716020	0.709831
360	0.725574	0.717767	0.710963	0.705021

Table 6.2.20 Effect of failure rate of the Melting vats subsystem on the fuzzy-reliability of the Butter oil production system

Time (days)	**Failure rate of the Melting vats**			
	0.00426	**0.00431**	**0.00436**	**0.00441**
30	0.858461	0.858211	0.857960	0.857710
60	0.822296	0.822055	0.821815	0.821574
90	0.800914	0.800686	0.800458	0.800231
120	0.785052	0.784833	0.784614	0.784395
150	0.772164	0.771951	0.771738	0.771526
180	0.761201	0.760993	0.760786	0.760578
210	0.751655	0.751451	0.751247	0.751043
240	0.743238	0.743037	0.742836	0.742636
270	0.735777	0.735579	0.735380	0.735182
300	0.729141	0.728945	0.728748	0.728552
330	0.723227	0.723032	0.722837	0.722642
360	0.717961	0.717767	0.717574	0.717380

Table 6.2.21 Effect of failure rate of the Butter oil clarifier subsystem on the fuzzy-reliability of the Butter oil production system

Time (days)	**Failure rate of the Butter oil clarifier**			
	0.00323	**0.00328**	**0.00333**	**0.00338**
30	0.858713	0.858211	0.857709	0.857208
60	0.822721	0.822055	0.821391	0.820728
90	0.801400	0.800686	0.799973	0.799261
120	0.785554	0.784833	0.784114	0.783396
150	0.772663	0.771951	0.771240	0.770531
180	0.761693	0.760993	0.760295	0.759599
210	0.752137	0.751451	0.750765	0.750082
240	0.743712	0.743037	0.742363	0.741691
270	0.736244	0.735579	0.734915	0.734252
300	0.729602	0.728945	0.728288	0.727633
330	0.723683	0.723032	0.722382	0.721733
360	0.718413	0.717767	0.717122	0.716479

Table 6.2.22 Effect of the imperfect fault coverage on the fuzzy-reliability of the Butter oil production system

Time (days)	***c*=0**	***c*=0.2**	***c*=0.4**	***c*=0.6**	***c*=0.8**	***c*=1**
30	0.8131	0.8350	0.8582	0.8828	0.9090	0.9369
60	0.7876	0.8044	0.8221	0.8407	0.8606	0.8817
90	0.7795	0.7900	0.8007	0.8115	0.8224	0.8335
120	0.7763	0.7809	0.7848	0.7880	0.7903	0.7914
150	0.7749	0.7741	0.7720	0.7682	0.7626	0.7546
180	0.7743	0.7686	0.7610	0.7511	0.7384	0.7224
210	0.7741	0.7640	0.7515	0.7361	0.7173	0.6943
240	0.7740	0.7599	0.7430	0.7229	0.6987	0.6698
270	0.7739	0.7563	0.7356	0.7112	0.6824	0.6484
300	0.7739	0.7531	0.7289	0.7009	0.6681	0.6296

330	0.7739	0.7502	0.7230	0.6917	0.6555	0.6133
360	0.7739	0.7476	0.7178	0.6836	0.6444	0.5989

6.3 PERFORMANCE ANALYSIS FOR THE STEAM GENERATION SYSTEM

The performance analysis for the Steam generation system is analyzed by developing decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

6.3.1 Performance analysis for Decision Support System of the Steam generation system

The decision support system of each subsystem for the reliability of the Steam generation system are developed for one year (i.e. time, t =30-360 days) by solving the equation (4.3.10) with Runge-Kutta method and shown in table 6.3.1, 6.3.2, 6.3.3, 6.3.4, 6.3.5 and 6.3.6. while, the decision support system of each subsystem for the availability of the Steam generation system are developed by solving the equation (4.3.23) with various combinations of failure and repair rates parameters of subsystems of the system and shown in tables 6.3.7, 6.3.8, 6.3.9, 6.3.10, 6.3.11. The table 6.3.12 reveals the optimal values of failure and repair rates of subsystems for maximum availability of the system.

(a) Effect of the failure and repair rates of the L.P. Heater subsystem on the reliability of the system

The effect of the failure rate of the L.P. heater (θ_1) on the reliability of the system is studied by varying their values as: θ_1=0.006, 0.0065, 0.007, 0.0075 at constant value of its repair rate i.e. ω_1=0.27. The failure and repair rates of other subsystems were taken as: θ_2=0.028, θ_3=0.0045, $\theta_4=\theta_3$, θ_5=0.0054, θ_6=0.0062, $\theta_7=\theta_6$, ω_2=0.18, ω_3=0.074, $\omega_4=\omega_3$, ω_5=0.38, ω_6=0.32, $\omega_7=\omega_6$. The reliability of the system is calculated using these values and the results are shown in table 6.3.1. This table reveals that the reliability of the system decreases by 0.13% approximately with the increase of time. However, it decreases from 0.4632 to 0.4624% approximately with the increase in the failure rate of the L.P. Heater subsystem from 0.006 to 0.0075 and MTBF decreases from 301.08 days to 299.69 days approximately.

The effect of the repair rate of the L.P. heater (ω_1) subsystem on the reliability of the system is studied by varying their values as: ω_1=0.22, 0.27, 0.32, 0.37 at constant value of its failure rate i.e. θ_1=0.0065. The failure and repair rates of other subsystems were taken as: θ_2=0.028, θ_3=0.0045, $\theta_4=\theta_3$, θ_5=0.0054, θ_6=0.0062, $\theta_7=\theta_6$, ω_2=0.18, ω_3=0.074, $\omega_4=\omega_3$, ω_5=0.38, ω_6=0.32, $\omega_7=\omega_6$. The reliability of the system is calculated using these values and the results are shown in table 6.3.1. This table reveals that the reliability of the system decreases by 0.13% approximately with the increase of time. However, it increases by 1% approximately with the increase in the repair rate of the L.P. Heater subsystem from 0.22 to 0.37 and MTBF increases from 299.25 days to 302.20 days approximately.

(b) Effect of the failure and repair rates of the Feed pump subsystem on the reliability of the system

The effect of the failure rate of the Feed pump (θ_2) subsystem on the reliability of the system is studied by varying their values as: θ_2=0.023, 0.028, 0.033, 0.038 at constant value of its repair rate i.e. ω_2=0.18. The failure and repair rates of other subsystems were taken as: θ_1=0.0065, θ_3=0.0045, $\theta_4=\theta_3$, θ_5=0.0054, θ_6=0.0062, $\theta_7=\theta_6$, ω_1=0.27, ω_3=0.074, $\omega_4=\omega_3$, ω_5=0.38, ω_6=0.32, $\omega_7=\omega_6$. The reliability of the system is calculated using these values and the results are shown in table 6.3.2. This table reveals that the reliability of the system decreases by 0.1326% approximately with the increase of time. However, it decreases from 6.653 to 6.649% approximately with the increase in the failure rate of the Feed Pump subsystem from 0.023 to 0.038 and MTBF decreases from 307.76 days to 287.29 days approximately.

The effect of the repair rate of the Feed pump (ω_2) subsystem on the reliability of the system is studied by varying their values as: ω_2=0.13, 0.18, 0.23, 0.28 at constant value of its failure rate i.e. θ_2=0.028. The failure and repair rates of other subsystems were taken as: θ_1=0.0065, θ_3=0.0045, $\theta_4=\theta_3$, θ_5=0.0054, θ_6=0.0062, $\theta_7=\theta_6$, ω_1=0.27, ω_3=0.074, $\omega_4=\omega_3$, ω_5=0.38, ω_6=0.32, $\omega_7=\omega_6$. The reliability of the system is calculated using these values and the results are shown in table 6.3.2. This table reveals that the reliability of the system decreases by 0.271% approximately with the increase of time. However, it increases by 10.1% approximately with the increase in the repair rate of the Feed pump subsystem from 0.22 to 0.37 and MTBF increases from 286.35 days to 315.23 days approximately.

(c) Effect of the failure and repair rates of the H.P. Heater subsystem on the reliability of the system

The effect of the failure rate of the H.P. heater (θ_3) subsystem on the reliability of the system is studied by varying their values as: θ_3=0.004, 0.0045, 0.005, 0.0055 at constant value of its repair rate i.e. ω_3=0.074. The failure and repair rates of other subsystems were taken as: θ_1=0.0065, θ_2=0.028, θ_5=0.0054, θ_6=0.0062, $\theta_7=\theta_6$, ω_1=0.27, ω_2=0.18, ω_5=0.38, ω_6=0.32, $\omega_7=\omega_6$. The reliability of the system is calculated using these values and the results are shown in table 6.3.3. This table reveals that the reliability of the system decreases by 0.15% approximately with the increase of time. However, it decreases from 6.653 to 6.649% approximately with the increase in the failure rate of the H.P. Heater subsystem from 0.1281 to 0.1976 and MTBF decreases from 300.79 days to 300.22 days approximately.

The effect of the repair rate of the H.P. heater (ω_3) subsystem on the reliability of the system is studied by varying their values as: ω_3=0.069, 0.074, 0.079, 0.084 at constant value of its failure rate i.e. θ_3=0.0045. The failure and repair rates of other subsystems were taken as: θ_1=0.0065, θ_2=0.028, θ_5=0.0054, θ_6=0.0062, $\theta_7=\theta_6$, ω_1=0.27, ω_2=0.18, ω_5=0.38, ω_6=0.32, $\omega_7=\omega_6$. The reliability of the system is calculated using these values and the results are shown in table 6.3.3. This table reveals that the reliability of the system decreases by 0.15% approximately with the increase of time. However, it increases by 0.1% approximately with the increase in the repair rate of the H.P. Heater subsystem from 0.22 to 0.37 and MTBF increases from 300.5 days to 300.8 days approximately.

(d) Effect of the failure and repair rates of the Economizer subsystem on the reliability of the system

The effect of the failure rate of Economizer (θ_5) subsystem on the reliability of the system is studied by varying their values as: θ_5=0.0049, 0.0054, 0.0059, 0.0064 at constant value of its repair rate i.e. ω_5=0.38. The failure and repair rates of other subsystems were taken as: θ_1=0.0065, θ_2=0.028, θ_3=0.0045 $\theta_4=\theta_3$, θ_6=0.0062, $\theta_7=\theta_6$, ω_1=0.27, ω_2=0.18, ω_3=0.074, $\omega_4=\omega_3$, ω_6=0.32, $\omega_7=\omega_6$. The reliability of the system is calculated using these values and the results are shown in table 6.3.4. This table reveals that the reliability of the system decreases by 0.13% approximately with the increase of time. However, it decreases from 0.329 to

0.328% approximately with the increase in the failure rate of the Economizer subsystem from 0.0049 to 0.0064 and MTBF decreases from 300.95 days to 299.96 days approximately.

The effect of the repair rate of the Economizer (ω_5) subsystem on the reliability of the system is studied by varying their values as: ω_5=0.33, 0.38, 0.43, 0.48 at constant value of its failure rate i.e. θ_5=0.0054. The failure and repair rates of other subsystems were taken as: θ_1=0.0065, θ_2=0.028, θ_3=0.0045 $\theta_4=\theta_3$, θ_6=0.0062, $\theta_7=\theta_6$, ω_1=0.27, ω_2=0.18, ω_3=0.074, $\omega_4=\omega_3$, ω_6=0.32, $\omega_7=\omega_6$. The reliability of the system is calculated using these values and the results are shown in table 6.3.4. This table reveals that the reliability of the system decreases by 0.13%. However, it increases by 0.43% approximately with the increase in the repair rate of Economizer (ω_5) from 0.33 to 0.48 and MTBF increases from 300 days to 301.36 days approximately.

(e) Effect of the failure and repair rates of the Boiler drum subsystem on the reliability of the system

The effect of the failure rate of the boiler drum (θ_6) subsystem on the reliability of the system is studied by varying their values as: θ_6=0.0057, 0.0062, 0.0067, 0.0072 at constant value of its repair rate i.e. ω_6=0.32. The failure and repair rates of other subsystems were taken as: θ_1=0.0065, θ_2=0.028, $\theta_3=\theta_4$=0.0045, θ_5=0.0054, $\theta_7=\theta_6$, ω_1=0.27, ω_2=0.18, $\omega_3=\omega_4$=0.074, ω_5=0.38, $\omega_7=\omega_6$. The reliability of the system is calculated using these values and the results are shown in table 6.3.5. This table reveals that the reliability of the system decreases by 0.13% approximately with the increase of time. However, it decreases by 0.015% approximately with the increase in the failure rate of the Boiler drum subsystem from 0.0057 to 0.0072 and MTBF decreases from 300.60 days to 300.59 days approximately.

The effect of the repair rate of boiler drum (ω_6) subsystem on the reliability of the system is studied by varying their values as: ω_6=0.27, 0.32, 0.37, 0.42 at constant value of its failure rate i.e. θ_6=0.0062. The failure and repair rates of other subsystems were taken as: θ_1=0.0065, θ_2=0.028, θ_3=0.045, θ_4=0.0054, $\theta_5= \theta_4$, θ_6=0.0062, $\theta_7=\theta_6$, ω_1=0.27, ω_2=0.18, ω_3=0.074, $\omega_4= \omega_3$, ω_5=0.38, $\omega_7=\omega_6$. The reliability of the system is calculated using these values and the results are shown in table 6.3.5. This table reveals that the reliability of the system decreases by 0.13%. However, it increases by 0.0251% approximately with the increase in the repair rate of the Economizer subsystem from 0.22 to 0.42 and MTBF increases from 300.62 days to 300.66 days approximately.

(f) Effect of the failure and repair rates of the subsystems on the reliability of the system

The reliability of the system decreases with the increase in the failure rate of its subsystems, while it increases with the increase in the repair rates of the subsystems as mentioned in table 6.3.6.

(g) Effect of the failure and repair rates of the L.P. Heater subsystem on the availability of the system

The effect of the failure and repair rates of the L.P. Heater subsystem on the availability of the system is studied by varying their values as: θ_1=0.006, 0.0065, 0.007, 0.0075 and ω_1=0.22, 0.27, 0.32, and 0.37. The failure and repair rates of other subsystems were taken as: θ_2=0.028, θ_3=0.0045, $\theta_4=\theta_3$, θ_5=0.0054, θ_6=0.0062, $\theta_7=\theta_6$, ω_2=0.18, ω_3=0.074, $\omega_4=\omega_3$, ω_5=0.38, ω_6=0.32, $\omega_7=\omega_6$. The availability of the system is calculated using these values and the results are shown in table 6.3.7. This table reveals that increase in the failure rate of the L.P. Heater subsystem has approximately 0.564% negative impacts on availability of the system while increase in the repair rate of the L.P. Heater subsystem has approximately 1.157% impacts on the availability of the system.

(h) Effect of the failure and repair rates of the Feed pump on the availability of the system

The effect of the failure and repair rates of the Feed Pump subsystem on the availability of the system is studied by varying their values as: θ_2=0.023, 0.028, 0.033, 0.038 and ω_2=0.13, 0.18, 0.23, and 0.28. The failure and repair rates of other subsystems were taken as: θ_1=0.0065, θ_3=0.0045, $\theta_4=\theta_3$, θ_5=0.0054, θ_6=0.0062, $\theta_7=\theta_6$, ω_1=0.27, ω_3=0.074, $\omega_4=\omega_3$, ω_5=0.38, ω_6=0.32, $\omega_7=\omega_6$. The availability of the system is calculated using these values and the results are shown in the table 6.3.8. This table reveals that increase in the failure rate of the Feed Pump subsystem has approximately 8.645% negative impacts on the availability of the system while increase in the repair rate of Feed Pump subsystem has approximately 13.287% impacts on the availability of the system.

(i) Effect of the failure and repair rates of the H.P. Heater subsystem on the availability of the system

The effect of the failure and repair rates of H.P. Heater subsystem on the availability of the system is studied by varying their values as: θ_3=0.004, 0.0045, 0.005, 0.0055 and ω_3=0.069, 0.074, 0.079, and 0.084. The failure and repair rates of other subsystems were taken as: $\theta_1=0.0065$, $\theta_2=0.028$, $\theta_4=\theta_3$, $\theta_5=0.0054$, $\theta_6=0.0062$, $\theta_7=\theta_6$, $\omega_1=0.27$, $\omega_2=0.18$, $\omega_4=\omega_3$, $\omega_5=0.38$, $\omega_6=0.32$, $\omega_7=\omega_6$. The availability of the system is calculated using these values and the results are shown in the table 6.3.9. This table reveals that increase in the failure rate of the H.P. Heater subsystem has approximately 0.265% negative impacts on the availability of the system while increase in the repair rate the H.P. Heater subsystem has approximately 0.1695% impacts on the availability of the system.

(j) Effect of the failure and repair rates of the Economizer subsystem on the availability of the system

The effect of the failure and repair rates of the Economizer subsystem on the availability of the system is studied by varying their values as: θ_5=0.0049, 0.0054, 0.0059, 0.0064 and ω_5=0.33, 0.38, 0.43, and 0.48. The failure and repair rates of other subsystems were taken as: $\theta_1=0.0065$, $\theta_2=0.028$, $\theta_4=\theta_3=0.0045$, $\theta_6=0.0062$, $\theta_7=\theta_6$, $\omega_1=0.27$, $\omega_2=0.18$, $\omega_3=0.074$, $\omega_4=\omega_3$, $\omega_6=0.32$, $\omega_7=\omega_6$. The availability of the system is calculated using these values and the results are shown in the table 6.3.10. This table reveals that increase in the failure rate of the Economizer subsystem has approximately 0.378% negative impacts on the availability of the system while increase in the repair rate of the Economizer subsystem has approximately 0.506% negative impacts on the availability of the system.

(k) Effect of the failure and repair rates of the Boiler drum subsystem on the availability of the system

The effect of the failure and repair rates of the Boiler drum subsystem on the availability of the system is studied by varying their values as: θ_6=0.0057, 0.0062, 0.0067, 0.0072 and ω_6=0.27, 0.32, 0.37, and 0.42. The failure and repair rates of other subsystems were taken as: $\theta_1=0.0065$, $\theta_2=0.028$, $\theta_4=\theta_3=0.0045$, $\theta_5=0.0054$, $\theta_7=\theta_6$, $\omega_1=0.27$, $\omega_2=0.18$, $\omega_3=0.074$, $\omega_4=\omega_3$, $\omega_5=0.38$, $\omega_7=\omega_6$. The availability of the system is calculated using these values and the results are shown in the table 6.3.11. This table reveals that increase in the failure rate of the boiler drum has approximately 0.0129% negative impacts on the availability of the system while increase in the repair rate of the Boiler drum subsystem has approximately 0.0575% impacts on the availability of the system.

Table 6.3.1 Decision matrix for the L.P. Heater subsystem on the reliability of the Steam generation system

Time (Days)	**Failure rate of L.P. heater (θ_1)**				**Repair rate of L.P. heater (ω_1)**			
	0.006	**0.0065**	**0.007**	**0.0075**	**0.22**	**0.27**	**0.32**	**0.37**
30	0.837327	0.836030	0.834737	0.833448	0.832219	0.836030	0.838670	0.840608
60	0.836434	0.835140	0.833851	0.832566	0.831343	0.835140	0.837771	0.839702
90	0.836273	0.834981	0.833692	0.832407	0.831184	0.834981	0.837611	0.839541
120	0.836239	0.834946	0.833657	0.832372	0.831150	0.834946	0.837577	0.839507
150	0.836232	0.834939	0.833650	0.832365	0.831143	0.834939	0.837570	0.839500
180	0.836231	0.834938	0.833649	0.832364	0.831141	0.834938	0.837568	0.839498
210	0.836231	0.834938	0.833649	0.832364	0.831141	0.834938	0.837568	0.839498
240	0.836231	0.834938	0.833649	0.832364	0.831141	0.834938	0.837568	0.839498
270	0.836231	0.834938	0.833649	0.832364	0.831141	0.834938	0.837568	0.839498
300	0.836231	0.834938	0.833649	0.832364	0.831141	0.834938	0.837568	0.839498
330	0.836231	0.834938	0.833649	0.832364	0.831141	0.834938	0.837568	0.839498
360	0.836231	0.834938	0.833649	0.832364	0.831141	0.834938	0.837568	0.839498
MTBF	301.08	300.62	300.15	299.69	299.25	300.62	301.57	302.26

Table 6.3.2 Decision matrix for the Feed pump subsystem on the reliability of the Steam generation system

Time	**Failure rate of Feed pump (θ_2)**				**Repair rate of Feed pump (ω_2)**			
(Days)	**0.023**	**0.028**	**0.033**	**0.038**	**0.13**	**0.18**	**0.23**	**0.28**
30	0.855897	0.836030	0.817066	0.798951	0.797383	0.836030	0.860159	0.876522
60	0.854968	0.835140	0.816212	0.798122	0.795414	0.835140	0.859406	0.875764
90	0.854804	0.834981	0.816056	0.797970	0.795257	0.834981	0.859239	0.875592
120	0.854770	0.834946	0.816021	0.797935	0.795224	0.834946	0.859205	0.875558
150	0.854763	0.834939	0.816014	0.797928	0.795216	0.834939	0.859198	0.875552
180	0.854762	0.834938	0.816012	0.797926	0.795214	0.834938	0.859197	0.875551
210	0.854762	0.834938	0.816012	0.797926	0.795214	0.834938	0.859197	0.875550
240	0.854762	0.834938	0.816012	0.797925	0.795214	0.834938	0.859197	0.875550
270	0.854762	0.834938	0.816012	0.797925	0.795214	0.834938	0.859197	0.875550
300	0.854762	0.834938	0.816012	0.797925	0.795214	0.834938	0.859197	0.875550
330	0.854762	0.834938	0.816012	0.797925	0.795214	0.834938	0.859197	0.875550
360	0.854762	0.834938	0.816012	0.797925	0.795214	0.834938	0.859197	0.875550
MTBF	307.76	300.62	293.80	287.29	286.350	300.618	309.348	315.235

Table 6.3.3 Decision matrix for the H.P. Heater subsystem on the reliability of the Steam generation system

Time	**Failure rate of H.P. heater (θ_3)**				**Repair rate of H.P. heater (ω_3)**			
(Days)	**0.004**	**0.0045**	**0.005**	**0.0055**	**0.069**	**0.074**	**0.079**	**0.084**
30	0.836352	0.836030	0.835673	0.835281	0.835904	0.836030	0.836144	0.836249
60	0.835597	0.835140	0.834635	0.834083	0.834871	0.835140	0.835373	0.835573
90	0.835470	0.834981	0.834440	0.833848	0.834652	0.834981	0.835255	0.835487
120	0.835443	0.834946	0.834398	0.833798	0.834600	0.834946	0.835233	0.835472
150	0.835437	0.834939	0.834389	0.833787	0.834588	0.834939	0.835229	0.835470

180	0.835436	0.834938	0.834387	0.833785	0.834585	0.834938	0.835228	0.835469
210	0.835436	0.834938	0.834387	0.833785	0.834584	0.834938	0.835228	0.835469
240	0.835436	0.834938	0.834387	0.833785	0.834584	0.834938	0.835228	0.835469
270	0.835436	0.834938	0.834387	0.833785	0.834584	0.834938	0.835228	0.835469
300	0.835436	0.834938	0.834387	0.833785	0.834584	0.834938	0.835228	0.835469
330	0.835436	0.834938	0.834387	0.833785	0.834584	0.834938	0.835228	0.835469
360	0.835436	0.834938	0.834387	0.833785	0.834584	0.834938	0.835228	0.835469
MTBF	300.79	300.62	300.43	300.22	300.50	300.62	300.71	300.80

Table 6.3.4 Decision matrix for the Economizer subsystem on the reliability of the Steam generation system

Time	**Failure rate of Economizer (θ_5)**				**Repair rate of Economizer (ω_5)**			
(Days)	**0.0049**	**0.0054**	**0.0059**	**0.0064**	**0.33**	**0.38**	**0.43**	**0.48**
30	0.836950	0.836030	0.835111	0.834195	0.834528	0.836030	0.837185	0.838116
60	0.836059	0.835140	0.834224	0.833310	0.833642	0.835140	0.836294	0.837209
90	0.835899	0.834981	0.834064	0.833150	0.833482	0.834981	0.836134	0.837050
120	0.835865	0.834946	0.834030	0.833116	0.833448	0.834946	0.836100	0.837015
150	0.835858	0.834939	0.834023	0.833109	0.833441	0.834939	0.836093	0.837008
180	0.835856	0.834938	0.834022	0.833107	0.833440	0.834938	0.836091	0.837007
210	0.835856	0.834938	0.834021	0.833107	0.833439	0.834938	0.836091	0.837007
240	0.835856	0.834938	0.834021	0.833107	0.833439	0.834938	0.836091	0.837007
270	0.835856	0.834938	0.834021	0.833107	0.833439	0.834938	0.836091	0.837007
300	0.835856	0.834938	0.834021	0.833107	0.833439	0.834938	0.836091	0.837007
330	0.835856	0.834938	0.834021	0.833107	0.833439	0.834938	0.836091	0.837007
360	0.835856	0.834938	0.834021	0.833107	0.833439	0.834938	0.836091	0.837007
MTBF	300.95	300.62	300.29	299.96	300.08	300.62	301.03	301.36

Table 6.3.5 Decision matrix for the Boiler drums subsystem on the reliability of the Steam generation system

Time	**Failure rate of Boiler drum (θ_6)**				**Repair rate of Boiler drum (ω_6)**			
(Days)	**0.0057**	**0.0062**	**0.0067**	**0.0072**	**0.27**	**0.32**	**0.37**	**0.42**
30	0.836070	0.836030	0.835986	0.835940	0.835933	0.836030	0.836092	0.836147
60	0.835180	0.835140	0.835098	0.835052	0.835038	0.835140	0.835205	0.835247
90	0.835020	0.834981	0.834938	0.834892	0.834878	0.834981	0.835045	0.835088
120	0.834986	0.834946	0.834904	0.834858	0.834844	0.834946	0.835011	0.835053
150	0.834979	0.834939	0.834897	0.834851	0.834837	0.834939	0.835004	0.835046
180	0.834977	0.834938	0.834895	0.834849	0.834835	0.834938	0.835002	0.835045
210	0.834977	0.834938	0.834895	0.834849	0.834835	0.834938	0.835002	0.835045
240	0.834977	0.834938	0.834895	0.834849	0.834835	0.834938	0.835002	0.835045
270	0.834977	0.834938	0.834895	0.834849	0.834835	0.834938	0.835002	0.835045
300	0.834977	0.834938	0.834895	0.834849	0.834835	0.834938	0.835002	0.835045
330	0.834977	0.834938	0.834895	0.834849	0.834835	0.834938	0.835002	0.835045
360	0.834977	0.834938	0.834895	0.834849	0.834835	0.834938	0.835002	0.835045
MTBF	300.63	300.62	300.60	300.59	300.58	300.62	300.64	300.66

Table 6.3.6 Decision matrix for the subsystems on the reliability of the Steam generation system

Time (Days)	**Change in Reliability of the system with failure rate of subsystems (% negative)**					**Change in Reliability of the system with repair rate of subsystems (% positive)**				
	L.P. heater (θ_1)	**Feed pump** (θ_2)	**H.P. heater** (θ_3)	**Economizer** (θ_5)	**Boiler drum** (θ_6)	**L.P. heater** (ω_1)	**Feed pump** (ω_2)	**H.P. heater** (ω_3)	**Economizer** (ω_5)	**Boiler drum** (ω_6)
30	0.4632	6.653	0.1281	0.3292	0.0156	1.0080	9.9248	0.0413	0.4300	0.0256
60	0.4624	6.649	0.1813	0.3288	0.0153	1.0055	10.1016	0.0841	0.4278	0.0251
90	0.4624	6.649	0.1940	0.3288	0.0153	1.0055	10.1018	0.1000	0.4280	0.0251
120	0.4624	6.649	0.1968	0.3288	0.0153	1.0055	10.1022	0.1045	0.4280	0.0251
150	0.4624	6.649	0.1974	0.3289	0.0153	1.0055	10.1024	0.1056	0.4280	0.0251
180	0.4624	6.649	0.1976	0.3289	0.0153	1.0055	10.1025	0.1059	0.4280	0.0251
210	0.4624	6.649	0.1976	0.3289	0.0153	1.0055	10.1025	0.1060	0.4280	0.0251
240	0.4624	6.649	0.1976	0.3289	0.0153	1.0055	10.1025	0.1060	0.4280	0.0251
270	0.4624	6.649	0.1976	0.3289	0.0153	1.0055	10.1025	0.1060	0.4280	0.0251
300	0.4624	6.649	0.1976	0.3289	0.0153	1.0055	10.1025	0.1060	0.4280	0.0251
330	0.4624	6.649	0.1976	0.3289	0.0153	1.0055	10.1025	0.1060	0.4280	0.0251
360	0.4624	6.649	0.1976	0.3289	0.0153	1.0055	10.1025	0.1060	0.4280	0.0251

Table 6.3.7 Decision matrix for the L.P. Heater subsystem on the availability of the Steam generation system

θ_1 ω_1	**0.006**	**0.0065**	**0.007**	**0.0075**
0.22	0.832212	0.830641	0.829076	0.827517
0.27	0.835725	0.834434	0.833146	0.831863
0.32	0.838157	0.837061	0.835968	0.834877
0.37	0.839941	0.838989	0.838039	0.837091

Table 6.3.8 Decision matrix for the Feed pump subsystem on the availability of the Steam generation system

θ_2 ω_2	**0.023**	**0.028**	**0.033**	**0.038**
0.13	0.819817	0.794757	0.771184	0.748968
0.18	0.854234	0.834434	0.815531	0.797465
0.23	0.874996	0.858663	0.842928	0.827760
0.28	0.888885	0.874996	0.861535	0.848481

Table 6.3.9 Decision matrix for the H.P. Heater subsystem on the availability of the Steam generation system

θ_3 ω_3	**0.004**	**0.0045**	**0.005**	**0.0055**
0.069	0.834718	0.834048	0.833311	0.832510
0.074	0.835027	0.834434	0.833780	0.833069
0.079	0.835283	0.834753	0.834169	0.833532
0.084	0.835497	0.835020	0.834494	0.833921

Table 6.3.10 Decision matrix for the Economizer subsystem on the availability of the Steam generation system

θ_5 ω_5	**0.0049**	**0.0054**	**0.0059**	**0.0064**
0.33	0.833990	0.832937	0.831887	0.830840
0.38	0.835351	0.834434	0.833519	0.832605
0.43	0.836398	0.835586	0.834775	0.833965
0.48	0.837230	0.836500	0.835772	0.835045

Table 6.3.11 Decision matrix for the Boiler drums subsystem on the availability of the Steam generation system

θ_6 ω_6	**0.0057**	**0.0062**	**0.0067**	**0.0072**
0.27	0.834303	0.834246	0.834185	0.834120
0.32	0.834475	0.834434	0.834389	0.834342
0.37	0.834593	0.834562	0.834528	0.834492
0.42	0.834679	0.834654	0.834627	0.834599

Table 6.3.12 Optimal values of failure and repair rates of subsystems for maximum availability of the Steam generation system

S. N.	**Subsystem**	**Failure rate (θ)**	**Repair rate (ω)**	**Max. Availability**
1	Feed pump	0.023	0.28	0.888885
2	L.P. heater	0.006	0.37	0.839941
3	Economizer	0.0049	0.48	0.837230
4	H.P. heater	0.004	0.084	0.835497
5	Boiler drum	0.0057	0.42	0.834679

The decision matrices for Steam generation system as given in tables (6.3.1 to 6.3.11) indicate that the Feed pump is the most critical subsystem as for as maintenance is concerned. So, this subsystem should be given top priority as the effect of its repair rates on the system availability is much higher than other subsystems. On the basis of repair rates, the repair priorities from maintenance point for Steam generation system as under.

Decision criteria for the repair priority of the Steam generation system

S. N.	Subsystem	Increase in failure rate (θ)	Decrease in		Increase in Repair rate (ω)	Increase in		Repair Priority
			Reliabiity	Availability		Reliabiity	Availability	
1	Feed pump	0.023-0.038	6.64933	5.3815	0.13-0.28	10.08753	1.7388	I
2	L.P. heater	0.006-0.0075	0.46247	0.3672	0.22-0.37	1.00571	0.1999	II
3	Economizer	0.33-0.48	0.32890	0.2628	0.33-0.48	0.42815	0.0956	III
4	H.P. heater	0.004-0.005	0.19007	0.1873	0.069-0.084	0.09812	0.0299	IV
5	Boiler drum	0.0057-0.0072	0.01533	0.0124	0.27-0.42	0.02514	0.0096	V

6.3.2 Performance analysis for RAMD of the Steam generation system

The RAMD indices for all the subsystems of the Steam generation system are computed and tabulated in table 6.3.13.

Table 6.3.13 RAMD indices for the subsystems of the Steam generation system

RAMD indices of the subsystems	Subsystem (S1)	Subsystem (S2)	Subsystem (S3)	Subsystem (S4)
Reliability	$e^{-0.0345t}$	$e^{-0.009t}$	$e^{-0.0054t}$	$e^{-0.0124t}$
Availability	0.8477	0.9965	0.9860	0.9996
Maintainability	$1-e^{-0.192t}$	$1-e^{-2.582t}$	$1-e^{-0.38t}$	$1-e^{-33.67t}$
Dependability ($D_{min.}$)	0.8747	0.9975	0.9898	0.9997
MTBF	28.9855 hr.	111.11 hr.	185.1852 hr.	80.6452 hr.
MTTR	5.2067 hr.	0.3873 hr.	2.6316 hr.	0.0297 hr.
Dependability ratio (d)	5.567	286.8642	70.3704	0.002715

6.3.3 Performance analysis for Fuzzy-reliability of the Steam generation system

The effect of the failure rate of the subsystems of the Steam generation system on the fuzzy-reliability of the system is computed by using the equation (4.3.71) for one year (i.e. time, t=30-360 days) and by taking an average value of coverage factor (i.e. c =0.5) as the value of system coverage factor (c) varies from 0 to 1. The table 6.3.14, 6.3.15. 6.3.16, 6.3.17 and 6.3.18 reveals the effect of the failure rate of each subsystem on fuzzy-reliability of the system while table 6.3.19 reveals the effect of coverage factor on fuzzy-reliability of the system.

(a) Effect of the failure rate of the L.P. Heater subsystem on the fuzzy-reliability of the system

The effect of the failure rate of L.P. heater (θ_1) subsystem on the fuzzy-reliability of the system is studied by varying its values as: θ_1=0.006, 0.0065, 0.007, 0.0075 and ω_1=0.27, θ_2=0.028, θ_3=0.0045, $\theta_4=\theta_3$, θ_5=0.0054, θ_6=0.0062, $\theta_7=\theta_6$, ω_2=0.18, ω_3=0.074, $\omega_4=\omega_3$, ω_5=0.38, ω_6=0.32, $\omega_7=\omega_6$. The table 6.3.14 reveals that the fuzzy-reliability of the system decreases from 0.2058 to 0.2051% when the failure rate of the L.P. Heater subsystem increases from 0.006 to 0.0075.

(b) Effect of the failure rate of the Feed pump subsystem on the fuzzy-reliability of the system

The effect of failure rate of Feed pump (θ_2) subsystem on fuzzy-reliability of the system is studied by varying its values as: θ_2=0.023, 0.028, 0.033, 0.038 and ω_2=0.18, θ_1=0.0065, θ_3=0.0045, $\theta_4=\theta_3$, θ_5=0.0054, θ_6=0.0062, $\theta_7=\theta_6$, ω_1=0.27, ω_3=0.074, $\omega_4=\omega_3$, ω_5=0.38, ω_6=0.32, $\omega_7=\omega_6$. The table 6.3.15 reveals that the fuzzy-reliability of the system decreases from 3.0284 to 3.0113% when the failure rate of the Feed pump subsystem increases from 0.023 to 0.038.

(c) Effect of the failure rate of the H.P. Heater subsystem on the fuzzy-reliability of the system

The effect of the failure rate of H.P. heater (θ_3) subsystem on the fuzzy-reliability is studied by varying its values as: θ_3=0.004, 0.0045, 0.005, 0.0055 and ω_3=0.074, θ_1=0.0065, θ_2=0.028, θ_5=0.0054, θ_6=0.0062, $\theta_7=\theta_6$, ω_1=0.27, ω_2=0.18, ω_5=0.38, ω_6=0.32, $\omega_7=\omega_6$. The table 6.3.16 reveals that the fuzzy-reliability of the system decreases from 0.6272 to 0.5393% when the failure rate of the H.P. Heater subsystem increases from 0.004 to 0.0055.

(d) Effect of failure rate of Economizer on fuzzy-reliability of the system

The effect of the failure rate of the economizer (θ_5) subsystem on the fuzzy-reliability is studied by varying its values as: θ_5=0.0049, 0.0054, 0.0059, 0.0064 and ω_5=0.38, θ_1=0.0065, θ_2=0.028, θ_3=0.0045 $\theta_4=\theta_3$, θ_6=0.0062, $\theta_7=\theta_6$, ω_1=0.27, ω_2=0.18, ω_3=0.074, $\omega_4=\omega_3$, ω_6=0.32, $\omega_7=\omega_6$. The table 6.3.17 reveals that the fuzzy-reliability of the system 0.1463 to 0.1457% when the failure rate of the Economizer subsystem increases from 0.0049 to 0.0064.

(e) Effect of the failure rate of the Boiler drum subsystem on the fuzzy-reliability of the system

The effect of the failure rate of boiler drum (θ_6) subsystem on the fuzzy-reliability of the system is studied by varying its values as: θ_6=0.0057, 0.0062, 0.0067, 0.0072 and ω_6=0.32, θ_1=0.0065, θ_2=0.028, $\theta_3=\theta_4$=0.0045, θ_5=0.0054, $\theta_7=\theta_6$, ω_1=0.27, ω_2=0.18, $\omega_3=\omega_4$=0.074, ω_5=0.38, $\omega_7=\omega_6$. The table 6.3.18 reveals that the fuzzy-reliability of the system decreases from 0.1857 to 0.1856% when the failure rate of the Boiler drum subsystem increases from 0.0057 to 0.0072.

(f) Effect of the system coverage factor on the fuzzy-reliability of the system

It is obtained by varying the values of imperfect fault coverage as: c=0, 0.2, 0.4, 0.6, 0.8, and 1.0. The failure and repair rates of other subsystems were taken as: θ_1=0.0065, θ_2=0.028, $\theta_3=\theta_4$=0.0045, θ_5=0.0054, $\theta_7=\theta_6$=0.0062, ω_1=0.27, ω_2=0.18, $\omega_3=\omega_4$=0.074, ω_5=0.38, $\omega_7=\omega_6$=0.32. The fuzzy-reliability of the system is calculated using these data and results are shown in table 6.3.19. The table 6.3.19 reveals that the fuzzy-reliability of the system increases with the increase in imperfect fault coverage and it decreases with time.

Table 6.3.14 Effect of failure rate of the L.P. Heater subsystem on the fuzzy-reliability of the Steam generation system

Time (days)	**Failure rate of L.P. heater**			
	0.006	**0.0065**	**0.007**	**0.0075**
30	0.883795	0.882918	0.882043	0.881169
60	0.882189	0.881313	0.880438	0.879565

90	0.881947	0.881070	0.880195	0.879322
120	0.881905	0.881028	0.880153	0.879279
150	0.881898	0.881021	0.880145	0.879272
180	0.881896	0.881019	0.880144	0.879270
210	0.881896	0.881019	0.880143	0.879270
240	0.881896	0.881019	0.880144	0.879270
270	0.881896	0.881019	0.880144	0.879270
300	0.881896	0.881019	0.880144	0.879270
330	0.881896	0.881019	0.880143	0.879270
360	0.881896	0.881019	0.880144	0.879270

Table 6.3.15 Effect of failure rate of the Feed pump subsystem on the fuzzy-reliability of the Steam generation system

Time (days)	**Failure rate of Feed pump**			
	0.023	**0.028**	**0.033**	**0.038**
30	0.896232	0.882918	0.869995	0.857443
60	0.894645	0.881313	0.868372	0.855807
90	0.894409	0.881070	0.868124	0.855553
120	0.894369	0.881028	0.868079	0.855506
150	0.894362	0.881021	0.868071	0.855497
180	0.894361	0.881019	0.868070	0.855496
210	0.894361	0.881019	0.868070	0.855495
240	0.894360	0.881019	0.868070	0.855495
270	0.894360	0.881019	0.868069	0.855495
300	0.894360	0.881019	0.868069	0.855495
330	0.894361	0.881019	0.868070	0.855495
360	0.894360	0.881019	0.868070	0.855495

Table 6.3.16 Effect of failure rate of the H.P. Heater subsystem on the fuzzy-reliability of the Steam generation system

Time (days)	**Failure rate of H.P. heater**			
	0.004	**0.0045**	**0.005**	**0.0055**
30	0.884002	0.882918	0.881830	0.880738
60	0.882567	0.881313	0.880051	0.878781
90	0.882356	0.881070	0.879775	0.878471
120	0.882320	0.881028	0.879727	0.878416
150	0.882314	0.881021	0.879718	0.878406
180	0.882313	0.881019	0.879716	0.878404
210	0.882312	0.881019	0.879716	0.878403
240	0.882312	0.881019	0.879716	0.878403
270	0.882312	0.881019	0.879716	0.878403
300	0.882313	0.881019	0.879716	0.878403
330	0.882312	0.881019	0.879716	0.878403
360	0.882312	0.881019	0.879716	0.878403

Table 6.3.17 Effect of failure rate of the Economizer subsystem on the fuzzy-reliability of the Steam generation system

Time (days)	**Failure rate of Economizer**			
	0.0049	**0.0054**	**0.0059**	**0.0064**
30	0.883541	0.882918	0.882296	0.881675
60	0.881936	0.881313	0.880691	0.880070
90	0.881693	0.881070	0.880448	0.879827
120	0.881651	0.881028	0.880406	0.879785
150	0.881644	0.881021	0.880399	0.879777
180	0.881642	0.881019	0.880397	0.879776
210	0.881642	0.881019	0.880397	0.879775
240	0.881642	0.881019	0.880397	0.879776
270	0.881642	0.881019	0.880397	0.879776

300	0.881642	0.881019	0.880397	0.879776
330	0.881642	0.881019	0.880397	0.879775
360	0.881642	0.881019	0.880397	0.879776

Table 6.3.18 Effect of failure rate of Boiler drum subsystem on the fuzzy-reliability of the Steam generation system

Time (days)	**Failure rate of Boiler drum**			
	0.0057	**0.0062**	**0.0067**	**0.0072**
30	0.881958	0.881675	0.881392	0.881107
60	0.880354	0.880070	0.879786	0.879502
90	0.880110	0.879827	0.879544	0.879260
120	0.880068	0.879785	0.879502	0.879218
150	0.880060	0.879777	0.879494	0.879210
180	0.880059	0.879776	0.879493	0.879209
210	0.880058	0.879775	0.879492	0.879208
240	0.880058	0.879776	0.879492	0.879208
270	0.880058	0.879776	0.879492	0.879208
300	0.880059	0.879776	0.879492	0.879208
330	0.880058	0.879775	0.879492	0.879208
360	0.880058	0.879776	0.879492	0.879208

Table 6.3.19 Effect of the imperfect fault coverage on the fuzzy-reliability of the Steam generation system

Time (days)	$c=0$	$c=0.2$	$c=0.4$	$c=0.6$	$c=0.8$	$c=1$
30	0.8131	0.8350	0.8582	0.8828	0.9090	0.9369
60	0.7876	0.8044	0.8221	0.8407	0.8606	0.8817
90	0.7795	0.7900	0.8007	0.8115	0.8224	0.8335
120	0.7763	0.7809	0.7848	0.7880	0.7903	0.7914
150	0.7749	0.7741	0.7720	0.7682	0.7626	0.7546
180	0.7743	0.7686	0.7610	0.7511	0.7384	0.7224
210	0.7741	0.7640	0.7515	0.7361	0.7173	0.6943

240	0.7740	0.7599	0.7430	0.7229	0.6987	0.6698
270	0.7739	0.7563	0.7356	0.7112	0.6824	0.6484
300	0.7739	0.7531	0.7289	0.7009	0.6681	0.6296
330	0.7739	0.7502	0.7230	0.6917	0.6555	0.6133
360	0.7739	0.7476	0.7178	0.6836	0.6444	0.5989

6.4 PERFORMANCE ANALYSIS FOR REFRIGERATION SYSTEM

The performance analysis for the Refrigeration system is analyzed by developing decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

6.4.1 Performance analysis for DSS of Refrigeration system

The Secision Support System of each subsystem for the reliability of the Refrigeration system are developed for one year (i.e. time, *t* =30-360 days) by solving the equation (4.1.10) with Runge-Kutta method and shown in table 6.4.1, 6.4.2, 6.4.3, 6.4.4, 6.4.5 and 6.4.6. While, the decision support system of each subsystem for the availability of the Refrigeration system are developed by solving the equation (4.4.20) with various combinations of failure and repair rates parameters of subsystems of the system and shown in tables 6.4.7, 6.4.8, 6.4.9, 6.4.10, 6.4.11. The table 6.4.12 reveals the optimal values of failure and repair rates of subsystems for maximum availability of the system.

(a) Effect of the failure and repair rates of the Compressor subsystem on the reliability of the system

The effect of the failure rate of the Compressor (ϕ_1) subsystem on the reliability of the system is studied by varying their values as: ϕ_1=0.061, 0.066, 0.071, 0.076 at constant value of its repair rate i.e. τ_1=0.31. The failure and repair rates of other subsystems were taken as: ϕ_3=0.038, ϕ_4=ϕ_3, ϕ_5=0.0063, ϕ_6=0.027, ϕ_7=0.046, τ_3=0.36, τ_4=τ_3, τ_5=0.26, τ_6=0.43, τ_7=0.18. The reliability of the system is calculated using these values and the results are shown in table 6.4.1. This table reveals that the reliability of the system decreases from 0.0382 to 0.048% approximately with the increase of time. However, it decreases by 1.2% approximately with the increase in the failure rate of Compressor subsystem from 0.061 to 0.0076 and MTBF decreases from 259.72 days to 256.60 days approximately.

The effect of the repair rate of the Compressor (τ_1) subsystem on the reliability of the system is studied by varying their values as: τ_1=0.26, 0.31, 0.36, 0.41 at constant value of its failure rate i.e. ϕ_1 =0.066. The failure and repair rates of other subsystems were taken as: ϕ_3=0.038, ϕ_4=ϕ_3, ϕ_5=0.0063, ϕ_6=0.027, ϕ_7=0.046, τ_3=0.36, τ_4=τ_3, τ_5=0.26, τ_6=0.43, τ_7=0.18.The reliability of the system is calculated using these values and the results are shown in table 6.4.1. This table reveals that the reliability of the system decreases from 0.0582 to 0.0279% approximately with the increase of time. However, it increases by 2.21% approximately with the increase in the repair rate of Compressor subsystem from 0.26 to 0.41 and MTBF increases from 256 days to 261.7 days approximately.

(b) Effect of the failure and repair rates of the Condenser subsystem on the reliability of the system

The effect of the failure rate of the Condenser (ϕ_3) subsystem on the reliability of the system is studied by varying their values as: ϕ_3=0.033, 0.038, 0.043, 0.048 at constant value of its repair rate i.e. τ_3=0.36. The failure and repair rates of other subsystems were taken as: ϕ_1= ϕ_2=0.066, ϕ_5=0.0063, ϕ_6=0.027, ϕ_7=0.046, τ_1= τ_2=0.31, τ_5=0.26, τ_6=0.43, τ_7=0.18. The reliability of the system is calculated using these values and the results are shown in table 6.4.2. This table reveals that the reliability of the system decreases from 0.0364 to 0.0357% approximately with the increase of time. However, it decreases by 0.56% approximately with the increase in the failure rate of the Condenser subsystem from 0.032 to 0.048 and MTBF decreases from 259.17 days to 257.71 days approximately.

The effect of repair rate of the Condenser (τ_3) subsystem on the reliability of the system is studied by varying their values as: τ_3=0.31, 0.36, 0.41, 0.46 at constant value of its failure rate i.e. ϕ_3 =0.038. The failure and repair rates of other subsystems were taken as: ϕ_1= ϕ_2=0.066, ϕ_5=0.0063, ϕ_6=0.027, ϕ_7=0.046, τ_1= τ_2=0.31, τ_5=0.26, τ_6=0.43, τ_7=0.18. The reliability of the system is calculated using these values and the results are shown in table 6.4.2. This table reveals that the reliability of the system decreases from 0.0384 to 0.0345% approximately with the increase of time. However, it increases by 0.523% approximately with the increase in repair rate of Condenser subsystem from 0.31 to 0.46 and MTBF increases from 258.11 days to 259.46 days approximately.

(c) Effect of the failure and repair rates of the Ammonia storage subsystem on the reliability of the system

The effect of the failure rate of the Ammonia storage (ϕ_5) subsystem on the reliability of the system is studied by varying their values as: ϕ_5=0.0058, 0.0063, 0.0068, 0.0073 at constant value of its repair rate i.e. τ_5=0.26. The failure and repair rates of other subsystems were taken as: ϕ_1= ϕ_2 =0.066, ϕ_3=0.038, ϕ_4=ϕ_3, ϕ_6=0.027, ϕ_7=0.046, τ_1= τ_2=0.31, τ_3=0.36, τ_4=τ_3, τ_6=0.43, τ_7=0.18. The reliability of the system is calculated using these values and the results are shown in table 6.4.3. This table reveals that the reliability of the system decreases from 0.0360 to 0.0358% approximately with the increase of time. However, it decreases by 0.4135% approximately with the increase in failure rate of the Ammonia storage subsystem from 0.0058 to 0.0073 and MTBF decreases from 259.08 days to 258 days approximately.

The effect of the repair rate of the ammonia storage (τ_5) subsystem on the reliability of the system is studied by varying their values as: τ_5=0.21, 0.26, 0.31, 0.36 at constant value of its failure rate i.e. ϕ_5 =0.063. The failure and repair rates of other subsystems were taken as: ϕ_1= ϕ_2 =0.066, ϕ_3=0.038, ϕ_4=ϕ_3, ϕ_6=0.027, ϕ_7=0.046, τ_1= τ_2=0.31, τ_3=0.36, τ_4=τ_3, τ_6=0.43, τ_7=0.18. The reliability of the system is calculated using these values and the results are shown in table 6.4.3. This table reveals that the reliability of the system decreases from 0.0367 to 0.0353% approximately with the increase of time. However, it increases by 0.9027% approximately with the increase in repair rate of the Ammonia storage subsystem from 0.21 to 0.36 and MTBF increases from 257.66 days to 259.98 days approximately.

(d) Effect of the failure and repair rates of the Expansion valve subsystem on the reliability of the system

The effect of the failure rate of the Expansion valve (ϕ_6) subsystem on the reliability of the system is studied by varying their values as: ϕ_6=0.022, 0.027, 0.032, 0.037 at constant value of its repair rate i.e. τ_6=0.46. The failure and repair rates of other subsystems were taken as: ϕ_1= ϕ_2=0.066, ϕ_3=0.038, ϕ_4=ϕ_3, ϕ_5=0.0063, ϕ_7=0.046, τ_1= τ_2, τ_3=0.36, τ_4=τ_3, τ_5=0.26, τ_7=0.18. The reliability of the system is calculated using these values and the results are shown in table 6.4.4. This table reveals that the reliability of the system decreases from 0.0364 to 0.0357% approximately with the increase of time. However, it decreases by

2.465% approximately with the increase in failure rate of expansive valve subsystem from 0.022 to 0.0037 and MTBF decreases from 260.91 days to 254.47 days approximately.

The effect of the repair rate of Expansion valve (τ_6) subsystem on the reliability of the system is studied by varying their values as: τ_6=0.38, 0.43, 0.48, 0.53 at constant value of its failure rate i.e. ϕ_6 =0.027. The failure and repair rates of other subsystems were taken as: ϕ_1= ϕ_2=0.066, ϕ_3=0.038, ϕ_4=ϕ_3, ϕ_5=0.0063, ϕ_7=0.046, τ_1= τ_2, τ_3=0.36, τ_4=τ_3, τ_5=0.26, τ_7=0.18.The reliability of the system is calculated using these values and the results are shown in table 6.4.4. This table reveals that the reliability of the system decreases from 0.0360 to 0.0357% approximately with the increase of time. However, it increases by 1.457% approximately with the increase in the repair rate of the Expansion valve subsystem from 0.38 to 0.53 and MTBF increases from 257.20days to 260.6 days approximately.

(e) Effect of the failure and repair rates of the Evaporator subsystem on the reliability of the system

The effect of the failure rate of the Evaporator (ϕ_7) subsystem on the reliability of the system is studied by varying their values as: ϕ_7=0.041, 0.046, 0.051, 0.056 at constant value of its repair rate i.e. τ_7=0.18. The failure and repair rates of other subsystems were taken as: ϕ_1= ϕ_2=0.066, ϕ_3=0.038, ϕ_4=ϕ_3, ϕ_5=0.0063, ϕ_6=0.027, τ_1= τ_2, τ_3=0.36, τ_4=τ_3, τ_5=0.26, τ_6=0.43. The reliability of the system is calculated using these values and the results are shown in table 6.4.5. This table reveals that the reliability of the system decreases from 0.0360 to 0.0356% approximately with the increase of time. However, it decreases by 5.759% approximately with the increase in the failure rate of Evaporator subsystem from 0.041 to 0.056 and MTBF decreases from 264 days to 248.79 days approximately.

The effect of the repair rate of Evaporator (τ_7) subsystem on the reliability of the system is studied by varying their values as: τ_7=0.13, 0.18, 0.23 and 0.28 at constant value of its failure rate i.e. ϕ_7 =0.046. The failure and repair rates of other subsystems were taken as: ϕ_1= ϕ_2=0.066, ϕ_3=0.038, ϕ_4=ϕ_3, ϕ_5=0.0063, ϕ_6=0.027, τ_1= τ_2, τ_3=0.36, τ_4=τ_3, τ_5=0.26, τ_6=0.43.The reliability of the system is calculated using these values and the results are shown in table 6.4.5. This table reveals that the reliability of the system decreases from 0.171 to 0.0132% approximately with the increase of time. However, it increases by 14.58% approximately with the increase in the repair rate of Evaporator subsystem from 0.38 to 0.53 and MTBF increases from 241.68 days to 276.88 days approximately.

(f) Effect of the failure and repair rates of the subsystems on the reliability of the system

The reliability of the system decreases with the increase in failure rate of its subsystems, while it increases with the increase in repair rates of the subsystems as mentioned in table 6.4.6

(g) Effect of the failure and repair rates of the Compressor subsystem on the availability of the system

The effect of the failure and repair rates of the Compressor subsystem on the availability of the system is studied by varying their values as: ϕ_1=0.061, 0.066, 0.071, 0.076 and τ_1=0.26, 0.31, 0.36, and 0.41. The failure and repair rates of other subsystems were taken as: ϕ_3= ϕ_4=0.038, ϕ_5=0.0063, ϕ_6=0.027, ϕ_7=0.056, τ_3= τ_4=0.36, τ_5=0.26, τ_6=0.43, τ_7=0.28. The availability of the system is calculated using these values and the results are shown in table 6.4.7. This table reveals that the increase in the failure rate of the Compressor subsystem has approximately 0.743 to 1.6% negative impacts on the availability of the system while increase in the repair rate of the Compressor subsystem has approximately 1.896 to 2.786% impacts on the availability of the system.

(h) Effect of the failure and repair rates of the Cream separator subsystem on the availability of the system

The effect of the failure and repair rates of the Condenser subsystem on the availability of the system is studied by varying their values as: ϕ_3=0.033, 0.038, 0.043, 0.048 and τ_3=0.31, 0.36, 0.41, and 0.46. The failure and repair rates of other subsystems were taken as: ϕ_1= ϕ_2=0.066, ϕ_5=0.0063, ϕ_6=0.027, ϕ_7=0.056, τ_1= τ_2=0.31, τ_5=0.26, τ_6=0.43, τ_7=0.28. The availability of the system is calculated using these values and the results are shown in table 6.4.8. This table reveals that increase in the failure rate of Condenser subsystem has approximately 0.3365 to 0.7034% negative impacts on the availability of the system while increase in repair rate of the condenser has approximately 0.414 to 0.785% impacts on the availability of the system.

(i) Effect of the failure and repair rates of the Ammonia storage subsystem on the availability of the system

The effect of the failure and repair rates of the Ammonia storage subsystem on the availability of the system is studied by varying their values as: ϕ_5=0.0058, 0.0063, 0.0068, 0.0073 and τ_5=0.21, 0.26, 0.31, and 0.36. The failure and repair rates of other subsystems were taken as: $\phi_1= \phi_2=0.066$, $\phi_3= \phi_4=0.038$, $\phi_6=0.027$, $\phi_7=0.056$, $\tau_1= \tau_2=0.31$, $\tau_3=\tau_4=0.36$, $\tau_6=0.43$, $\tau_7=0.28$. The availability of the system is calculated using these values and the results are shown in Table 6.4.9. This table reveals that the increase in the failure rate of the Ammonia storage subsystem has approximately 0.3 to 0.5% negative impacts on the availability of the system while increase in the repair rate of the Ammonia storage subsystem has approximately 0.8321 to 1% impacts on the availability of the system.

(j) Effect of the failure and repair rates of the Expansion valve subsystem on the availability of the system

The effect of the failure and repair rates of the Expansion valve subsystem on the availability of the system is studied by varying their values as: ϕ_6=0.022, 0.027, 0.032, 0.037 and τ_6=0.38, 0.43, 0.48, and 0.53. The failure and repair rates of other subsystems were taken as: $\phi_1= \phi_2=0.066$, $\phi_3= \phi_4=0.038$, $\phi_5=0.0063$, $\phi_7=0.056$, $\tau_1= \tau_2=0.31$, $\tau_3=\tau_4=0.36$, $\tau_5=0.26$, $\tau_7=0.28$. The availability of the system is calculated using these values and the results are shown in table 6.4.10. This table reveals that the increase in failure rate of the Expansion valve subsystem has approximately 2 to 2.77% negative impacts on the availability of the system while increase in the repair rate of the Expansion valve subsystem has approximately 1.196 to 1.971% negative impacts on the availability of the system.

(k) Effect of the failure and repair rates of the Evaporator subsystem on the availability of the system

The effect of the failure and repair rates of the Evaporator on the availability of the system is studied by varying their values as: ϕ_7=0.041, 0.046, 0.051, 0.056 and τ_7=0.13, 0.18, 0.23, and 0.28. The failure and repair rates of other subsystems were taken as: $\phi_1= \phi_2=0.066$, $\phi_3= \phi_4=0.038$, $\phi_5=0.0063$, $\phi_6=0.027$, $\tau_1= \tau_2=0.31$, $\tau_3=\tau_4=0.36$, $\tau_5=0.26$, $\tau_6=0.43$. The availability of the system is calculated using these values and the results are shown in table

6.4.11. This table reveals that the increase in the failure rate of the Evaporator subsystem has approximately 4 to 7.36% negative impacts on the availability of the system while increase in the repair rate of the Evaporator subsystem has approximately 13.18 to 17.28% impacts on the availability of the system.

Table 6.4.1 Decision matrix for the Compressor subsystem on the reliability of the Refrigeration system

Time (Days)	**Failure rate of Compressor (ϕ_1)**				**Repair rate of Compressor (τ_1)**			
	0.061	**0.066**	**0.071**	**0.076**	**0.26**	**0.31**	**0.36**	**0.41**
30	0.721663	0.718920	0.716038	0.713027	0.711568	0.718920	0.723773	0.727127
60	0.721413	0.718663	0.715774	0.712756	0.711159	0.718663	0.723558	0.726924
90	0.721411	0.718662	0.715772	0.712755	0.711154	0.718662	0.723558	0.726924
120	0.721411	0.718661	0.715772	0.712755	0.711153	0.718661	0.723558	0.726924
150	0.721411	0.718662	0.715772	0.712755	0.711154	0.718662	0.723558	0.726924
180	0.721412	0.718661	0.715772	0.712755	0.711154	0.718661	0.723557	0.726924
210	0.721412	0.718662	0.715773	0.712754	0.711154	0.718662	0.723557	0.726924
240	0.721412	0.718662	0.715773	0.712755	0.711154	0.718662	0.723558	0.726924
270	0.721412	0.718661	0.715773	0.712754	0.711154	0.718661	0.723557	0.726924
300	0.721412	0.718662	0.715772	0.712755	0.711154	0.718662	0.723557	0.726924
330	0.721412	0.718662	0.715772	0.712755	0.711154	0.718662	0.723558	0.726924
360	0.721412	0.718662	0.715772	0.712755	0.711154	0.718662	0.723558	0.726924
MTBF	259.72	258.73	257.69	256.60	256.03	258.73	260.49	261.70

Table 6.4.2 Decision matrix for the Condenser subsystem on the reliability of the Refrigeration system

Time (Days)	**Failure rate of Condenser (ϕ_3)**				**Repair rate of Condenser (τ_3)**			
	0.033	**0.038**	**0.043**	**0.048**	**0.31**	**0.36**	**0.41**	**0.46**
30	0.720151	0.718920	0.717570	0.716109	0.717220	0.718920	0.720098	0.720948
60	0.719896	0.718663	0.717312	0.715850	0.716946	0.718663	0.719847	0.720700
90	0.719895	0.718662	0.717311	0.715848	0.716945	0.718662	0.719846	0.720699
120	0.719894	0.718661	0.717311	0.715848	0.716944	0.718661	0.719846	0.720699
150	0.719894	0.718662	0.717311	0.715847	0.716944	0.718662	0.719846	0.720699
180	0.719894	0.718661	0.717311	0.715848	0.716945	0.718661	0.719846	0.720699
210	0.719894	0.718662	0.717311	0.715848	0.716945	0.718662	0.719846	0.720699
240	0.719894	0.718662	0.717310	0.715848	0.716944	0.718662	0.719846	0.720699
270	0.719894	0.718661	0.717310	0.715848	0.716944	0.718661	0.719846	0.720699
300	0.719895	0.718662	0.717311	0.715848	0.716945	0.718662	0.719846	0.720699
330	0.719895	0.718662	0.717311	0.715848	0.716945	0.718662	0.719846	0.720699
360	0.719895	0.718662	0.717311	0.715848	0.716945	0.718662	0.719846	0.720699
MTBF	259.17	258.73	258.24	257.71	258.11	258.73	259.15	259.46

Table 6.4.3 Decision matrix for the Ammonia storage subsystem on the reliability of the Refrigeration system

Time (Days)	**Failure rate of Ammonia storage (ϕ_5)**				**Repair rate of Ammonia storage (τ_5)**			
	0.0058	**0.0063**	**0.0068**	**0.0073**	**0.21**	**0.26**	**0.31**	**0.36**
30	0.719915	0.718920	0.717927	0.716937	0.715947	0.718920	0.720949	0.722420
60	0.719657	0.718663	0.717671	0.716682	0.715696	0.718663	0.720687	0.722156
90	0.719656	0.718662	0.717670	0.716681	0.715694	0.718662	0.720686	0.722155

120	0.719656	0.718661	0.717670	0.716681	0.715694	0.718661	0.720686	0.722155
150	0.719656	0.718662	0.717670	0.716681	0.715694	0.718662	0.720686	0.722155
180	0.719656	0.718661	0.717670	0.716680	0.715694	0.718661	0.720686	0.722155
210	0.719656	0.718662	0.717670	0.716681	0.715694	0.718662	0.720686	0.722155
240	0.719656	0.718662	0.717670	0.716681	0.715694	0.718662	0.720686	0.722155
270	0.719656	0.718661	0.717670	0.716680	0.715694	0.718661	0.720686	0.722154
300	0.719656	0.718662	0.717670	0.716680	0.715694	0.718662	0.720686	0.722155
330	0.719656	0.718662	0.717670	0.716681	0.715694	0.718662	0.720686	0.722155
360	0.719656	0.718662	0.717670	0.716681	0.715694	0.718662	0.720686	0.722155
MTBF	259.08	258.73	258.37	258.01	257.66	258.73	259.45	259.98

Table 6.4.4 Decision matrix for the Expansion valve subsystem on the reliability of the Refrigeration system

Time (Days)	**Failure rate of Expansion valve (ϕ_6)**				**Repair rate of Expansion valve (τ_6)**			
	0.022	**0.027**	**0.032**	**0.037**	**0.38**	**0.43**	**0.48**	**0.53**
30	0.724976	0.718920	0.712964	0.707105	0.714675	0.718920	0.722316	0.725094
60	0.724719	0.718663	0.712707	0.706850	0.714421	0.718663	0.722057	0.724834
90	0.724718	0.718662	0.712706	0.706848	0.714420	0.718662	0.722055	0.724833
120	0.724717	0.718661	0.712706	0.706848	0.714419	0.718661	0.722056	0.724833
150	0.724717	0.718662	0.712706	0.706847	0.714420	0.718662	0.722056	0.724833
180	0.724718	0.718661	0.712706	0.706848	0.714420	0.718661	0.722056	0.724833
210	0.724717	0.718662	0.712706	0.706848	0.714420	0.718662	0.722056	0.724833
240	0.724717	0.718662	0.712705	0.706848	0.714420	0.718662	0.722056	0.724832
270	0.724717	0.718661	0.712706	0.706848	0.714420	0.718661	0.722055	0.724833

300	0.724718	0.718662	0.712706	0.706848	0.714420	0.718662	0.722055	0.724833
330	0.724717	0.718662	0.712706	0.706848	0.714420	0.718662	0.722056	0.724833
360	0.724718	0.718662	0.712706	0.706848	0.714420	0.718662	0.722056	0.724833
MTBF	260.91	258.73	256.58	254.47	257.20	258.73	259.95	260.95

Table 6.4.5 Decision matrix for the Evaporator subsystem on the reliability of the Refrigeration system

Time (Days)	**Failure rate of Evaporator (ϕ_7)**				**Repair rate of Evaporator (τ_7)**			
	0.041	**0.046**	**0.051**	**0.056**	**0.13**	**0.18**	**0.23**	**0.28**
30	0.733562	0.718920	0.704850	0.691319	0.672398	0.718920	0.748670	0.769210
60	0.733301	0.718663	0.704597	0.691072	0.671256	0.718663	0.748548	0.769109
90	0.733300	0.718662	0.704596	0.691070	0.671246	0.718662	0.748548	0.769109
120	0.733300	0.718661	0.704596	0.691070	0.671246	0.718661	0.748548	0.769109
150	0.733300	0.718662	0.704596	0.691070	0.671246	0.718662	0.748548	0.769109
180	0.733300	0.718661	0.704596	0.691070	0.671246	0.718661	0.748548	0.769109
210	0.733300	0.718662	0.704596	0.691070	0.671246	0.718662	0.748548	0.769109
240	0.733300	0.718662	0.704595	0.691070	0.671246	0.718662	0.748547	0.769109
270	0.733300	0.718661	0.704595	0.691070	0.671246	0.718661	0.748548	0.769109
300	0.733300	0.718662	0.704596	0.691070	0.671246	0.718662	0.748548	0.769109
330	0.733300	0.718662	0.704596	0.691070	0.671246	0.718662	0.748547	0.769109
360	0.733300	0.718662	0.704596	0.691070	0.671246	0.718662	0.748548	0.769109
MTBF	264.00	258.73	253.66	248.79	241.68	258.73	269.48	276.88

Table 6.4.6 Decision matrix for the subsystems on reliability of the Refrigeration system

Time (Days)	**Change in reliability of the system with failure rate of subsystems (% negative)**					**Change in reliability of the system with repair rate of subsystems (% positive)**				
	Compressor (ϕ_1)	**Condenser (ϕ_3)**	**Ammonia storage (ϕ_5)**	**Expansion valve (ϕ_6)**	**Evaporator (ϕ_7)**	**Compressor (τ_1)**	**Condenser (τ_3)**	**Ammonia storage (τ_5)**	**Expansion valve (τ_6)**	**Evaporator (τ_7)**
30	1.197	0.561	0.414	2.465	5.759	2.187	0.520	0.904	1.458	14.398
60	1.200	0.562	0.413	2.466	5.759	2.217	0.524	0.903	1.458	14.578
90	1.200	0.562	0.413	2.466	5.759	2.218	0.524	0.903	1.458	14.579
120	1.200	0.562	0.413	2.466	5.759	2.218	0.524	0.903	1.458	14.579
150	1.200	0.562	0.413	2.466	5.759	2.218	0.524	0.903	1.458	14.579
180	1.200	0.562	0.413	2.466	5.759	2.218	0.524	0.903	1.458	14.579
210	1.200	0.562	0.413	2.466	5.759	2.218	0.524	0.903	1.458	14.579
240	1.200	0.562	0.413	2.466	5.759	2.218	0.524	0.903	1.458	14.579
270	1.200	0.562	0.413	2.466	5.759	2.218	0.524	0.903	1.458	14.579
300	1.200	0.562	0.413	2.466	5.759	2.217	0.524	0.903	1.458	14.579
330	1.200	0.562	0.413	2.466	5.759	2.218	0.524	0.903	1.458	14.579
360	1.200	0.562	0.413	2.466	5.759	2.2175	0.524	0.903	1.458	14.579

Table 6.4.7 Decision matrix for the Compressor subsystem on the availability of the Refrigeration system

ϕ_1 τ_1	**0.061**	**0.066**	**0.071**	**0.076**
0.26	0.715177	0.711537	0.707713	0.703721
0.31	0.721626	0.718886	0.715992	0.712954
0.36	0.725839	0.723710	0.721452	0.719072
0.41	0.728740	0.727042	0.725236	0.723327

Table 6.4.8 Decision matrix for the Condenser subsystem on availability of the Refrigeration system

ϕ_3 τ_3	**0.033**	**0.038**	**0.043**	**0.048**
0.31	0.718679	0.717181	0.715493	0.713624
0.36	0.720021	0.718886	0.717595	0.716157
0.41	0.720963	0.720079	0.719067	0.717931
0.46	0.721653	0.720951	0.720141	0.719225

Table 6.4.9 Decision matrix for the Ammonia storage subsystem on the availability of the Refrigeration system

ϕ_5 τ_5	**0.0058**	**0.0063**	**0.0068**	**0.0073**
0.21	0.717139	0.715916	0.714698	0.713484
0.26	0.719881	0.718886	0.717893	0.716903
0.31	0.721750	0.720911	0.720074	0.719239
0.36	0.723107	0.722381	0.721657	0.720934

Table 6.4.10 Decision matrix for the Expansion valve subsystem on the availability of the Refrigeration system

ϕ_6 τ_6	**0.022**	**0.027**	**0.032**	**0.037**
0.38	0.721425	0.714641	0.707984	0.701449
0.43	0.724946	0.718886	0.712926	0.707065
0.48	0.727757	0.722282	0.716888	0.711574
0.53	0.730055	0.725061	0.720135	0.715276

Table 6.4.11 Decision matrix for the Evaporator subsystem on the availability of the Refrigeration system

ϕ_7 τ_7	**0.041**	**0.046**	**0.051**	**0.056**
0.13	0.689241	0.671442	0.654539	0.638465
0.18	0.733534	0.718886	0.704811	0.691277
0.23	0.761182	0.748791	0.736797	0.725182
0.28	0.780083	0.748791	0.758939	0.748791

Table 6.4.12 Optimal values of failure and repair rates of subsystems for maximum availability of the Refrigeration system

S. No.	**Subsystem**	**Failure rate (ϕ)**	**Repair rate (τ)**	**Max. Availability**
1	Evaporator	0.041	0.28	0.780083
2	Expansion valve	0.022	0.53	0.730055
3	Compressor	0.061	0.41	0.728740
4	Ammonia storage	0.0058	0.36	0.723107
5	Condenser	0.033	0.46	0.721653

The decision matrices for Refrigeration system as given in tables (6.4.1 to 6.4.11) indicate that the Evaporator is the most critical subsystem as for as maintenance is concerned. So, this subsystem should be given top priority as the effect of its repair rates on the system availability is much higher than other subsystems. On the basis of repair rates, the repair priorities from maintenance point of view for Refrigeration system as under.

Decision criteria for the repair priority of the Refrigeration system

S. N.	**Subsystem**	**Increase in failure rate (ϕ)**	**Decrease in**		**Increase in Repair rate (τ)**	**Increase in**		**Repair Priority**
			Reliabiity	**Availability**		**Reliabiity**	**Availability**	
1	Evaporator	0.041-0.056	5.75900	4.0081	0.13-0.28	14.56383	1.6163	I
2	Compressor	0.061-0.076	1.1975	0.8077	0.26-0.41	2.21521	0.3568	II
3	Expension valve	0.022-0.037	2.46592	1.7205	0.38-0.53	1.45800	0.3007	III
4	Ammonia storage	0.0058-0.0073	0.41308	0.2829	0.21-0.36	0.90308	0.1526	IV
5	Condensor	0.033-0.048	0.56192	0.3595	0.31-0.46	0.52367	0.0982	V

6.4.2 Performance analysis for RAMD of the Refrigeration system

The RAMD indices for all the subsystems of Refrigeration system are computed and tabulated in table 6.4.13.

Table 6.4.13 RAMD indices for the subsystems of the Refrigeration system

RAMD indices of subsystems	**Subsystem (S1)**	**Subsystem (S2)**	**Subsystem (S3)**	**Subsystem (S4)**	**System (S)**
Reliability	$e^{-0.132t}$	$e^{-0.076t}$	$e^{-0.0333t}$	$e^{-0.046t}$	$e^{-0.0138t}$
Availability	0.9640	0.9900	0.9199	0.7965	0.6993
Maintainability	$1-e^{-3.5323t}$	$1-e^{-7.5415t}$	$1-e^{-0.3826t}$	$1-e^{-0.18t}$	$1-e^{-0.1165t}$
Dependability ($D_{min.}$)	0.9736	0.9927	0.9396	0.8169	0.7419
MTBF	7.5758 hr.	13.1579 hr.	30.03 hr.	21.7391 hr.	72.50 hr.
MTTR	0.2831 hr.	0.1326 hr.	2.6133 hr.	5.5556 hr.	8.5846 hr.
Dependability ratio (d)	26.7585	99.2244	11.4914	3.9130	

6.4.3 Performance analysis for fuzzy-reliability of the Refrigeration system

The effect of the failure rate of the subsystems of the Refrigeration system on the fuzzy-reliability of the system is computed by using the equation (4.4.68) for one year (i.e. time, t=30-360 days) and by taking an average value of coverage factor (i.e. c =0.5) as the value of system coverage factor (c) varies from 0 to 1. The table 6.4.14, 6.4.15. 6.4.16, 6.4.17, 6.4.18 reveals the effect of the failure rate of each subsystem on fuzzy-reliability of the system while table 6.4.19 reveals the effect of coverage factor on fuzzy-reliability of the system.

(a) Effect of the failure rate of the Compressor subsystem on the fuzzy-reliability of the system

The effect of the failure rate of Compressor (ϕ_1) subsystem on the fuzzy-reliability of the system is studied by varying its values as: ϕ_1=0.061, 0.066, 0.071, 0.076 and τ_1=0.31 ϕ_3=0.038, $\phi_4=\phi_3$, ϕ_5=0.0063, ϕ_6=0.027, ϕ_7=0.046, τ_3=0.36, $\tau_4=\tau_3$, τ_5=0.26, τ_6=0.43, τ_7=0.18. The table 6.4.14 reveals that the fuzzy-reliability of the system decreases from 1.56 to 1.55% when the failure rate of the L.P. Heater subsystem increases from 0.061 to 0.076.

(b) Effect of the failure rate of the Condenser subsystem on the fuzzy-reliability of the system

The effect of the failure rate of Condenser (ϕ_3) subsystem on the fuzzy-reliability of the system is studied by varying its values as: ϕ_3=0.033, 0.038, 0.043, 0.048 and τ_3=0.36, ϕ_1= ϕ_2=0.066, ϕ_5=0.0063, ϕ_6=0.027, ϕ_7=0.046, τ_1= τ_2=0.31, τ_5=0.26, τ_6=0.43, τ_7=0.18. The table 6.4.15 reveals that the fuzzy-reliability of the system decreases from 1.3017 to 1.3010% when the failure rate of the Condenser subsystem increases from 0.033 to 0.048.

(c) Effect of the failure rate of the Ammonia storage subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Ammonia storage (ϕ_5) subsystem on the fuzzy-reliability of the system is studied by varying its values as: ϕ_5=0.0058, 0.0063, 0.0068, 0.0073 and τ_5=0.26, ϕ_1= ϕ_2 =0.066, ϕ_3=0.038, $\phi_4=\phi_3$, ϕ_6=0.027, ϕ_7=0.046, τ_1= τ_2=0.31, τ_3=0.36, $\tau_4=\tau_3$, τ_6=0.43, τ_7=0.18. The table 6.4.16 reveals that the fuzzy-reliability of the system decreases from 0.2006 to 0.2005% when the failure rate of the Ammonia storage subsystem increases from 0.0058 to 0.0073.

(d) Effect of the failure rate of the Expansion valve subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Expansion valve (ϕ_6) subsystem on the fuzzy-reliability of the system is studied by varying its values as: ϕ_6=0.022, 0.027, 0.032, 0.037 and τ_6=0.46, ϕ_1= ϕ_2=0.066, ϕ_3=0.038, ϕ_4=ϕ_3, ϕ_5=0.0063, ϕ_7=0.046, τ_1= τ_2, τ_3=0.36, τ_4=τ_3, τ_5=0.26, τ_7=0.18. The table 6.4.17 reveals that the fuzzy-reliability of the system decreases from 0.6454 to 0.6455% when the failure rate of the Expansion valve subsystem increases from 0.022 to 0.037.

(e) Effect of the failure rate of the Evaporator subsystem on the fuzzy-reliability of the system

The effect of the failure rate of Evaporator (ϕ_7) subsystem on the fuzzy-reliability of the system is studied by varying its values as: ϕ_7=0.041, 0.046, 0.051, 0.056 and τ_7=0.18, ϕ_1= ϕ_2=0.066, ϕ_3=0.038, ϕ_4=ϕ_3, ϕ_5=0.0063, ϕ_6=0.027, τ_1= τ_2, τ_3=0.36, τ_4=τ_3, τ_5=0.26, τ_6=0.43. The table 6.4.18 reveals that the fuzzy-reliability of the system decreases from 2.8400 to 1.5326 when the failure rate of the Evaporator subsystem increases from 0.041 to 0.056.

(f) Effect of the system coverage factor on the fuzzy-reliability of the system

It is obtained by varying the values of the imperfect fault coverage as: c=0, 0.2, 0.4, 0.6, 0.8, and 1.0. The failure and repair rates of other subsystems were taken as: β_1=0.0065, β_2=0.028, β_3=β_4=0.0045, β_5=0.0054, β_7=β_6=0.0062, τ_1=0.27, τ_2=0.18, τ_3=τ_4=0.074, τ_5=0.38, τ_7=τ_6=0.32. The fuzzy-reliability of the system is calculated using these data and results are shown in table 6.4.19. The table 6.4.19 reveals that the fuzzy-reliability of the system increases with the increase in imperfect fault coverage and it decreases with time.

Table 6.4.14 Effect of failure rate of the Compressor subsystem on the fuzzy-reliability of the Refrigeration system

Time (days)	**Failure rate of Compressor**			
	0.061	**0.066**	**0.071**	**0.076**
30	0.800882	0.796717	0.792554	0.788397
60	0.800617	0.796448	0.792282	0.788123
90	0.800616	0.796447	0.792282	0.788123
120	0.800617	0.796446	0.792282	0.788122
150	0.800616	0.796448	0.792281	0.788122
180	0.800616	0.796447	0.792281	0.788122
210	0.800616	0.796447	0.792281	0.788122
240	0.800616	0.796446	0.792281	0.788122
270	0.800616	0.796446	0.792282	0.788122
300	0.800617	0.796446	0.792282	0.788121
330	0.800616	0.796447	0.792281	0.788122
360	0.800617	0.796446	0.792281	0.788122

Table 6.4.15 Effect of failure rate of the Condenser subsystem on the fuzzy-reliability of the Refrigeration system

Time (days)	**Failure rate of Condenser**			
	0.033	**0.038**	**0.043**	**0.048**
30	0.800185	0.796717	0.793246	0.789775
60	0.799916	0.796448	0.792977	0.789504
90	0.799915	0.796447	0.792976	0.789503
120	0.799915	0.796446	0.792976	0.789504
150	0.799915	0.796448	0.792976	0.789503
180	0.799915	0.796447	0.792975	0.789503
210	0.799916	0.796447	0.792975	0.789504
240	0.799915	0.796446	0.792975	0.789504
270	0.799916	0.796446	0.792976	0.789503

300	0.799915	0.796446	0.792976	0.789503
330	0.799916	0.796447	0.792975	0.789503
360	0.799916	0.796446	0.792976	0.789503

Table 6.4.16 Effect of failure rate of the Ammonia storage subsystem on the fuzzy-reliability of the Refrigeration system

Time	**Failure rate of Ammonia storage**			
(days)	**0.0058**	**0.0063**	**0.0068**	**0.0073**
30	0.797250	0.796717	0.796184	0.795651
60	0.796981	0.796448	0.795915	0.795383
90	0.796980	0.796447	0.795914	0.795382
120	0.796980	0.796446	0.795913	0.795381
150	0.796981	0.796448	0.795915	0.795383
180	0.796980	0.796447	0.795914	0.795382
210	0.796980	0.796447	0.795914	0.795382
240	0.796980	0.796446	0.795914	0.795382
270	0.796980	0.796446	0.795913	0.795381
300	0.796980	0.796446	0.795914	0.795381
330	0.796980	0.796447	0.795914	0.795382
360	0.796980	0.796446	0.795914	0.795382

Table 6.4.17 Effect of failure rate of the Expansion valve subsystem on fuzzy-reliability of the Refrigeration system

Time	**Failure rate of Expansion valve**			
(days)	**0.022**	**0.027**	**0.032**	**0.037**
30	0.799954	0.796717	0.793505	0.790320
60	0.799684	0.796448	0.793237	0.790052
90	0.799683	0.796447	0.793236	0.790051
120	0.799683	0.796446	0.793236	0.790051
150	0.799683	0.796448	0.793236	0.790051

180	0.799683	0.796447	0.793236	0.790051
210	0.799683	0.796447	0.793236	0.790051
240	0.799683	0.796446	0.793235	0.790050
270	0.799683	0.796446	0.793236	0.790051
300	0.799683	0.796446	0.793235	0.790052
330	0.799683	0.796447	0.793236	0.790051
360	0.799683	0.796446	0.793236	0.790052

Table 6.4.18 Effect of failure rate of the Evaporator subsystem on the fuzzy-reliability of the Refrigeration system

Time (days)	**Failure rate of Evaporator**			
	0.041	**0.046**	**0.051**	**0.056**
30	0.804478	0.796717	0.789102	0.781631
60	0.804223	0.796448	0.788821	0.781339
90	0.804222	0.796447	0.788820	0.781338
120	0.804222	0.796446	0.788820	0.781338
150	0.804222	0.796448	0.788821	0.781338
180	0.804222	0.796447	0.788820	0.781338
210	0.804222	0.796447	0.788819	0.781337
240	0.804223	0.796446	0.788820	0.781337
270	0.804222	0.796446	0.788820	0.781338
300	0.804222	0.796446	0.788820	0.781338
330	0.804222	0.796447	0.788820	0.781338
360	0.804222	0.796446	0.788820	0.781338

Table 6.4.19 Effect of the imperfect fault coverage on the fuzzy-reliability of the Refrigeration system

Time (days)	***c*=0**	***c*=0.2**	***c*=0.4**	***c*=0.6**	***c*=0.8**	***c*=1**
30	0.745042	0.756059	0.773053	0.796717	0.828090	0.868688
60	0.744839	0.755755	0.772739	0.796448	0.827916	0.868687
90	0.744829	0.755753	0.772737	0.796447	0.827915	0.868686
120	0.744836	0.755753	0.772738	0.796446	0.827915	0.868686
150	0.744780	0.755753	0.772737	0.796448	0.827916	0.868686
180	0.744852	0.755753	0.772738	0.796447	0.827915	0.868686
210	0.744835	0.755753	0.772737	0.796447	0.827915	0.868686
240	0.744846	0.755753	0.772738	0.796446	0.827917	0.868687
270	0.744849	0.755753	0.772737	0.796446	0.827915	0.868686
300	0.744792	0.755753	0.772737	0.796446	0.827915	0.868686
330	0.744838	0.755753	0.772737	0.796447	0.827917	0.868686
360	0.744850	0.755753	0.772737	0.796446	0.827915	0.868686

6.5 PERFORMANCE ANALYSIS FOR THE FEEDING SYSTEM

The performance analysis for the Feeding system is analyzed by developing decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

6.5.1 Performance analysis for DSS of the Feeding system

The decision support system of each subsystem for the reliability of the Feeding system are developed for one year (i.e. time, t =30-360 days) by solving the equation (4.5.18) with Runge-Kutta method and shown in table 6.5.1, 6.5.2, 6.5.3, 6.5.4, 6.5.5. The decision support system of each subsystem for availability of the Feeding system are developed by solving the equation (4.5.44) with various combinations of failure and repair rates parameters of subsystems of the system and shown in tables 6.5.6, 6.5.7, 6.5.8, 6.5.9. The table 6.5.10 reveals the optimal values of failure and repair rates of subsystems for maximum availability of the system.

(a) Effect of the failure and repair rates of the Cutting subsystem on the reliability of the system

The effect of the failure rate of the Cutting subsystem (ε_1) on the reliability of the system is studied by varying their values as: ε_1=0.0076, 0.0086, 0.0096 and 0.0106 at repair rate (Δ_1) of 0.22. The failure and repair rates of other subsystems were taken as: ε_3=0.007, ε_4=0.0085, $\varepsilon_5=\varepsilon_4$, ε_6=0.008, $\varepsilon_7=\varepsilon_6$, Δ_3=0.13, Δ_4=0.17, $\Delta_5= \Delta_4$, Δ_6=0.14, $\Delta_2= \Delta_1$, $\Delta_7=\Delta_6$. The reliability of the system is calculated using these values and the results are shown in table 6.5.1. This table reveals that the reliability of the system decreases by 0.118% approximately with the increase of time. However, it decreases by 0.0689% approximately with the increase in the failure rate of the Cutting subsystem from 0.0076 to 0.0106 and MTBF decreases from 339.76 days to 339.53 days approximately.

The effect of the repair rate of the Cutting subsystem (Δ_1) on the reliability of the system is studied by varying their values as: Δ_1=0.17, 0.22, 0.27 and 0.32 at constant failure rate i.e. ε_1= 0.0086. The failure and repair rates of other subsystems were taken as: ε_3=0.007, ε_4=0.0085, $\varepsilon_5=\varepsilon_4$, ε_6=0.008, $\varepsilon_2=\varepsilon_1$, $\varepsilon_7=\varepsilon_6$, Δ_3=0.13, Δ_4=0.17, Δ_6=0.14, $\Delta_5= \Delta_4$, $\Delta_7=\Delta_6$.The reliability of the system is calculated using these values and the results are shown in table 6.5.1. This table reveals that the reliability of the system decreases from 0.1225 to 0.1178% approximately with the increase of time. However, it increases from 0.0799 to 0.0846% approximately with the increase in the repair rate of the Cutting subsystem from 0.17 to 0.32 and MTBF increases from 339.53 days to 339.81 days.

(b) Effect of the failure and repair rates of the Crushing subsystem on the reliability of the system

The effect of the failure rate of the Crushing subsystem (ε_3) on the reliability of the system is studied by varying their values as: ε_3=0.006, 0.007, 0.008 and 0.009 at constant value of repair rate i.e. Δ_3= 0.13.The failure and repair rates of other subsystems were taken as: ε_1=0.0086, ε_4=0.0085, $\varepsilon_5=\varepsilon_4$, ε_6=0.008, $\varepsilon_2=\varepsilon_1$, $\varepsilon_7=\varepsilon_6$, Δ_1=0.22, Δ_4=0.17, $\Delta_5= \Delta_4$, Δ_6=0.14, $\Delta_2= \Delta_1$, $\Delta_7=\Delta_6$. The reliability of the system is calculated using these values and the results are shown in table 6.5.2. This table reveals that the reliability of the system decreases from 0.1082 to 0.1354% approximately with the increase of time. However, it decreases by

2.1445% approximately with the increase in the failure rate of the Crushing subsystem from 0.006 to 0.009 and MTBF decreases from 342.18 days to 334.85 days approximately.

The effect of the repair rate of the Crushing subsystem (Δ_3) on the reliability of the system is studied by varying their values as: Δ_3=0.08, 0.13, 0.18 and 0.23 at constant value of failure rate i.e. ε_3= 0.007. The failure and repair rates of other subsystems were taken as: ε_1=0.0086, $\varepsilon_2=\varepsilon_1$, ε_4=0.0085, ε_6=0.008, $\varepsilon_5=\varepsilon_4$, $\varepsilon_7=\varepsilon_6$, Δ_1=0.22, Δ_4=0.17, $\Delta_5=\Delta_4$, Δ_6=0.14, $\Delta_2=\Delta_1$, $\Delta_7=\Delta_6$. The reliability of the system is calculated using these values and the results are shown in table 6.5.2. This table reveals that the reliability of the system decreases by 0.6583% approximately with the increase of time. However, it increases from 4.84 to 5.50% approximately with the increase in the repair rate of the Crushing subsystem from 0.08 to 0.23 and MTBF increases from 329.41 to 347.34 days approximately.

(c) Effect of the failure and repair rates of the Bagasse carrying subsystem on the reliability of the system

The effect of the failure rate of the Bagasse carrying subsystem on the reliability of the system is studied by varying their values as: ε_4=0.0075, 0.0085, 0.0095, 0.0105 at constant value of repair rate i.e. Δ_4= 0.17.The failure and repair rates of other subsystems were taken as: ε_1=0.0086, $\varepsilon_2=\varepsilon_1$, ε_3=0.007, ε_6=0.008, $\varepsilon_5=\varepsilon_4$, $\varepsilon_7=\varepsilon_6$, Δ_1=0.22, Δ_3=0.13, Δ_6=0.14, $\Delta_2=\Delta_1$, $\Delta_7=\Delta_6$. The reliability of the system is calculated using these values and the results are shown in table 6.5.3. This table reveals that the reliability of the system decreases from 0.1216 to 0.1165% approximately with the increase of time. However, it decreases from 0.1333 to 0.1282% approximately with the increase in the failure rate of the Bagasse carrying subsystem from 0.0075 to 0.0105 and MTBF decreases from 339.83 days to 339.38 days approximately.

The effect of the repair rate of the Bagasse carrying subsystem on the reliability of the system is studied by varying their values as: Δ_4=0.12, 0.17, 0.22, 0.27 at constant value of the failure rate i.e. ε_4= 0.0085. The failure and repair rates of other subsystems were taken as: ε_1=0.0086, $\varepsilon_2=\varepsilon_1$, ε_3=0.007, ε_6=0.008, $\varepsilon_5=\varepsilon_4$, $\varepsilon_7=\varepsilon_6$, Δ_1=0.22, $\Delta_2=\Delta_1$, Δ_3=0.13, Δ_6=0.14, $\Delta_7=\Delta_6$.The reliability of the system is calculated using these values and the results are shown in table 6.5.3. This table reveals that the reliability of the system decreases from 0.1624 to 0.1109% approximately with the increase of time. However, it increases from 0.2683 to

0.32% approximately with the increase in repair rate of the Bagasse carrying subsystem from 0.12 to 0.27 and MTBF increases from 339 days to 340 days approximately.

(d) Effect of the failure and repair rates of the Heat generating subsystem on the reliability of the system

The effect of the failure rate of the Heat generating subsystem on the reliability of the system is studied by varying their values as: ε_6=0.007, 0.008, 0.009, 0.01 at constant value of the repair rate i.e. $\Delta_6 = 0.14$.The failure and repair rates of other subsystems were taken as: ε_1=0.0086, ε_2=ε_1, ε_3=0.007, ε_4=0.0085, ε_5=ε_4, Δ_1=0.22, Δ_2= Δ_1, Δ_3=0.13, Δ_4=0.17, Δ_5=Δ_4, Δ_7=Δ_6. The reliability of the system is calculated using these values and the results are shown in table 6.5.4. This table reveals that the reliability of the system decreases from 0.13 to 0.113% approximately with the increase of time. However, it decreases from 0.2243 to 0.2074% approximately with the increase in the failure rate of the Heat generating subsystem from 0.007 to 0.01 and MTBF decreases from 339.92 days to 339.17 days approximately.

The effect of the repair rate of the Heat generating subsystem on the reliability of the system is studied by varying their values as: Δ_6=0.09, 0.14, 0.19 and 0.24 at constant value of the failure rate i.e. $\varepsilon_6 = 0.008$. The failure and repair rates of other subsystems were taken as: ε_1=0.0086, ε_2=ε_1, ε_3=0.007, ε_4=0.0085, ε_5=ε_4, ε_7=ε_6, Δ_1=0.22, Δ_2= Δ_1, Δ_3=0.13, Δ_4=0.17, Δ_5= Δ_4.The reliability of the system is calculated using these values and the results are shown in table 6.5.4. This table reveals that the reliability of the system decreases from 0.2594 to 0.1% approximately with the increase of time. However, it increases from 0.4180 to 0.5820% approximately with the increase in the repair rate of the Heat generating subsystem from 0.09 to 0.26 and MTBF increases from 338.42 days to 340.34 days approximately.

(e) Effect of the failure and repair rates of the Cutting subsystem on the availability of the system

The effect of the failure and repair rates of the Cutting subsystem on the availability of the system is studied by varying their values as: ε_1=0.0076, 0.0086, 0.0096, 0.0106 and Δ_1=0.17, 0.22, 0.27, and 0.32. The failure and repair rates of other subsystems were taken as: ε_2=ε_1, ε_3=0.007, ε_4=0.0085, ε_5=ε_4, ε_6=0.0085, ε_7=ε_6, Δ_2=Δ_1, Δ_3=0.13, Δ_4=0.17, Δ_5=Δ_4, Δ_6=0.14,

$\Delta_7=\Delta_6$. The availability of the system is calculated using these values and the results are shown in table 6.5.6.

(f) Effect of the failure and repair rates of the Crushing subsystem on the availability of the system

The effect of the failure and repair rates of the Crushing subsystem on the availability of the system is studied by varying their values as: ε_3=0.006, 0.007, 0.008, 0.009 and Δ_3=0.08, 0.13, 0.18, and 0.23. The failure and repair rates of other subsystems were taken as: $\varepsilon_1=0.0086$, $\varepsilon_2=\varepsilon_1$, $\varepsilon_4=0.0085$, $\varepsilon_5=\varepsilon_4$, $\varepsilon_6=0.0085$, $\varepsilon_7=\varepsilon_6$, $\Delta_1=0.22$, $\Delta_2=\Delta_1$, $\Delta_4=0.17$, $\Delta_5=\Delta_4$, $\Delta_6=0.14$, $\Delta_7=\Delta_6$. The availability of the system is calculated using these values and the results are shown in table 6.5.7.

(g) Effect of the failure and repair rates of the Bagasse carrying subsystem on the availability of the system

The effect of the failure and repair rates of the Bagasse carrying subsystem on the availability of the system is studied by varying their values as: ε_4=0.0075, 0.0085, 0.0095, 0.0105 and Δ_4=0.12, 0.17, 0.22, and 0.27. The failure and repair rates of other subsystems were taken as: $\varepsilon_1=0.0086$, $\varepsilon_2=\varepsilon_1$, $\varepsilon_3=0.007$, $\varepsilon_5=0.0085$, $\varepsilon_6=0.0085$, $\varepsilon_7=\varepsilon_6$, $\Delta_1=0.22$, $\Delta_2=\Delta_1$, $\Delta_3=0.13$, $\Delta_5=0.17$, $\Delta_6=0.14$, $\Delta_7=\Delta_6$. The availability of the system is calculated using these values and the results are shown in table 6.5.8.

(h) Effect of the failure and repair rates of the Feeding subsystem on the availability of the system

The effect of the failure and repair rates of the Feeding subsystem on the availability of the system is studied by varying their values as: ε_6=0.007, 0.008, 0.009, 0.01 and Δ_6=0.09, 0.14, 0.19, and 0.24. The failure and repair rates of other subsystems were taken as: $\varepsilon_1=0.0086$, $\varepsilon_2=\varepsilon_1$, $\varepsilon_3=0.007$, $\varepsilon_4=0.0085$, $\varepsilon_5=\varepsilon_4$, $\varepsilon_7=\varepsilon_6$, $\Delta_1=0.22$, $\Delta_2=\Delta_1$, $\Delta_3=0.13$, $\Delta_4=0.17$, $\Delta_5=\Delta_4$, $\Delta_6=0.14$, $\Delta_7=\Delta_6$. The availability of the system is calculated using these values and the results are shown in table 6.5.9.

Table 6.5.1 Decision matrix for the Cutting subsystem on the reliability of the Feeding system

Time	**Failure rate of Cutting subsystem (ε_1)**				**Repair rate of Cutting subsystem (Δ_1)**			
(Days)	**0.0076**	**0.0086**	**0.0096**	**0.0106**	**0.17**	**0.22**	**0.27**	**0.32**
30	0.944807	0.944622	0.944405	0.944158	0.944188	0.944622	0.944831	0.944942
60	0.943716	0.943532	0.943315	0.943066	0.943056	0.943532	0.943744	0.943853
90	0.943694	0.943509	0.943292	0.943043	0.943032	0.943509	0.943721	0.943830
120	0.943693	0.943508	0.943291	0.943043	0.943031	0.943508	0.943721	0.943829
150	0.943693	0.943508	0.943291	0.943043	0.943031	0.943508	0.943721	0.943829
180	0.943693	0.943508	0.943291	0.943043	0.943031	0.943508	0.943721	0.943829
210	0.943693	0.943508	0.943291	0.943043	0.943031	0.943508	0.943721	0.943829
240	0.943693	0.943508	0.943291	0.943043	0.943031	0.943508	0.943721	0.943829
270	0.943693	0.943508	0.943291	0.943043	0.943031	0.943508	0.943721	0.943829
300	0.943693	0.943508	0.943291	0.943043	0.943031	0.943508	0.943721	0.943829
330	0.943693	0.943508	0.943291	0.943043	0.943031	0.943508	0.943720	0.943829
360	0.943693	0.943508	0.943291	0.943043	0.943031	0.943508	0.943720	0.943829
MTBF	339.76	339.70	339.62	339.53	339.53	339.70	339.77	339.81

Table 6.5.2 Decision matrix for the Crushing subsystem on the reliability of the Feeding system

Time	**Failure rate of Crushing subsystem** (ε_3)				**Repair rate of Crushing subsystem** (Δ_3)			
(Days)	**0.006**	**0.007**	**0.008**	**0.009**	**0.08**	**0.13**	**0.18**	**0.23**
30	0.951430	0.944622	0.937906	0.931280	0.920553	0.944622	0.957452	0.965152
60	0.950423	0.943532	0.936740	0.930044	0.914926	0.943532	0.957014	0.964813
90	0.950401	0.943509	0.936716	0.930020	0.914525	0.943509	0.957003	0.964803
120	0.950400	0.943508	0.936715	0.930019	0.914496	0.943508	0.957003	0.964802
150	0.950400	0.943508	0.936715	0.930019	0.914494	0.943508	0.957003	0.964802
180	0.950400	0.943508	0.936715	0.930019	0.914494	0.943508	0.957003	0.964802
210	0.950400	0.943508	0.936715	0.930019	0.914493	0.943508	0.957003	0.964802
240	0.950400	0.943508	0.936715	0.930019	0.914493	0.943508	0.957003	0.964802
270	0.950400	0.943508	0.936715	0.930019	0.914494	0.943508	0.957003	0.964802
300	0.950400	0.943508	0.936715	0.930019	0.914493	0.943508	0.957002	0.964802

330	0.950400	0.943508	0.936715	0.930019	0.914494	0.943508	0.957003	0.964802
360	0.950400	0.943508	0.936715	0.930019	0.914493	0.943508	0.957003	0.964802
MTBF	342.18	339.70	337.25	334.85	329.41	339.70	344.53	347.34

Table 6.5.3 Decision matrix for the Bagasse carrying subsystem on the reliability of the Feeding system

Time (Days)	**Failure rate of Bagasse carrying subsystem (ε_4)**				**Repair rate of Bagasse carrying subsystem (Δ_4)**			
	0.0075	**0.0085**	**0.0095**	**0.0105**	**0.12**	**0.17**	**0.22**	**0.27**
30	0.944975	0.944622	0.944218	0.943764	0.943122	0.944622	0.945308	0.945652
60	0.943898	0.943532	0.943112	0.942641	0.941645	0.943532	0.944275	0.944626
90	0.943875	0.943509	0.943089	0.942617	0.941593	0.943509	0.944254	0.944604
120	0.943874	0.943508	0.943088	0.942617	0.941590	0.943508	0.944253	0.944604
150	0.943874	0.943508	0.943088	0.942616	0.941590	0.943508	0.944253	0.944604
180	0.943875	0.943508	0.943088	0.942616	0.941590	0.943508	0.944253	0.944603
210	0.943874	0.943508	0.943088	0.942617	0.941590	0.943508	0.944253	0.944603
240	0.943874	0.943508	0.943088	0.942616	0.941590	0.943508	0.944253	0.944604
270	0.943875	0.943508	0.943088	0.942616	0.941590	0.943508	0.944253	0.944604
300	0.943875	0.943508	0.943088	0.942616	0.941590	0.943508	0.944253	0.944604
330	0.943874	0.943508	0.943088	0.942616	0.941590	0.943508	0.944253	0.944603
360	0.943874	0.943508	0.943088	0.942616	0.941590	0.943508	0.944253	0.944603
MTBF	339.83	339.70	339.55	339.38	339.02	339.70	339.96	340.09

Table 6.5.4 Decision matrix for the Heat generating subsystem on the reliability of the Feeding system

Time (Days)	**Failure rate of Heat generating subsystem (ε_6)**				**Repair rate of Heat generating subsystem (Δ_6)**			
	0.007	**0.008**	**0.009**	**0.01**	**0.09**	**0.14**	**0.19**	**0.24**
30	0.945206	0.944622	0.943968	0.943246	0.942273	0.944622	0.945678	0.946211
60	0.944160	0.943532	0.942827	0.942050	0.940059	0.943532	0.944755	0.945313
90	0.944139	0.943509	0.942802	0.942022	0.939857	0.943509	0.944740	0.945298
120	0.944139	0.943508	0.942801	0.942021	0.939832	0.943508	0.944740	0.945298

150	0.944139	0.943508	0.942801	0.942021	0.939829	0.943508	0.944740	0.945298
180	0.944139	0.943508	0.942801	0.942021	0.939828	0.943508	0.944740	0.945297
210	0.944139	0.943508	0.942801	0.942021	0.939828	0.943508	0.944740	0.945298
240	0.944139	0.943508	0.942802	0.942021	0.939828	0.943508	0.944740	0.945298
270	0.944139	0.943508	0.942801	0.942021	0.939828	0.943508	0.944740	0.945298
300	0.944139	0.943508	0.942801	0.942021	0.939828	0.943508	0.944740	0.945298
330	0.944139	0.943508	0.942802	0.942021	0.939828	0.943508	0.944740	0.945298
360	0.944139	0.943508	0.942801	0.942021	0.939828	0.943508	0.944740	0.945298
MTBF	339.92	339.70	339.44	339.17	338.42	339.70	340.14	340.34

Table 6.5.5 Decision matrix for the subsystems on the reliability of the Feeding system

Time (Days)	**Change in reliability of the system with failure rate of subsystems (% negative)**				**Change in reliability of the system with repair rate of subsystems (% positive)**			
	Cutting subsystem (ε_1)	**Crushing subsystem (ε_3)**	**Bagasse carrying subsystem (ε_4)**	**Heat generating subsystem (ε_6)**	**Cutting subsystem (Δ_1)**	**Crushing subsystem (Δ_3)**	**Bagasse carrying subsystem (Δ_4)**	**Heat generating subsystem (Δ_6)**
30	0.069	2.118	0.128	0.207	0.080	4.845	0.268	0.418
60	0.069	2.144	0.133	0.224	0.085	5.453	0.317	0.559
90	0.069	2.144	0.133	0.224	0.085	5.498	0.320	0.579
120	0.069	2.144	0.133	0.224	0.085	5.501	0.320	0.582
150	0.069	2.144	0.133	0.224	0.085	5.501	0.320	0.582
180	0.069	2.144	0.133	0.224	0.085	5.501	0.320	0.582
210	0.069	2.144	0.133	0.224	0.085	5.501	0.320	0.582
240	0.069	2.145	0.133	0.224	0.085	5.501	0.320	0.582
270	0.069	2.145	0.133	0.224	0.085	5.501	0.320	0.582
300	0.069	2.144	0.133	0.224	0.085	5.501	0.320	0.582
330	0.069	2.144	0.133	0.224	0.085	5.501	0.320	0.582
360	0.069	2.145	0.133	0.224	0.085	5.501	0.320	0.582

Table 6.5.6 Decision matrix for the Cutting subsystem on the availability of the Feeding system

ε_1 Δ_1	**0.0076**	**0.0086**	**0.0096**	**0.0106**
0.17	0.942304	0.941840	0.941323	0.940755
0.22	0.942970	0.942688	0.942373	0.942027
0.27	0.943307	0.943117	0.942905	0.942672
0.32	0.943501	0.943364	0.943212	0.943044

Table 6.5.7 Decision matrix for the Crushing subsystem on the availability of the Feeding system

ε_3 Δ_3	**0.006**	**0.007**	**0.008**	**0.009**
0.08	0.924257	0.913701	0.903383	0.893295
0.13	0.949574	0.942688	0.935901	0.929211
0.18	0.961276	0.956170	0.951117	0.946118
0.23	0.968019	0.963962	0.959939	0.955949

Table 6.5.8 Decision matrix for the Bagasse carrying subsystem on the availability of the Feeding system

ε_4 Δ_4	**0.0075**	**0.0085**	**0.0095**	**0.0105**
0.12	0.941535	0.940639	0.939646	0.938558
0.17	0.943148	0.942688	0.942175	0.941610
0.22	0.943815	0.943536	0.943224	0.942881
0.27	0.944157	0.943971	0.943763	0.943533

Table 6.5.9 Decision matrix for the Heat generating subsystem on availability of the Feeding system

ε_6 Δ_6	**0.007**	**0.008**	**0.009**	**0.01**
0.09	0.940437	0.938982	0.937364	0.935589
0.14	0.943319	0.942688	0.941981	0.941200
0.19	0.944279	0.943929	0.943535	0.943098
0.24	0.944712	0.944490	0.944239	0.943961

Table 6.5.10 Optimal values of failure and repair rates of subsystems for maximum availability of the Feeding system

S. N.	**Subsystem**	**Failure rate (ε)**	**Repair rate (Δ)**	**Max. Availability**
1	Crushing	0.006	0.23	0.968019
2	Heat generating	0.007	0.24	0.944712
3	Bagasse carrying	0.0075	0.27	0.944157
5	Cutting	0.0076	0.17	0.943501

The decision matrices for Feeding system as given in tables (6.5.1 to 6.5.9) indicate that the Crushing subsystem is the most critical subsystem as for as maintenance is concerned. So, this subsystem should be given top priority as the effect of its repair rates on the system availability is much higher than other subsystems. On the basis of repair rates, the repair priorities from maintenance point of view for Feeding system as under.

Decision criteria for the repair priority of the Feeding system

S. N.	Subsystem	Increase in failure rate (ε)	Decrease in		Increase in Repair rate (Δ)	Increase in		Repair Priority
			Reliabiity	Availability		Reliabiity	Availability	
1	Crushing subsystem	0.006-0.009	2.14208	1.9638	0.08-0.23	5.44208	0.8297	I
2	Heat generating subsystem	0.007-0.01	0.22258	0.2225	0.09-0.24	0.56617	0.0640	II
3	Bagasse carrying subsystem	0.0075-0.0105	0.13258	0.1518	0.12-0.27	0.31542	0.0492	III
4	Cutting subsystem	0.0076-0.0106	0.06900	0.0896	0.17-0.32	0.08458	0.0280	IV

6.5.2 Performance analysis for RAMD of the Feeding system

The RAMD indices for all the subsystems of Feeding system are computed and tabulated in table 6.5.11.

Table 6.5.11 RAMD indices for the subsystems of the Feeding system

RAMD indices of subsystems	Subsystem (S1)	Subsystem (S2)	Subsystem (S3)	Subsystem (S4)	System (S)
Reliability	$e^{-0.0172t}$	$e^{-0.007t}$	$e^{-0.0017t}$	$e^{-0.016t}$	$e^{-0.031}$
Availability	0.9985	0.9489	0.9976	0.9969	0.9423
Maintainability	$1-e^{-11.696t}$	$1-e^{-0.13t}$	$1-e^{-7.1378t}$	$1-e^{-5.1786t}$	$1-e^{-0.1233t}$
Dependability ($D_{min.}$)	0.9989	0.9623	0.9983	0.9977	0.9574
MTBF	58.1395 hr.	142.8571 hr.	58.8235 hr.	62.50 hr.	322.320
MTTR	0.0855 hr.	7.6923 hr.	0.1401 hr.	0.1931 hr.	8.111
Dependability ratio (d)	679.9892	18.5714	420.00	323.75	

6.5.3 Performance analysis for Fuzzy-reliability of the Feeding system

The effect of the failure rate of the subsystems of the Feeding system on the fuzzy-reliability of the system is computed by using the equation (4.5.92) for one year (i.e. time, t=30-360 days) and by taking an average value of coverage factor (i.e. c =0.5) as the value of system coverage factor (*c*) varies from 0 to 1. The table 6.5.12, 6.5.13. 6.5.14, 6.5.15 reveals the effect of the failure rate of each subsystem on fuzzy-reliability of the system while table 6.5.16 reveals the effect of coverage factor on fuzzy-reliability of the system.

(a) Effect of the failure rate of the Cutting subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Cutting subsystem on the fuzzy-reliability of the system is studied by varying their values as: ε_1=0.0076, 0.0086, 0.0096 and 0.0106 at repair rate (Δ_1) of 0.22. The failure and repair rates of other subsystems were taken as: ε_3=0.007, ε_4=0.0085, $\varepsilon_5=\varepsilon_4$, ε_6=0.008, $\varepsilon_7=\varepsilon_6$, Δ_3=0.13, Δ_4=0.17, $\Delta_5= \Delta_4$, Δ_6=0.14, $\Delta_2= \Delta_1$, $\Delta_7=\Delta_6$. The fuzzy reliability of the system is calculated using these values and the results are shown in table 6.5.12. The table 6.5.12 reveals that the fuzzy-reliability of the system decreases from 0.9821 to 0.26% when the failure rate of the Cutting subsystem increases from 0.0076 to 0.0106.

(b) Effect of the failure rate of the Crushing subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Crushing subsystem on fuzzy-reliability of the system is studied by varying their values as: ε_3=0.006, 0.007, 0.008 and 0.009 at repair rate of (Δ_3) 0.13.The failure and repair rates of other subsystems were taken as: ε_1=0.0086, ε_4=0.0085, $\varepsilon_5=\varepsilon_4$, ε_6=0.008, $\varepsilon_2=\varepsilon_1$, $\varepsilon_7=\varepsilon_6$, Δ_1=0.22, Δ_4=0.17, $\Delta_5= \Delta_4$, Δ_6=0.14, $\Delta_2= \Delta_1$, $\Delta_7=\Delta_6$. The fuzzy-reliability of the system is calculated using these values and the results are shown in table 6.5.13. The table 6.5.13 reveals that the fuzzy-reliability of the system decreases from 0.8784 to 0.8767% when the failure rate of the Crushing subsystem increases from 0.006 to 0.009.

(c) Effect of the failure rate of the Bagasse carrying subsystem on the fuzzy-reliability of the system

The effect of the failure rate of Bagasse carrying subsystem on the reliability of the system is studied by varying their values as: ε_4=0.0075, 0.0085, 0.0095 and 0.0105 at repair rate of (Δ_4) 0.17.The failure and repair rates of other subsystems were taken as: ε_1=0.0086, ε_2=ε_1, ε_3=0.007, ε_6=0.008, ε_5=ε_4, ε_7=ε_6, Δ_1=0.22, Δ_3=0.13, Δ_6=0.14, Δ_2= Δ_1, Δ_7=Δ_6. The fuzzy-reliability of the system is calculated using these values and the results are shown in table 6.5.14. The table 6.5.14 reveals that the fuzzy-reliability of the system decreases from 1.0547 to 0.3253% when the failure rate of the Bagasse carrying subsystem increases from 0.0075 to 0.0105.

(d) Effect of the failure rate of the Heat generating subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Heat generating subsystem on the fuzzy-reliability of the system is studied by varying their values as: ε_6=0.007, 0.008, 0.009 and 0.01 at repair rate of (Δ_6) 0.14.The failure and repair rates of other subsystems were taken as: ε_1=0.0086, ε_2=ε_1, ε_3=0.007, ε_4=0.0085, ε_5=ε_4, Δ_1=0.22, Δ_2= Δ_1, Δ_3=0.13, Δ_4=0.17, Δ_5= Δ_4, Δ_7=Δ_6. The fuzzy-reliability of the system is calculated using these values and the results are shown in table 6.5.15. The table 6.5.15 reveals that the fuzzy-reliability of the system decreases from 0.9318 to 0.9332% when the failure rate of the Heat generating subsystem increases from 0.007 to 0.01.

Table 6.5.12 Effect of the failure rate of the Cutting subsystem on the fuzzy-reliability of the Feeding system

Time (days)	**Failure rate of Cutting subsystem**			
	0.0076	**0.0086**	**0.0096**	**0.0106**
30	0.941577	0.940766	0.939952	0.939135
60	0.939057	0.938040	0.937020	0.935998
90	0.937412	0.936189	0.934966	0.933741
120	0.935789	0.934362	0.932935	0.931510

150	0.934171	0.932539	0.930910	0.929285
180	0.932555	0.930719	0.928889	0.927064
210	0.930942	0.928903	0.926873	0.924849
240	0.929331	0.927091	0.924860	0.922640
270	0.927724	0.925282	0.922853	0.920435
300	0.926119	0.923477	0.920849	0.918236
330	0.924517	0.921675	0.918850	0.916042
360	0.922918	0.919877	0.916855	0.913853

Table 6.5.13 Effect of the failure rate of the Crushing subsystem on the fuzzy-reliability of the Feeding system

Time (days)	**Failure rate of Crushing subsystem**			
	0.006	**0.007**	**0.008**	**0.009**
30	0.943544	0.940766	0.938004	0.935256
60	0.940859	0.938040	0.935237	0.932451
90	0.938999	0.936189	0.933396	0.930620
120	0.937161	0.934362	0.931580	0.928814
150	0.935327	0.932539	0.929767	0.927013
180	0.933496	0.930719	0.927959	0.925215
210	0.931669	0.928903	0.926154	0.923420
240	0.929846	0.927091	0.924352	0.921629
270	0.928026	0.925282	0.922554	0.919842
300	0.926210	0.923477	0.920759	0.918058
330	0.924398	0.921675	0.918968	0.916277
360	0.922589	0.919877	0.917181	0.914500

Table 6.5.14 Effect of the failure rate of the Bagasse carrying subsystem on the fuzzy-reliability of the Feeding system

Time (days)	**Failure rate of Bagasse carrying system storage**			
	0.0075	**0.0083**	**0.0095**	**0.0105**
30	0.940153	0.938840	0.937530	0.936222
60	0.936581	0.934905	0.933236	0.931574
90	0.933736	0.931704	0.929684	0.927676
120	0.930912	0.928527	0.926159	0.923807
150	0.928098	0.925361	0.922647	0.919955
180	0.925292	0.922206	0.919149	0.916119
210	0.922494	0.919062	0.915664	0.912300
240	0.919705	0.915928	0.912192	0.908495
270	0.916924	0.912805	0.908733	0.904707
300	0.914152	0.909693	0.905288	0.900935
330	0.911388	0.906592	0.901856	0.897179
360	0.908632	0.903501	0.898437	0.893438

Table 6.5.15 Effect of the failure rate of the Heat generating subsystem on the fuzzy-reliability of the Feeding system

Time (days)	**Failure rate of Heat generating system**			
	0.007	**0.008**	**0.009**	**0.01**
30	0.943708	0.940766	0.937831	0.934901
60	0.941028	0.938040	0.935056	0.932076
90	0.939167	0.936189	0.933215	0.930245
120	0.937328	0.934362	0.931400	0.928443
150	0.935492	0.932539	0.929589	0.926644
180	0.933661	0.930719	0.927782	0.924849
210	0.931833	0.928903	0.925978	0.923057

240	0.930008	0.927091	0.924177	0.921268
270	0.928188	0.925282	0.922380	0.919483
300	0.926371	0.923477	0.920587	0.917702
330	0.924557	0.921675	0.918797	0.915923
360	0.922747	0.919877	0.917011	0.914149

6.6 PERFORMANCE ANALYSIS FOR THE CRUSHING SYSTEM

The performance analysis for the Crushing system is analyzed by developing decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

6.6.1 Performance analysis for DSS of the Crushing system

The decision support system of each subsystem for the reliability of the Crushing system are developed for one year (i.e. time, *t* =30-360 days) by solving the equation (4.6.6) with Runge-Kutta method and shown in table 6.6.1, 6.6.2, 6.6.3, 6.6.4. while, the decision support system of each subsystem for the availability of the Crushing system are developed by solving the equation (4.6.12) with various combinations of failure and repair rates parameters of subsystems of the system and shown in tables 6.6.5, 6.6.6, 6.6.7, 6.6.8, The table 6.6.9 reveals the optimal values of failure and repair rates of subsystems for maximum availability of the system.

(a) Effect of the failure and repair rates of the Cane preparation subsystem on the reliability of the system

The effect of the failure rate of the Cane preparation (σ_1) subsystem on the reliability of the system is studied by varying their values as: σ_1=0.0047, 0.0057, 0.0067 and 0.0077 at constant value of its repair rate i.e. ρ_1=0.016. The failure and repair rates of other subsystems were taken as: σ_2=0.0082, σ_3=0.0076, σ_4=σ_3, ρ_2=0.021, ρ_3=0.032, ρ_4=ρ_3. The reliability of the system is calculated using these values and the results are shown in table 6.6.1. This table reveals that the reliability of the system decreases from 27.16 to 24.82% approximately with the increase of time. However, it decreases from 9.375 to 6.46% approximately with the increase in the failure rate of the Cane preparation subsystem from 0.0047 to 0.0077 and MTBF decreases from 210.33 days to 191.27 days approximately.

The effect of the repair rate of the Cane preparation (ρ_1) subsystem on the reliability of the system is studied by varying their values as: ρ_1=0.011, 0.016, 0.021 and 0.026 at constant value of its failure rate i.e. σ_1=0.0057. The failure and repair rates of other subsystems were taken as: σ_2=0.0082, σ_3=0.0076, $\sigma_4=\sigma_3$, ρ_2=0.021, ρ_3=0.032, $\rho_4=\rho_3$. The reliability of the system is calculated using these values and the results are shown in table 6.6.1. This table reveals that the reliability of the system decreases from 30.8 to 21.24% approximately with the increase of time. However, it increases from 2.88 to 17.13% approximately with the increase in the repair rate of the Cane preparation subsystem from 0.011 to 0.026 and MTBF increases from 191.27 days to 217.33 days approximately.

(b) Effect of the failure and repair rates of the Pressure feeder subsystem on the reliability of the system

The effect of the failure rate of the Pressure feeder (σ_2) subsystem on the reliability of the system is studied by varying their values as: σ_2=0.0072, 0.0082, 0.0092 and 0.0102 at constant value of its repair rate i.e. ρ_2=0.021. The failure and repair rates of other subsystems were taken as: σ_1=0.0057, σ_3=0.0076, $\sigma_4=\sigma_3$, ρ_1=0.016, ρ_3=0.032, $\rho_4=\rho_3$. The reliability of the system is calculated using these values and the results are shown in table 6.6.2. This table reveals that the reliability of the system decreases from 26.3 to 25.3% approximately with the increase of time. However, it decreases from 7.25 to 6% approximately with the increase in the failure rate of the Pressure feeder subsystem from 0.0072 to 0.0102 and MTBF decreases from 208.88 days to 193.74 days approximately.

The effect of the repair rate of Pressure feeder (ρ_2) subsystem on the reliability of the system is studied by varying their values as: ρ_2=0.016, 0.021, 0.026 and 0.031 at constant value of its failure rate i.e. σ_2=0.0082. The failure and repair rates of other subsystems were taken as: σ_1=0.0057, σ_3=0.0076, $\sigma_4=\sigma_3$, ρ_1=0.016, ρ_3=0.032, $\rho_4=\rho_3$. The reliability of the system is calculated using these values and the results are shown in table 6.6.2. This table reveals that the reliability of the system decreases from 29.27 to 22.16% approximately with the increase of time. However, it increases from 3.75 to 14.2% approximately with the increase in the repair rate of the Pressure feeder subsystem from 0.016 to 0.031 and MTBF increases from 192.88 days to 217 days approximately.

(c) Effect of the failure and repair rates of the Milling train subsystem on the reliability of the system

The effect of the failure rate of the Milling train (σ_3) subsystem on the reliability of the system is studied by varying their values as: σ_3=0.0066, 0.0076, 0.0086 and 0.0096 at constant value of its repair rate i.e. ρ_3=0.032. The failure and repair rates of other subsystems were taken as: σ_1=0.0057, σ_2=0.0082, ρ_1=0.016, ρ_2=0.021. The reliability of the system is calculated using these values and the results are shown in table 6.6.3. This table reveals that the reliability of the system decreases from 26.38 to 25.26% approximately with the increase of time. However, it decreases from 2.65 to 1.17% approximately with the increase in the failure rate of the Milling train subsystem from 0.0066 to 0.0096 and MTBF decreases from 205.34 days to 200 days approximately.

The effect of the repair rate of the Milling train (ρ_3) subsystem on the reliability of the system is studied by varying their values as: ρ_3=0.027, 0.032, 0.037 and 0.042 at constant value of its failure rate i.e. σ_3=0.0076. The failure and repair rates of other subsystems were taken as: σ_1=0.0057, σ_2=0.0082, ρ_1=0.016, ρ_2=0.021. The reliability of the system is calculated using these values and the results are shown in table 6.6.3. This table reveals that the reliability of the system decreases from 26.45 to 24.7% approximately with the increase of time. However, it increases from 0.22 to 2.6% approximately with the increase in the repair rate of the Milling train subsystem from 0.027 to 0.042 and MTBF increases from 201.96 days to 205.82 days approximately.

(d) Effect of the failure and repair rates of the subsystems on the reliability of the system

The table 6.6.4 reveals the change in reliability (%) of the system with the change in failure and repair rates of subsystems.

(e) Effect of the failure and repair rates of the Cane preparation subsystem on the availability of the system

The effect of the failure and repair rates of the Cane preparation subsystem on the availability of the system is studied by varying their values as: σ_1=0.0047, 0.0057, 0.0067, 0.0077 and ρ_1=0.011, 0.016, 0.021, and 0.026. The failure and repair rates of other subsystems were taken as: σ_2=0.0082, σ_3=0.0076, $\sigma_4=\sigma_3$, ρ_2=0.021, ρ_3=0.032, $\rho_4=\rho_3$. The availability of the system is calculated using these values and results are shown in table 6.6.5.

(f) Effect of the failure and repair rates of the Pressure feeder subsystem on the availability of the system

The effect of the failure and repair rates of the Pressure feeder subsystem on the availability of the system is studied by varying their values as: σ_2=0.0072, 0.0082, 0.0092, 0.0102 and ρ_2=0.016, 0.021, 0.026, and 0.031. The failure and repair rates of other subsystems were taken as: σ_1=0.0057, σ_3=0.0076, $\sigma_4=\sigma_3$, ρ_1=0.016, ρ_3=0.032, $\rho_4=\rho_3$. The availability of the system is calculated using these values and results are shown in table 6.6.6.

(g) Effect of the failure and repair rates of the Milling train subsystem on the availability of the system

The effect of failure and repair rates of the Milling train subsystem on the availability of the system is studied by varying their values as: σ_3=0.0066, 0.0076, 0.0086, 0.0096 and ρ_3=0.027, 0.032, 0.037, and 0.042. The failure and repair rates of other subsystems were taken as: σ_1=0.0057, σ_2=0.0086, ρ_1=0.016, ρ_2=0.021. The availability of the system is calculated using these values and results are shown in table 6.6.7.

Table 6.6.1 Decision matrix for the Cane preparation subsystem on the reliability of the Crushing system

Time	**Failure rate of Cane preparation (σ_1)**				**Repair rate of Cane preparation (ρ_1)**			
(Days)	**0.0047**	**0.0057**	**0.0067**	**0.0077**	**0.011**	**0.016**	**0.021**	**0.026**
30	0.739783	0.723408	0.707470	0.691956	0.715857	0.723408	0.730254	0.736467
60	0.633090	0.613404	0.594609	0.576659	0.594802	0.613404	0.628788	0.641583
90	0.590541	0.570783	0.552128	0.534502	0.543679	0.570783	0.591461	0.607444
120	0.573274	0.553937	0.535776	0.518698	0.521170	0.553937	0.577319	0.594417
150	0.565775	0.546762	0.528947	0.512227	0.510375	0.546762	0.571406	0.588734
180	0.562114	0.543301	0.525687	0.509164	0.504617	0.543301	0.568497	0.585772
210	0.560040	0.541345	0.523846	0.507435	0.501200	0.541345	0.566765	0.583933
240	0.558708	0.540081	0.522650	0.506304	0.499006	0.540081	0.565579	0.582654
270	0.557774	0.539188	0.521798	0.505492	0.497519	0.539188	0.564704	0.581712
300	0.557086	0.538524	0.521158	0.504877	0.496475	0.538524	0.564034	0.580998
330	0.556562	0.538014	0.520663	0.504398	0.495725	0.538014	0.563513	0.580450
360	0.556158	0.537617	0.520275	0.504018	0.495174	0.537617	0.563105	0.580027
MTBF	210.33	203.59	197.25	191.27	191.27	203.59	211.66	217.33

Table 6.6.2 Decision matrix for the Pressure feeder subsystem on the reliability of the Crushing system

Time	**Failure rate of Pressure feeder (σ_2)**				**Repair rate of Pressure feeder (ρ_2)**			
(Days)	**0.0072**	**0.0082**	**0.0092**	**0.0102**	**0.016**	**0.021**	**0.026**	**0.031**
30	0.738562	0.723408	0.708647	0.694268	0.713609	0.723408	0.732317	0.740428

60	0.630321	0.613404	0.597203	0.581684	0.591664	0.613404	0.631577	0.646855
90	0.586807	0.570783	0.555556	0.541073	0.542076	0.570783	0.593182	0.610891
120	0.569054	0.553937	0.539600	0.525979	0.522070	0.553937	0.577548	0.595443
150	0.561342	0.546762	0.532934	0.519799	0.513721	0.546762	0.570384	0.587850
180	0.557595	0.543301	0.529728	0.516823	0.509952	0.543301	0.566617	0.583633
210	0.555493	0.541345	0.527902	0.515113	0.508011	0.541345	0.564357	0.581059
240	0.554156	0.540081	0.526704	0.513976	0.506853	0.540081	0.562866	0.579376
270	0.553226	0.539188	0.525846	0.513150	0.506073	0.539188	0.561823	0.578223
300	0.552542	0.538524	0.525200	0.512521	0.505500	0.538524	0.561065	0.577405
330	0.552024	0.538014	0.524700	0.512030	0.505058	0.538014	0.560500	0.576809
360	0.551623	0.537617	0.524307	0.511641	0.504708	0.537617	0.560072	0.576366
MTBF	208.88	203.59	198.55	193.74	192.88	203.59	211.27	217.03

Table 6.6.3 Decision matrix for the Milling train subsystem on the reliability of the Crushing system

Time (Days)	**Failure rate of Milling train (σ_3)**				**Repair rate of Milling train (ρ_3)**			
	0.0066	**0.0076**	**0.0086**	**0.0096**	**0.027**	**0.032**	**0.037**	**0.042**
30	0.725979	0.723408	0.720567	0.717475	0.722850	0.723408	0.723927	0.724410
60	0.617983	0.613404	0.608510	0.603357	0.611366	0.613404	0.615176	0.616723
90	0.575975	0.570783	0.565395	0.559881	0.567401	0.570783	0.573561	0.575861
120	0.559208	0.553937	0.548592	0.543230	0.549670	0.553937	0.557307	0.559997
150	0.552012	0.546762	0.541534	0.536375	0.541974	0.546762	0.550456	0.553370
180	0.548511	0.543301	0.538162	0.533131	0.538177	0.543301	0.547187	0.550224
210	0.546515	0.541345	0.536279	0.531342	0.535983	0.541345	0.545377	0.548513

240	0.545212	0.540081	0.535079	0.530218	0.534538	0.540081	0.544232	0.547453
270	0.544276	0.539188	0.534245	0.529450	0.533504	0.539188	0.543436	0.546730
300	0.543566	0.538524	0.533637	0.528900	0.532726	0.538524	0.542852	0.546205
330	0.543010	0.538014	0.533180	0.528496	0.532125	0.538014	0.542407	0.545809
360	0.542565	0.537617	0.532832	0.528194	0.531655	0.537617	0.542062	0.545504
MTBF	205.34	203.59	201.84	200.10	201.96	203.59	204.84	205.82

Table 6.6.4 Decision matrix for the subsystems on the reliability of the Crushing system

Time (Days)	**Change in reliability of the system with failure rate of subsystems (% negative)**			**Change in reliability of the system with repair rate of subsystems (% positive)**		
	Cane preparation (σ_1)	**Pressure feeder (σ_2)**	**Milling train (σ_3)**	**Cane preparation (ρ_1)**	**Pressure feeder (ρ_2)**	**Milling train (ρ_3)**
30	6.4650	5.9974	1.1714	2.8791	3.7582	0.2159
60	8.9135	7.7163	2.3668	7.8649	9.3281	0.8763
90	9.4894	7.7938	2.7943	11.7284	12.6948	1.4910
120	9.5201	7.5696	2.8574	14.0543	14.0543	1.8787
150	9.4646	7.4006	2.8328	15.3532	14.4297	2.1026
180	9.4198	7.3121	2.8040	16.0827	14.4485	2.2385
210	9.3932	7.2693	2.7764	16.5069	14.3791	2.3378
240	9.3794	7.2507	2.7501	16.7631	14.3084	2.4160
270	9.3734	7.2440	2.7241	16.9227	14.2569	2.4792
300	9.3717	7.2431	2.6982	17.0246	14.2245	2.5303
330	9.3727	7.2449	2.6728	17.0912	14.2064	2.5716
360	9.3751	7.2480	2.6487	17.1360	14.1979	2.6049

Table 6.6.5 Decision matrix for the Cane preparation subsystem on availability of the Crushing system

σ_1 ρ_1	**0.0047**	**0.0057**	**0.0067**	**0.0077**
0.011	0.516396	0.493241	0.472073	0.452647
0.016	0.554638	0.536056	0.518679	0.502392
0.021	0.577022	0.561591	0.546964	0.533079
0.026	0.591718	0.578551	0.565957	0.553900

Table 6.6.6 Decision matrix for the Pressure feeder subsystem on the availability of the Crushing system

σ_2 ρ_2	**0.0072**	**0.0082**	**0.0092**	**0.0102**
0.016	0.519481	0.503145	0.487805	0.473373
0.021	0.550098	0.536056	0.522713	0.510018
0.026	0.570801	0.558539	0.546793	0.535530
0.031	0.585735	0.574873	0.564406	0.554314

Table 6.6.7 Decision matrix for the Milling train subsystem on the availability of the Crushing system

σ_3 ρ_3	**0.0066**	**0.0076**	**0.0086**	**0.0096**
0.027	0.535060	0.529811	0.524663	0.519614
0.032	0.540584	0.536056	0.531604	0.527224
0.037	0.544687	0.540707	0.536785	0.532920
0.042	0.547856	0.544306	0.540802	0.537342

Table 6.6.8 Optimal values of failure and repair rates of the subsystems for maximum availability of the Crushing system

S. No.	Subsystem	Failure rate (σ)	Repair rate (ρ)	Max. Availability
1	Cane preparation	0.0047	0.026	0.591718
2	Pressure feeder	0.0072	0.031	0.585735
3	Milling train	0.0066	0.042	0.547856

The decision matrices for Crushing system as given in tables (6.6.1 to 6.6.7) indicate that the Cane preparation subsystem is the most critical subsystem as for as maintenance is concerned. So, this subsystem should be given top priority as the effect of its repair rates on the system availability is much higher than other subsystems. On the basis of repair rates, the repair priorities from maintenance point of view for the Crushing system as under.

Decision criteria for the repair priority of the Crushing system

S. N.	Subsystem	Increase in failure rate (σ)	Decrease in		Increase in Repair rate (ρ)	Increase in		Repair Priority
			Reliabiity	Availability		Reliabiity	Availability	
1	Cane preparation	0.0047-0.0077	9.12816	4.9439	0.011-0.026	14.11726	1.7868	I
2	Pressure feeder	0.0072-0.0102	7.27415	3.8220	0.016-0.031	12.85723	1.6916	II
3	Milling train	0.0066-0.0096	2.59142	1.2772	0.027-0.042	1.97857	0.3802	III

6.6.2 Performance analysis for RAMD of the Crushing system

The RAMD indices for all the subsystems of Crushing system are computed and tabulated in table 6.6.9.

Table 6.6.9 RAMD indices for subsystems of the Crushing system

RAMD indices of subsystems	Subsystem (S1)	Subsystem (S2)	Subsystem (S3)	System (S)
Reliability	$e^{-0.0057t}$	$e^{-0.0082t}$	$e^{-0.0152t}$	$e^{-0.0218t}$
Availability	0.7373	0.7192	0.9564	0.5072
Maintainability	$1-e^{-0.016t}$	$1-e^{-0.021t}$	$1-e^{-0.3335t}$	$1-e^{-0.00884t}$
Dependability ($D_{min.}$)	0.7280	0.6931	0.9680	0.5036
MTBF	175.4386 hr.	121.9512 hr.	65.7895 hr.	363.18 hr.
MTTR	62.5 hr.	47.6190 hr.	2.9987 hr.	113.1177 hr.
Dependability ratio (d)	2.8070	2.5610	21.9391	

6.6.3 Performance analysis for fuzzy-reliability of the Crushing system

The effect of the failure rate of the subsystems of the Crushing system on the fuzzy-reliability of the system is computed by using the equation (4.6.54) for one year (i.e. time, t=30-360 days) and by taking an average value of coverage factor (i.e. *c* =0.5) as the value of system coverage factor (*c*) varies from 0 to 1. The table 6.6.10, 6.6.11, 6.6.12 reveals the effect of the failure rate of each subsystem on fuzzy-reliability of the system while table 6.6.13 reveals the effect of the coverage factor on the fuzzy-reliability of the system.

(a) Effect of the failure rate of the Can preparation subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Can preparation subsystem on fuzzy-reliability of the system is studied by varying their values as: σ_1=0.0047, 0.0057, 0.0067 and 0.0077 at constant value of its repair rate i.e. ρ_1=0.016. The failure and repair rates of other subsystems were taken as: σ_2=0.0082, σ_3=0.0076, σ_4=σ_3, ρ_2=0.021, ρ_3=0.032, ρ_4=ρ_3. The fuzzy reliability of the system is calculated using these values and the results are shown in table 6.6.10. The table 6.6.10 reveals that the fuzzy-reliability of the system decreases from 4.7976 to 2.7356% when the failure rate of the Can preparation subsystem increases from 0.0047 to 0.0077.

(b) Effect of the failure rate of Pressure feeder subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Pressure feeder subsystem on the fuzzy-reliability of the system is studied by varying their values as: σ_2=0.0072, 0.0082, 0.0092 and 0.0102 at constant value of its repair rate i.e. ρ_2=0.021. The failure and repair rates of other subsystems were taken as: σ_1=0.0057, σ_3=0.0076, σ_4=σ_3, ρ_1=0.016, ρ_3=0.032, ρ_4=ρ_3. The fuzzy-reliability of the system is calculated using these values and the results are shown in table 6.6.11. The table 6.6.11 reveals that the fuzzy-reliability of the system decreases from 3.669 to 2.5449% when the failure rate of the Pressure feeder subsystem increases from 0.0072 to 0.0102.

(c) Effect of failure rate of Milling train subsystem on fuzzy-reliability of the system

The effect of the failure rate of Milling train subsystem on the fuzzy-reliability of the system is studied by varying their values as: σ_3=0.0066, 0.0076, 0.0086 and 0.0096 at constant value of its repair rate i.e. ρ_3=0.032. The failure and repair rates of other subsystems were taken as: σ_1=0.0057, σ_2=0.0082, ρ_1=0.016, ρ_2=0.021. The fuzzy-reliability of the system is calculated using these values and the results are shown in the table 6.6.12. The table 6.6.12 reveals that the fuzzy-reliability of the system decreases from 5.8756 to 3.2630% when the failure rate of the Milling train subsystem increases from 0.0022 to 0.0052.

Table 6.6.10 Effect of failure rate of the Cane preparation subsystem on the fuzzy-reliability of the Crushing system

Time (days)	**Failure rate of Cane preparation**			
	0.0047	**0.0057**	**0.0067**	**0.0077**
30	0.832601	0.824926	0.817334	0.809825
60	0.738845	0.728541	0.718437	0.708528
90	0.683242	0.672332	0.661700	0.651337
120	0.647801	0.637021	0.626557	0.616398
150	0.623458	0.613019	0.602913	0.593123
180	0.605597	0.595512	0.585760	0.576326

210	0.591830	0.582042	0.572585	0.563443
240	0.580854	0.571296	0.562065	0.553144
270	0.571912	0.562520	0.553453	0.544693
300	0.564529	0.555252	0.546297	0.537648
330	0.558386	0.549180	0.540297	0.531720
360	0.553249	0.544083	0.535241	0.526706

Table 6.6.11 Effect of failure rate of the Pressure feeder subsystem on the fuzzy-reliability of the Crushing system

Time (days)	**Failure rate of Pressure feeder**			
	0.0072	**0.0082**	**0.0092**	**0.0102**
30	0.832059	0.824926	0.817868	0.810885
60	0.737505	0.728541	0.719741	0.711100
90	0.681321	0.672332	0.663550	0.654968
120	0.645554	0.637021	0.628704	0.620597
150	0.621066	0.613019	0.605185	0.597555
180	0.603169	0.595512	0.588059	0.580801
210	0.589418	0.582042	0.574862	0.567870
240	0.578480	0.571296	0.564302	0.557490
270	0.569581	0.562520	0.555647	0.548955
300	0.562236	0.555252	0.548454	0.541835
330	0.556123	0.549180	0.542425	0.535849
360	0.551008	0.544083	0.537347	0.530791

Table 6.6.12 Effect of failure rate of the Milling train subsystem on the fuzzy-reliability of the Crushing system

Time (days)	**Failure rate of Milling train**			
	0.0066	**0.0076**	**0.0086**	**0.0096**
30	0.832111	0.824926	0.817828	0.810815
60	0.739920	0.728541	0.717517	0.706834

90	0.685964	0.672332	0.659413	0.647163
120	0.651742	0.637021	0.623374	0.610713
150	0.628123	0.613019	0.599310	0.586850
180	0.610572	0.595512	0.582115	0.570166
210	0.596790	0.582042	0.569167	0.557882
240	0.585555	0.571296	0.559060	0.548500
270	0.576181	0.562520	0.550982	0.541161
300	0.568247	0.555252	0.544433	0.535333
330	0.561476	0.549180	0.539075	0.530663
360	0.555671	0.544083	0.534670	0.526899

Table 6.6.13 Effect of the imperfect fault coverage on the fuzzy-reliability of the Crushing system

Time (days)	***c*=0**	***c*=0.2**	***c*=0.4**	***c*=0.6**	***c*=0.8**	***c*=1**
30	0.7346	0.7625	0.7925	0.8249	0.8600	0.8981
60	0.6349	0.6622	0.6932	0.7285	0.7694	0.8169
90	0.5971	0.6183	0.6430	0.6723	0.7080	0.7523
120	0.5825	0.5975	0.6153	0.6370	0.6645	0.7009
150	0.5767	0.5866	0.5983	0.6130	0.6325	0.6599
180	0.5744	0.5800	0.5867	0.5955	0.6080	0.6273
210	0.5734	0.5754	0.5780	0.5820	0.5888	0.6014
240	0.5729	0.5719	0.5711	0.5713	0.5736	0.5807
270	0.5727	0.5690	0.5655	0.5625	0.5613	0.5642
300	0.5726	0.5666	0.5607	0.5553	0.5513	0.5511
330	0.5726	0.5646	0.5566	0.5492	0.5432	0.5407
360	0.5725	0.5628	0.5532	0.5441	0.5365	0.5324

6.7 PERFORMANCE ANALYSIS FOR THE REFINING SYSTEM

The performance analysis for the Refining system is analyzed by developing decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

6.7.1 Performance analysis for DSS of the Refining system

The decision support system of each subsystem for the reliability of the Refining system are developed for one year (i.e. time, *t* =30-360 days) by solving the equation (4.7.14) with Runge-Kutta method and shown in table 6.7.1, 6.7.2, 6.7.3, 6.7.4, 6.7.5. while, the decision support system of each subsystem for the availability of the Feeding system are developed by solving the equation (4.7.34) with various combinations of failure and repair rates parameters of subsystems of the system and shown in tables 6.7.6, 6.7.7, 6.7.8, 6.7.9. The table 6.7.10 reveals the optimal values of failure and repair rates of subsystems for maximum availability of the system.

(a)Effect of the failure and repair rates of the Filter subsystem on the reliability of the system

The effect of the failure rate of Filter (η_1) subsystem on the reliability of the system is studied by varying their values as: η_1=0.005, 0.006, 0.007 and 0.008 at constant value of its repair rate i.e. ξ_1=0.134. The failure and repair rates of other subsystems were taken as: η_4=0.0057, η_5=0.003, η_7=0.0086, $\eta_2=\eta_3=\eta_1$, $\eta_6=\eta_5$, ξ_4=0.54, ξ_5=0.048, ξ_7=0.051, $\xi_2=\xi_3=\xi_1$, $\xi_6=\xi_5$. The reliability of the system is calculated using these values and the results are shown in table 6.7.1. This table reveals that the reliability of the system decreases by 2.89% approximately with the increase of time. However, it decreases from 0.3177 to 0.3123% approximately with the increase in the failure rate of Filter subsystem from 0.005 to 0.008 and MTBF decreases from 303.63 days to 304.60 days approximately.

The effect of the repair rate of Filter (ξ_1) subsystem on the reliability of the system is studied by varying their values as: ξ_1=0.129, 0.134, 0.139 and 0.144 at constant value of its failure rate i.e. η_1=0.006. The failure and repair rates of other subsystems were taken as: η_4=0.0057, η_5=0.003, η_7=0.0086, $\eta_2=\eta_3=\eta_1$, $\eta_6=\eta_5$, ξ_4=0.54, ξ_5=0.048, ξ_7=0.051, $\xi_2=\xi_3=\xi_1$, $\xi_6=\xi_5$.The reliability of the system is calculated using these values and the results are shown in table 6.7.1. This table reveals that the reliability of the system decreases by 2.88% approximately with the increase of time. However, it increases by 0.0635% approximately with the increase in the repair rate of the Filter subsystem from 0.129 to 0.144 and MTBF increases from 304.25 days to 304.44 days approximately.

(b) Effect of the failure and repair rates of the Clarifier subsystem on the reliability of the system

The effect of the failure rate of the Clarifier (η_4) subsystem on the reliability of the system is studied by varying their values as: η_4=0.0047, 0.0057, 0.0067 and 0.0077 at constant value of its repair rate i.e. ξ_4=0.54. The failure and repair rates of other subsystems were taken as: η_1=0.006, η_5=0.003, η_7=0.0086, $\eta_2=\eta_3=\eta_1$, $\eta_6=\eta_5$, ξ_1=0.134, ξ_5=0.048, ξ_7=0.051, $\xi_2=\xi_3=\xi_1$, $\xi_6=\xi_5$. The reliability of the Refining system is computed and mentioned in the table 6.7.2. The table 6.7.2 concludes that the reliability of the system decreases by 2.89% approximately with the increase of time. However, it decreases from 0.4815 to 0.4667% approximately with the increase in the failure rate of the Clarifier subsystem from 0.0047 to 0.0077 and MTBF decreases from 304.8 days to 303.37 days approximately.

The effect of the repair rate of the Clarifier (ξ_4) subsystem on the reliability of the system is studied by varying their values as: ξ_4=0.49, 0.54, 0.59 and 0.64 at constant value of its failure rate i.e. η_4=0.0057. The failure and repair rates of other subsystems were taken as: η_1=0.006, η_5=0.003, η_7=0.0086, $\eta_2=\eta_3=\eta_1$, $\eta_6=\eta_5$, ξ_1=0.134, ξ_5=0.048, ξ_7=0.051, $\xi_2=\xi_3=\xi_1$, $\xi_6=\xi_5$. The reliability of the Refining system is computed and mentioned in the table 6.7.2. the table 6.7.2 concludes that the reliability of the system decreases by 2.88% approx. with the increase of time. However, it increases by 0.23% approx. with the increase in repair rate of Clarifier subsystem from 0.49 to 0.64 and MTBF increases by 0.23% approx.

(c) Effect of the failure and repair rates of the Sulphonation subsystem on the reliability of the system

The effect of the change in the failure rate of the Sulphonation (η_5) subsystem on the reliability of the Refining system is studied by varying their values as: η_5=0.002, 0.003, 0.004 and 0.005 at constant value of its repair rate i.e. ξ_5=0.048. The failure and repair rates of other subsystems were taken as: η_1=0.006, η_4=0.0057, η_7=0.0086, $\eta_2=\eta_3=\eta_1$, $\eta_6=\eta_5$, ξ_1=0.134, ξ_4=0.54, ξ_7=0.051, $\xi_2=\xi_3=\xi_1$, $\xi_6=\xi_5$. The reliability of the Refining system is computed and mentioned in the table 6.7.3. The table 6.7.3 concludes that the reliability of the system decreases from 3.14 to 2.8% approx. with the increase of time. However, it decreases from 0.6842 to 0.3273% approximately with the increase in failure rate of the Sulphonation subsystem from 0.002 to 0.005 and MTBF decreases by 0.636% approximately.

The effect of the repair rate of the Sulphonation (ξ_5) subsystem on the reliability of the system is studied by varying their values as: ξ_5=0.043, 0.048, 0.053 and 0.058 at constant value of its failure rate i.e. η_5=0.003. The failure and repair rates of other subsystems were taken as: η_1=0.006, η_4=0.0057, η_7=0.0086, η_2=η_3=η_1, η_6=η_5, ξ_1=0.134, ξ_4=0.54, ξ_7=0.051, ξ_2=ξ_3=ξ_1, ξ_6=ξ_5.The reliability of the Refining system is computed and mentioned in the table 6.7.3. The table 6.7.3 concludes that the reliability of the system decreases from 2.94 to 2.81% approx. with the increase of time. However, the reliability increases from 0.036 to 0.17% approx. with the increase in the repair rate of the Sulphonation subsystem from 0.43 to 0.58 and MTBF increases by 0.1472% approximately.

(d) Effect of the failure and repair rates of the Heater subsystem on the reliability of the system

The effect of the failure rate of Heater (η_7) subsystem on the reliability of the system is studied by varying their values as: η_7=0.0076, 0.0086, 0.0096 and 0.0106 at constant value of its repair rate i.e. ξ_7=0.051. The failure and repair rates of other subsystems were taken as: η_1=0.006, η_4=0.0057, η_5=0.003, η_2=η_3=η_1, η_6=η_5, ξ_1=0.134, ξ_4=0.54, ξ_5=0.048, ξ_2=ξ_3=ξ_1, ξ_6=ξ_5. The reliability of the system is calculated using these values and the results are shown in table 6.7.4. This table reveals that the reliability of the system decreases from 3.3 to 2.65% approximately with the increase of time. However, it decreases from 4.8 to 4.165% approximately with the increase in the failure rate of Heater subsystem from 0.0076 to 0.0106 and MTBF decreases by 4.74% approximately.

The effect of the repair rate of the Heater (ξ_7) subsystem on the reliability of the system is studied by varying their values as: ξ_7=0.046, 0.051, 0.056 and 0.061 at constant value of its failure rate i.e. η_7=0.0086. The failure and repair rates of other subsystems were taken as: η_1=0.006, η_4=0.0057, η_5=0.003, η_2=η_3=η_1, η_6=η_5, ξ_1=0.134, ξ_4=0.54, ξ_5=0.048, ξ_2=ξ_3=ξ_1, ξ_6=ξ_5. The reliability of the system is calculated using these values and the results are shown in table 6.7.4. This table reveals that the reliability of the system decreases from 3.63 to 1.88% approximately with the increase of time. However, it increases from 2.11 to 3.97%

approximately with the increase in the repair rate of Heater subsystem from 0.046 to 0.061 and MTBF increases by 3.75% approximately.

(e) Effect of the failure and repair rates of the Filter subsystem on the availability of the system

The effect of the failure rate and repair rate of the Filter subsystem of the Refining system were analyzed by varying their values as: η_1=0.005, 0.006, 0.007, 0.008 and ξ_1=0.129, 0.134, 0.139, and 0.144. The failure and repair rates of other subsystems were taken as: η_4=0.0057, η_5=0.003, η_6= η_5, η_7=0.008, ξ_4=0.54, ξ_5=0.48, ξ_6=ξ_5, ξ_7=0.14. The availability of the system is calculated using these values and the results are shown in table 6.7.6.

(f) Effect of the failure and repair rates of the Clarifier subsystem on the availability of the system

The effect of the failure and repair rates of the Clarifier subsystem on the availability of the system is studied by varying their values as: η_4=0.0047, 0.0057, 0.0067, 0.0077 and ξ_4=0.49, 0.54, 0.59 and 0.64. The failure and repair rates of other subsystems were taken as: η_1=0.006, η_5=0.003, η_6=η_5, η_7=0.008, ξ_1=0.134, ξ_5=0.48, ξ_6=ξ_5 ,ξ_7=0.14. The availability of the system is calculated using these values and results are shown in table 6.7.7.

(g) Effect of the failure and repair rates of the Sulphonation subsystem on the availability of the system

The effect of the failure and repair rates of the Sulphonation subsystem on the availability of the system is studied by varying their values as: η_5=0.002, 0.003, 0.004, 0.005 and ξ_5=0.043, 0.048, 0.053, and 0.058. The failure and repair rates of other subsystems were taken as: η_1=0.006, η_4=0.0057, η_7=η_6, ξ_1=0.134, ξ_4=0.54, ξ_7=ξ_6.The availability of the system is calculated using these values and results are shown in table 6.7.8.

(h) Effect of the failure and repair rates of the heater on the availability of the system

The effects of the failure rate and repair rate of the Heater subsystem of the Refining system on the availability were analyzed by varying their values as: η_7=0.0076, 0.0086, 0.0096, 0.0106 and ξ_7=0.046, 0.051, 0.056, and 0.061. The failure and repair rates of other subsystems were taken as: η_1=0.006, η_4=0.0057, η_5=0.003, η_6=η_5, ξ_1=0.134, ξ_4=0.54, ξ_5=0.48, ξ_6=ξ_5.The availability of the system is calculated using these values and results are shown in table 6.7.9.

Table 6.7.1 Decision matrix for the Filter subsystem on the reliability of the Refining system

Time (Days)	**Failure rate of Filter (η_1)**				**Repair rate of Filter (ξ_1)**			
	0.005	**0.006**	**0.007**	**0.008**	**0.129**	**0.134**	**0.139**	**0.144**
30	0.868588	0.867805	0.866900	0.865876	0.867636	0.867805	0.867962	0.868106
60	0.848022	0.847236	0.846327	0.845302	0.847036	0.847236	0.847415	0.847577
90	0.844413	0.843637	0.842740	0.841727	0.843439	0.843637	0.843815	0.843976
120	0.843744	0.842969	0.842074	0.841064	0.842771	0.842969	0.843147	0.843307
150	0.843608	0.842834	0.841939	0.840928	0.842636	0.842834	0.843011	0.843171
180	0.843577	0.842803	0.841908	0.840897	0.842605	0.842803	0.842980	0.843140
210	0.843567	0.842792	0.841897	0.840887	0.842595	0.842792	0.842970	0.843130
240	0.843564	0.842790	0.841895	0.840885	0.842592	0.842790	0.842967	0.843127
270	0.843562	0.842788	0.841894	0.840884	0.842591	0.842788	0.842966	0.843126
300	0.843562	0.842788	0.841893	0.840883	0.842590	0.842788	0.842965	0.843125
330	0.843561	0.842787	0.841892	0.840882	0.842590	0.842787	0.842965	0.843125
360	0.843562	0.842788	0.841893	0.840883	0.842590	0.842788	0.842965	0.843125
MTBF	304.60	304.32	304.00	303.63	304.25	304.32	304.38	304.44

Table 6.7.2 Decision matrix for the Clarifier subsystem on the reliability of the Refining system

Time (Days)	**Failure rate of Clarifier (η_4)**				**Repair rate of Clarifier (ξ_4)**			
	0.0047	**0.0057**	**0.0067**	**0.0077**	**0.49**	**0.54**	**0.59**	**0.64**
30	0.869205	0.867805	0.866410	0.865020	0.866995	0.867805	0.868488	0.869074

60	0.848564	0.847236	0.845911	0.844591	0.846453	0.847236	0.847875	0.848417
90	0.844956	0.843637	0.842322	0.841011	0.842874	0.843637	0.844272	0.844810
120	0.844287	0.842969	0.841655	0.840346	0.842205	0.842969	0.843607	0.844141
150	0.844151	0.842834	0.841520	0.840211	0.842068	0.842834	0.843467	0.844007
180	0.844120	0.842803	0.841489	0.840180	0.842031	0.842803	0.843433	0.843973
210	0.844110	0.842792	0.841479	0.840169	0.842029	0.842792	0.843431	0.843964
240	0.844107	0.842790	0.841476	0.840167	0.842023	0.842790	0.843425	0.843963
270	0.844105	0.842788	0.841476	0.840166	0.842024	0.842788	0.843424	0.843957
300	0.844105	0.842788	0.841475	0.840165	0.842023	0.842788	0.843425	0.843956
330	0.844104	0.842787	0.841474	0.840165	0.842023	0.842787	0.843422	0.843960
360	0.844106	0.842788	0.841474	0.840165	0.842023	0.842788	0.843424	0.843960
MTBF	304.80	304.32	303.84	303.37	304.04	304.32	304.55	304.75

Table 6.7.3 Decision matrix for the Sulphonation subsystem on the reliability of the Refining system

Time (Days)	**Failure rate of Sulphonation (η_5)**				**Repair rate of Sulphonation (ξ_5)**			
	0.002	**0.003**	**0.004**	**0.005**	**0.043**	**0.048**	**0.053**	**0.058**
30	0.868500	0.867805	0.866854	0.865657	0.867690	0.867805	0.867910	0.868004
60	0.848391	0.847236	0.845666	0.843708	0.846905	0.847236	0.847512	0.847744
90	0.844964	0.843637	0.841838	0.839599	0.843161	0.843637	0.844014	0.844315
120	0.844360	0.842969	0.841085	0.838742	0.842417	0.842969	0.843393	0.843722
150	0.844248	0.842834	0.840917	0.838534	0.842245	0.842834	0.843277	0.843618
180	0.844227	0.842803	0.840873	0.838475	0.842197	0.842803	0.843255	0.843599
210	0.844220	0.842792	0.840858	0.838453	0.842178	0.842792	0.843248	0.843594
240	0.844219	0.842790	0.840854	0.838446	0.842172	0.842790	0.843246	0.843594

270	0.844218	0.842788	0.840852	0.838443	0.842170	0.842788	0.843246	0.843593
300	0.844217	0.842788	0.840851	0.838442	0.842168	0.842788	0.843245	0.843593
330	0.844217	0.842787	0.840850	0.838441	0.842167	0.842787	0.843245	0.843592
360	0.844218	0.842788	0.840851	0.838442	0.842168	0.842788	0.843246	0.843593
MTBF	304.80	304.32	303.67	302.86	304.13	304.32	304.47	304.58

Table 6.7.4 Decision matrix for the Heater subsystem on the reliability of the Refining system

Time (Days)	**Failure rate of Heater (η_7)**				**Repair rate of Heater (ξ_7)**			
	0.0076	**0.0086**	**0.0096**	**0.0106**	**0.046**	**0.051**	**0.056**	**0.061**
30	0.880295	0.867805	0.855587	0.843631	0.861223	0.867805	0.873858	0.879431
60	0.861238	0.847236	0.833650	0.820465	0.836241	0.847236	0.856854	0.865312
90	0.857793	0.843637	0.829934	0.816663	0.831271	0.843637	0.854209	0.863332
120	0.857133	0.842969	0.829268	0.816000	0.830253	0.842969	0.853749	0.862996
150	0.856996	0.842834	0.829138	0.815873	0.830036	0.842834	0.853655	0.862923
180	0.856964	0.842803	0.829101	0.815838	0.829987	0.842803	0.853632	0.862903
210	0.856954	0.842792	0.829094	0.815832	0.829973	0.842792	0.853623	0.862895
240	0.856950	0.842790	0.829089	0.815830	0.829969	0.842790	0.853621	0.862893
270	0.856949	0.842788	0.829088	0.815826	0.829968	0.842788	0.853620	0.862892
300	0.856948	0.842788	0.829086	0.815825	0.829967	0.842788	0.853619	0.862891
330	0.856948	0.842787	0.829083	0.815822	0.829966	0.842787	0.853619	0.862891
360	0.856950	0.842788	0.829087	0.815824	0.829967	0.842788	0.853620	0.862891
MTBF	309.36	304.32	299.44	294.70	299.96	304.32	308.03	311.23

Table 6.7.5 Decision matrix the subsystems on the reliability of the Refining system

Time (Days)	**Change in reliability of the system with failure rate of subsystems (% negative)**				**Change in reliability of the system with repair rate of subsystems (% positive)**			
	Filter (η_1)	**Clarifier (η_4)**	**Sulphonation (η_5)**	**Heater (η_7)**	**Filter (ξ_1)**	**Clarifier (ξ_4)**	**Sulphonation (ξ_5)**	**Heater (ξ_7)**
30	0.3123	0.4815	0.3273	4.1649	0.0541	0.2398	0.0361	2.1141
60	0.3207	0.4683	0.5520	4.7342	0.0639	0.2320	0.0991	3.4765
90	0.3181	0.4669	0.6349	4.7948	0.0636	0.2297	0.1369	3.8569
120	0.3176	0.4668	0.6653	4.7989	0.0635	0.2299	0.1550	3.9438
150	0.3176	0.4668	0.6768	4.7985	0.0635	0.2303	0.1630	3.9621
180	0.3176	0.4668	0.6813	4.7990	0.0635	0.2306	0.1666	3.9659
210	0.3176	0.4669	0.6831	4.7986	0.0635	0.2298	0.1681	3.9667
240	0.3176	0.4668	0.6838	4.7985	0.0635	0.2303	0.1688	3.9669
270	0.3176	0.4666	0.6840	4.7987	0.0635	0.2295	0.1690	3.9669
300	0.3176	0.4668	0.6841	4.7988	0.0635	0.2296	0.1692	3.9669
330	0.3176	0.4667	0.6842	4.7991	0.0635	0.2300	0.1692	3.9669
360	0.3177	0.4668	0.6842	4.7991	0.0635	0.2300	0.1692	3.9670

Table 6.7.6 Decision matrix for the Filter subsystem on the availability of the Refining system

η_1 ξ_1	**0.005**	**0.006**	**0.007**	**0.008**
0.129	0.836637	0.835677	0.834601	0.833415
0.134	0.836841	0.835949	0.834947	0.833840
0.139	0.837025	0.836192	0.835257	0.834223
0.144	0.837190	0.836412	0.835537	0.834569

Table 6.7.7 Decision matrix for the Clarifier subsystem on the availability of the Refining system

η_4 ξ_4	**0.0047**	**0.0057**	**0.0067**	**0.0077**
0.49	0.837188	0.835880	0.834576	0.833276
0.54	0.837245	0.835949	0.834657	0.833368
0.59	0.837301	0.836016	0.834736	0.833459
0.64	0.837356	0.836083	0.834814	0.833549

Table 6.7.8 Decision matrix for the Sulphonation subsystem on the availability of the Refining system

η_5 ξ_5	**0.002**	**0.003**	**0.004**	**0.005**
0.043	0.837936	0.834214	0.830073	0.825550
0.048	0.839013	0.835949	0.832524	0.828767
0.053	0.839820	0.837254	0.834376	0.831207
0.058	0.840440	0.838260	0.835808	0.833100

Table 6.7.9 Decision matrix for the Heater subsystem on the availability of the Refining system

η_7 ξ_7	**0.0076**	**0.0086**	**0.0096**	**0.0106**
0.046	0.839027	0.823333	0.808237	0.793705
0.051	0.850587	0.835949	0.821828	0.808197
0.056	0.860324	0.846604	0.833338	0.820503
0.061	0.868637	0.855723	0.843212	0.831083

Table 6.7.10 Optimal values of failure and repair rates of subsystems for maximum availability of the Refining system

S. N.	**Subsystem**	**Failure rate (η)**	**Repair rate (ξ)**	**Max. Availability**
1	Heater	0.0076	0.061	0.868637
2	Sulphonation	0.002	0.058	0.840440
3	Clarifier	0.0047	0.550	0.837356
4	Filter	0.005	0.144	0.837190

The decision matrices for Refining system as given in tables (6.7.1 to 6.7.9) indicate that the Heater subsystem is the most critical subsystem as for as maintenance is concerned. So, this subsystem should be given top priority as the effect of its repair rates on the system availability is much higher than other subsystems. On the basis of repair rates, the repair priorities from maintenance point of view for Refining system is as under.

Decision criteria for the repair priority of Refining system

S. N.	**Subsystem**	**Increase in failure rate (η)**	**Decrease in**		**Increase in Repair rate (ξ)**	**Increase in**		**Repair Priority**
			Reliabiity	**Availability**		**Reliabiity**	**Availability**	
1	Heater	0.0076-0.0106	4.74026	4.1272	0.046-0.061	3.76005	0.9471	I
2	Sulphonation	0.002-0.005	0.63675	0.9646	0.043-0.058	0.14752	0.1238	II
3	Filter	0.005-0.008	0.31747	0.2911	0.129-0.144	0.06276	0.0253	III
4	clar4ifier	0.0047-0.007	0.46814	0.3860	0.49-0.64	0.23096	0.0075	IV

6.7.2 Performance analysis for RAMD of the Refining system

The RAMD indices for all the subsystems of the Refining system are computed and tabulated in table 6.7.11.

Table 6.7.11 RAMD indices for subsystems of the Refining system

RAMD indices of subsystems	**Subsystem (S1)**	**Subsystem (S2)**	**Subsystem (S3)**	**Subsystem (S4)**	**System (S)**
Reliability	$e^{-0.018t}$	$e^{-0.0057t}$	$e^{-0.006t}$	$e^{-0.0086t}$	$e^{-0.001946t}$
Availability	0.99812	0.98956	0.99633	0.85570	0.8420
Maintainability	$1-e^{-9.551836t}$	$1-e^{-0.54t}$	$1-e^{-1.632t}$	$1-e^{-0.051t}$	$1-e^{-0.045t}$
Dependability ($D_{min.}$)	0.99862	0.99237	0.99732	0.8827	0.8724
MTBF	55.556 hr.	175.4386 hr.	166.667 hr.	116.279 hr.	513.94 hr.
MTTR	0.1047 hr.	1.852 hr.	0.61274 hr.	19.6079 hr.	22.1773 hr.
Dependability ratio (d)	5.3066	94.7268	272	5.93	

6.7.3 Performance analysis for fuzzy-reliability of the Refining system

The effect of the failure rate of the subsystems of the Refining system on the fuzzy-reliability of the system is computed by using the equation (4.7.87) for one year (i.e. time, t=30-360 days) and by taking an average value of coverage factor (i.e. *c* =0.5) as the value of system coverage factor (*c*) varies from 0 to 1. The table 6.7.12, 6.7.13, 6.7.14, 6.7.15 reveals the effect of the failure rate of each subsystem on fuzzy-reliability of the system while table 6.7.16 reveals the effect of the coverage factor on the fuzzy-reliability of the system.

(a) Effect of the failure rate of the Filter subsystem on the fuzzy-reliability of the system

The effect of the Filter subsystem on the fuzzy reliability of the system is studied by varying their values as: η_1=0.005, 0.006, 0.007 and 0.008 at constant value of its repair rate i.e. ξ_1=0.134. The failure and repair rates of other subsystems were taken as: η_4=0.0057, η_5=0.003, η_7=0.0086, $\eta_2=\eta_3=\eta_1$, $\eta_6=\eta_5$, ξ_4=0.54, ξ_5=0.048, ξ_7=0.051, $\xi_2=\xi_3=\xi_1$, $\xi_6=\xi_5$. The fuzzy-reliability of the system is calculated using these values and the results are shown in table 6.7.12. The table 6.7.12 reveals that the fuzzy-reliability of the system decreases from 0.7116 to 0.6912% when the failure rate of the Filter subsystem increases from 0.005 to 0.008.

(b) Effect of the failure rate of the Clarifier subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Clarifier subsystem on the fuzzy-reliability of the system is studied by varying their values as: η_4=0.0047, 0.0057, 0.0067 and 0.0077 at constant value of its repair rate i.e. ξ_4=0.54. The failure and repair rates of other subsystems were taken as: η_1=0.006, η_5=0.003, η_7=0.0086, $\eta_2=\eta_3=\eta_1$, $\eta_6=\eta_5$, ξ_1=0.134, ξ_5=0.048, ξ_7=0.051, $\xi_2=\xi_3=\xi_1$, $\xi_6=\xi_5$. The fuzzy-reliability of the system is calculated using these values and the results are shown in table 6.7.13. The table 6.7.13 reveals that the fuzzy-reliability of the system decreases from 0.2090 to 0.2068% when the failure rate of the Crushing subsystem increases from 0.0047 to 0.0077.

(c) Effect of the failure rate of the Sulphonation subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Sulphonation subsystem on fuzzy-reliability of the system is studied by varying their values as: η_5=0.002, 0.003, 0.004 and 0.005 at constant value of its repair rate i.e. ξ_5=0.048. The failure and repair rates of other subsystems were taken as: η_1=0.006, η_4=0.0057, η_7=0.0086, $\eta_2=\eta_3=\eta_1$, $\eta_6=\eta_5$, ξ_1=0.134, ξ_4=0.54, ξ_7=0.051, $\xi_2=\xi_3=\xi_1$, $\xi_6=\xi_5$. The fuzzy-reliability of the system is calculated using these values and the results are shown in table 6.7.14. The table 6.7.14 reveals that the fuzzy-reliability of the system decreases from 1.0882 to 0.7771% when the failure rate of the Bagasse carrying subsystem increases from 0.002 to 0.005.

(d) Effect of the failure rate of the Heater subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Heater subsystem on the fuzzy-reliability of the system is studied by varying their values as: η_7=0.0076, 0.0086, 0.0096 and 0.0106 at constant value of its repair rate i.e. ξ_7=0.051. The failure and repair rates of other subsystems were taken as: η_1=0.006, η_4=0.0057, η_5=0.003, $\eta_2=\eta_3=\eta_1$, $\eta_6=\eta_5$, ξ_1=0.134, ξ_4=0.54, ξ_5=0.048, $\xi_2=\xi_3=\xi_1$, $\xi_6=\xi_5$. The fuzzy-reliability of the system is calculated using these values and the results are shown in table 6.7.15. The table 6.7.15 reveals that the fuzzy-reliability of the system decreases from 2.16 to 1.7673% when the failure rate of the Heat generating subsystem increases from 0.0076 to 0.0106.

(e) Effect of the system coverage factor on the fuzzy-reliability of the system

It is obtained by varying the values of imperfect fault coverage as: c=0, 0.2, 0.4, 0.6, 0.8, and 1.0. The failure and repair rates of other subsystems were taken as: η_1=0.006, η_4=0.0057, η_5=0.003, $\eta_2=\eta_3=\eta_1$, $\eta_6=\eta_5$, η_7=0.0086, ξ_1=0.134, ξ_4=0.54, ξ_5=0.048, $\xi_2=\xi_3=\xi_1$, $\xi_6=\xi_5$, ξ_7=0.051. The fuzzy-reliability of the system is calculated using these data and results are shown in table 7.21. The table 7.21 reveals that the fuzzy-reliability of the system increases with the increase in the imperfect fault coverage and it decreases with time.

Table 6.7.12 Effect of the failure rate of the Filter subsystem on the fuzzy-reliability of the Refining system

Time (days)	**Failure rate of Filter subsystem**			
	0.005	**0.006**	**0.007**	**0.008**
30	0.927912	0.925779	0.923641	0.921499
60	0.916261	0.914098	0.911929	0.909756
90	0.913873	0.911711	0.909544	0.907373
120	0.913354	0.911192	0.909026	0.906854
150	0.913235	0.911073	0.908907	0.906735
180	0.913206	0.911044	0.908878	0.906706
210	0.913199	0.911037	0.908870	0.906699
240	0.913197	0.911036	0.908869	0.906697
270	0.913196	0.911035	0.908868	0.906698
300	0.913195	0.911034	0.908868	0.906697
330	0.913193	0.911032	0.908867	0.906695
360	0.913195	0.911034	0.908867	0.906696

Table 6.7.13 Effect of failure rate of the Clarifier subsystem on the fuzzy-reliability of the Refining system

Time (days)	**Failure rate of Clarifier subsystem**			
	0.0047	**0.0057**	**0.0067**	**0.0077**
30	0.926425	0.925779	0.925134	0.924489
60	0.914730	0.914098	0.913466	0.912835
90	0.912341	0.911711	0.911082	0.910453
120	0.911822	0.911192	0.910563	0.909935
150	0.911705	0.911073	0.910445	0.909817
180	0.911676	0.911044	0.910416	0.909788
210	0.911667	0.911037	0.910409	0.909781
240	0.911664	0.911036	0.910407	0.909780

270	0.911663	0.911035	0.910406	0.909779
300	0.911663	0.911034	0.910406	0.909779
330	0.911661	0.911032	0.910406	0.909779
360	0.911663	0.911034	0.910406	0.909778

Table 6.7.14 Effect of failure rate of the Sulphonation subsystem on the fuzzy-reliability of the Refining system

Time (days)	**Failure rate of Sulphonation subsystem**			
	0.002	**0.003**	**0.004**	**0.005**
30	0.928151	0.925779	0.923374	0.920938
60	0.917070	0.914098	0.911061	0.907964
90	0.914859	0.911711	0.908484	0.905183
120	0.914396	0.911192	0.907904	0.904537
150	0.914295	0.911073	0.907765	0.904375
180	0.914272	0.911044	0.907729	0.904332
210	0.914267	0.911037	0.907720	0.904320
240	0.914266	0.911036	0.907718	0.904317
270	0.914265	0.911035	0.907716	0.904315
300	0.914265	0.911034	0.907716	0.904314
330	0.914262	0.911032	0.907714	0.904312
360	0.914264	0.911034	0.907715	0.904314

Table 6.7.15 Effect of failure rate of the Heater on the fuzzy-reliability of the Refining system

Time (days)	**Failure rate of Heater**			
	0.0076	**0.0086**	**0.0096**	**0.0106**
30	0.931315	0.925779	0.920293	0.914855
60	0.920595	0.914098	0.907683	0.901351
90	0.918377	0.911711	0.905138	0.898657
120	0.917889	0.911192	0.904591	0.898085

150	0.917777	0.911073	0.904467	0.897956
180	0.917749	0.911044	0.904437	0.897925
210	0.917742	0.911037	0.904429	0.897917
240	0.917741	0.911036	0.904428	0.897915
270	0.917740	0.911035	0.904426	0.897914
300	0.917739	0.911034	0.904426	0.897914
330	0.917737	0.911032	0.904426	0.897913
360	0.917739	0.911034	0.904426	0.897913

Table 6.7.16 Effect of the imperfect fault coverage on the fuzzy-reliability of the Refining system

Time (days)	***c*=0**	***c*=0.2**	***c*=0.4**	***c*=0.6**	***c*=0.8**	***c*=1**
30	0.8717	0.8887	0.9067	0.9258	0.9461	0.9677
60	0.8520	0.8711	0.8917	0.9141	0.9384	0.9649
90	0.8487	0.8679	0.8888	0.9117	0.9368	0.9643
120	0.8482	0.8673	0.8882	0.9112	0.9364	0.9642
150	0.8481	0.8671	0.8881	0.9111	0.9363	0.9641
180	0.8481	0.8671	0.8881	0.9110	0.9363	0.9641
210	0.8480	0.8671	0.8880	0.9110	0.9363	0.9641
240	0.8480	0.8671	0.8880	0.9110	0.9363	0.9641
270	0.8480	0.8671	0.8880	0.9110	0.9363	0.9641
300	0.8480	0.8671	0.8880	0.9110	0.9363	0.9641
330	0.8480	0.8671	0.8880	0.9110	0.9363	0.9641
360	0.8480	0.8671	0.8880	0.9110	0.9363	0.9641

6.8 PERFORMANCE ANALYSIS FOR THE EVAPORATION SYSTEM

The performance analysis for the Evaporation system is analyzed by developing decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

6.8.1 Performance analysis for DSS of the Evaporation system

The Decision Support System of each subsystem for the reliability of the Evaporation system are developed for one year (i.e. time, *t* =30-360 days) by solving the equation (4.8.10) with Runge-Kutta method and shown in table 6.8.1, 6.8.2, 6.8.3, 6.8.4. While, the decision support system of each subsystem for the availability of the Feeding system are developed by solving the equation (4.8.21) with various combinations of failure and repair rates parameters of subsystems of the system and shown in tables 6.8.5, 6.8.6, 6.8.7, 6.8.8. The table 6.8.9 reveals the optimal values of failure and repair rates of subsystems for maximum availability of the system.

(a) Effect of the failure and repair rates of the Evaporator subsystem on the reliability of the system

The effect of the failure rate of Evaporator (ψ_1) subsystem on the reliability of the system is studied by varying their values as: ψ_1=0.0007, 0.0017, 0.0027 and 0.0037 at constant value of its repair rate i.e. γ_1=0.022. The failure and repair rates of other subsystems were taken as: ψ_3=0.0082, ψ_4=0.0032, ψ_5=ψ_4 γ_3=0.014, γ_4=0.035, γ_5=γ_4. The reliability of the evaporator system was computed using these values and the results are mentioned in table 6.8.1. The table 6.8.1 reveals that the reliability of the evaporator system decreases from 29.15 to 27.6% approx. with the increase of time. However, it decreases from 2.38 to 0.256% approx. with the increase in the failure rate of Evaporator subsystem from 0.0007 to 0.0037 and MTBF decreases from 231.71 days to 230.67 days approximately.

The effect of the repair rate of Evaporator (γ_1) subsystem on the reliability of the system is studied by varying their values as: γ_1=0.017, 0.022, 0.027 and 0.032 at constant value of its failure rate i.e. ψ_1=0.0017. The failure and repair rates of other subsystems were taken as: ψ_3=0.0082, ψ_4=0.0032, ψ_5=ψ_4 γ_3=0.014, γ_4=0.035, γ_5=γ_4. The reliability of the system is calculated using these values and the results are shown in table 6.8.1. This table 6.8.1 concludes that the reliability of the evaporator system decreases from 28.11 to 28% approx. with the increase of time. However, it increases from 0.016 to 0.24% approx. with the increase in the repair rate of the Evaporator subsystem from 0.017 to 0.032 and MTBF increases from 28 days to 28.11 approximately.

(b) Effect of the failure and repair rates of the Pump subsystem on the reliability of the system

The effect of the failure rate of Pump (ψ_3) subsystem on the reliability of the system is studied by varying their values as: ψ_3=0.0072, 0.0082, 0.0092 and 0.0102 at constant value of its repair rate i.e. γ_3=0.014. The failure and repair rates of other subsystems were taken as: ψ_1=0.0017, ψ_4=0.0032, $\psi_5=\psi_4$, γ_1=0.022, γ_4=0.035, $\gamma_5=\gamma_4$. The reliability of the system is calculated using these values and the results are shown in table 6.8.2. This table reveals that the reliability of the system decreases from 31 to 26.3% approximately with the increase of time. However, it decreases from 12.9 to 6.87% approximately with the increase in the failure rate of the Pump subsystem from 0.0072 to 0.0102 and MTBF decreases from 242 days to 213.36 days approximately.

The effect of the repair rate of Pump (γ_3) subsystem on the reliability of the system is studied by varying their values as: γ_3=0.009, 0.014, 0.019 and 0.024 at constant value of its failure rate i.e. ψ_3=0.0082. The failure and repair rates of other subsystems were taken as: ψ_1=0.0017, ψ_4=0.0032, $\psi_5=\psi_4$ γ_1=0.022, γ_4=0.035, $\gamma_5=\gamma_4$. The reliability of the system is calculated using these values and the results are shown in table 6.8.2. This table reveals that the reliability of the system decreases from 39.91 to 16.27% approximately with the increase of time. However, it increases from 4.27 to 45.3% approximately with the increase in the repair rate of the Pump subsystem from 0.009 to 0.024 and MTBF increases from 202.81 days to 265.77 days approximately.

(c) Effect of the failure and repair rates of the Vacuum pan subsystem on the reliability of the system

The effect of the failure rate of Vacuum pan (ψ_4) subsystem on the reliability of the system is studied by varying their values as: ψ_4=0.0022, 0.0032, 0.0042 and 0.0052 at constant value of its repair rate i.e. γ_4=0.035. The failure and repair rates of other subsystems were taken as: ψ_1=0.0017, ψ_3=0.0082, $\psi_5=\psi_4$ γ_1=0.022, γ_3=0.014, $\gamma_5=\gamma_4$. The reliability of the system is calculated using these values and the results are shown in table 6.8.3. This table reveals that the reliability of the system decreases from 33.55 to 25.96% approximately with the increase of time. However, it decreases from 10.78 to 0.6% approximately with the increase in the failure rate of the Vacuum pan subsystem from 0.0022 to 0.0052 and MTBF decreases from 234.9 days to 222.8 days approximately.

The effect of the repair rate of the Vacuum pan (γ_4) subsystem on the reliability of the system is studied by varying their values as: γ_4=0.030, 0.035, 0.04 and 0.045 at constant value of its failure rate i.e. ψ_4=0.0032. The failure and repair rates of other subsystems were taken as: ψ_1=0.0017, ψ_3=0.0082, ψ_5=ψ_4 γ_1=0.022, γ_3=0.014, γ_5=γ_4. The reliability of the system is calculated using these values and the results are shown in table 6.8.3. This table reveals that the reliability of the system decreases from 28.26 to 27.73% approximately with the increase of time. However, it increases from 0.054 to 0.78% approximately with the increase in the repair rate of the Vacuum pan subsystem from 0.030 to 0.045 and MTBF increases from 231.28 days to 232.73 days approximately.

(d) Effect of the failure and repair rates of the subsystems on the reliability of the system

The table 6.8.4 reveals the change in reliability (%) of the system with the change in failure and repair rates of the subsystems.

(e) Effect of the failure and repair rates of the Evaporator subsystem on the availability of the system

The effect of the failure and repair rates of the Evaporator subsystem on the availability of the system is studied by varying their values as: ψ_1=0.0007, 0.0017, 0.0027, 0.0037 and γ_1=0.017, 0.022, 0.027, and 0.032. The failure and repair rates of other subsystems were taken as: ψ_3=0.0082, ψ_4=0.0032, ψ_5=ψ_4 γ_3=0.014, γ_4=0.035, γ_5=γ_4. The availability of the system is calculated using these values and results are shown in table 6.8.5.

(f) Effect of the failure and repair rates of the Pump subsystem on the availability of the system

The effect of the failure and repair rates of the Pump subsystem on the availability of the system is studied by varying their values as: ψ_3=0.0072, 0.0082, 0.0092, 0.0102 and γ_3=0.009, 0.014, 0.019, and 0.024. The failure and repair rates of other subsystems were taken as: ψ_1=0.0017, ψ_4=0.0032, ψ_5=ψ_4, γ_1=0.022, γ_4=0.035, γ_5=γ_4. The availability of the system is calculated using these values and results are shown in table 6.8.6.

(g) Effect of failure and repair rates of Vacuum pan subsystem on availability of the system

The effect of the failure and repair rates of the Vacuum pan subsystem on the availability of the system is studied by varying their values as: ψ_4=0.0022, 0.0032, 0.0042, 0.0052 and γ_4=0.030, 0.035, 0.040, 0.045. The failure and repair rates of other subsystems were taken as: ψ_1=0.0017, ψ_3=0.0082, γ_1=0.022, γ_3=0.014. The availability of the system is calculated using these values and results are shown in table 6.8.7.

Table 6.8.1 Decision matrix for the Evaporator subsystem on the reliability of the Evaporation system

Time (Days)	**Failure rate of Evaporator subsystem (ψ_1)**				**Repair rate of Evaporator subsystem (γ_1)**			
	0.0007	**0.0017**	**0.0027**	**0.0037**	**0.017**	**0.022**	**0.027**	**0.032**
30	0.817929	0.817654	0.816950	0.815837	0.817605	0.817654	0.817697	0.817735
60	0.722366	0.722378	0.721489	0.719774	0.722247	0.722378	0.722473	0.722538
90	0.672157	0.672911	0.672511	0.671073	0.672807	0.672911	0.672942	0.672928
120	0.645188	0.646658	0.646883	0.645997	0.646702	0.646658	0.646535	0.646375
150	0.629959	0.631828	0.632471	0.632017	0.632077	0.631828	0.631532	0.631236
180	0.620568	0.622430	0.623133	0.622808	0.622870	0.622430	0.622001	0.621619
210	0.614028	0.615468	0.615860	0.615322	0.616041	0.615468	0.614979	0.614581
240	0.608852	0.609510	0.609253	0.608187	0.610143	0.609510	0.609034	0.608687
270	0.604320	0.603917	0.602742	0.600890	0.604545	0.603917	0.603516	0.603268
300	0.600099	0.598450	0.596169	0.593343	0.599029	0.598450	0.598160	0.598039
330	0.596050	0.593061	0.589568	0.585656	0.593577	0.593061	0.592894	0.592908
360	0.592127	0.587785	0.583053	0.578011	0.588252	0.587785	0.587729	0.587864
MTBF	231.71	231.66	231.30	230.67	231.78	231.66	231.58	231.53

Table 6.8.2 Decision matrix for the Pump subsystem on the reliability of the Evaporation system

Time (Days)	**Failure rate of Pump (ψ_3)**				**Repair rate of Pump (γ_3)**			
	0.0072	**0.0082**	**0.0092**	**0.0102**	**0.009**	**0.014**	**0.019**	**0.024**
30	0.837355	0.817654	0.798490	0.779848	0.805109	0.817654	0.829071	0.839474
60	0.749543	0.722378	0.696535	0.671943	0.687575	0.722378	0.751548	0.776136
90	0.702537	0.672911	0.645182	0.619209	0.617362	0.672911	0.716344	0.750750
120	0.676888	0.646658	0.618674	0.592732	0.574916	0.646658	0.699672	0.739750
150	0.662081	0.631828	0.604022	0.578413	0.548421	0.631828	0.690803	0.733940
180	0.652586	0.622430	0.594843	0.569537	0.530965	0.622430	0.685005	0.729790
210	0.645540	0.615468	0.588057	0.562990	0.518583	0.615468	0.680215	0.725946
240	0.639519	0.609510	0.582249	0.557391	0.509072	0.609510	0.675585	0.721930
270	0.633849	0.603917	0.576823	0.552194	0.501259	0.603917	0.670806	0.717600
300	0.628251	0.598450	0.571580	0.547237	0.494568	0.598450	0.665803	0.712943
330	0.622649	0.593061	0.566498	0.542517	0.488747	0.593061	0.660603	0.707997
360	0.617059	0.587785	0.561622	0.538082	0.483710	0.587785	0.655266	0.702818
MTBF	242.04	231.66	222.14	213.36	202.81	231.66	251.42	265.77

Table 6.8.3 Decision matrix for the Vacuum pan subsystem on the reliability of the Evaporation system

Time (Days)	**Failure rate of Vacuum pan subsystem (ψ_4)**				**Repair rate of Vacuum pan subsystem (γ_4)**			
	0.0022	**0.0032**	**0.0042**	**0.0052**	**0.030**	**0.035**	**0.04**	**0.045**
30	0.818836	0.817654	0.816026	0.813975	0.817497	0.817654	0.817801	0.817938
60	0.725024	0.722378	0.718697	0.714070	0.721776	0.722378	0.722910	0.723379

90	0.676736	0.672911	0.667567	0.660873	0.671864	0.672911	0.673784	0.674514
120	0.651580	0.646658	0.639829	0.631339	0.645318	0.646658	0.647712	0.648539
150	0.637937	0.631828	0.623499	0.613275	0.630372	0.631828	0.632898	0.633679
180	0.629886	0.622430	0.612491	0.600475	0.621003	0.622430	0.623395	0.624034
210	0.624450	0.615468	0.603779	0.589874	0.614163	0.615468	0.616277	0.616766
240	0.620188	0.609510	0.595928	0.580023	0.608362	0.609510	0.610182	0.610594
270	0.616433	0.603917	0.588314	0.570302	0.602899	0.603917	0.604541	0.605016
300	0.612906	0.598450	0.580725	0.560515	0.597478	0.598450	0.599169	0.599896
330	0.609519	0.593061	0.573146	0.550672	0.592004	0.593061	0.594057	0.595237
360	0.606265	0.587785	0.565651	0.540875	0.586482	0.587785	0.589252	0.591073
MTBF	234.89	231.66	227.57	222.79	231.28	231.66	231.96	232.22

Table 6.8.4 Decision matrix for the subsystems on the reliability of the Evaporation system

Time (Days)	**Change in reliability of the system with failure rate of subsystems (% negative)**			**Change in reliability of the system with repair rate of subsystems (% positive)**		
	Evaporator (ψ_1)	**Pump** (ψ_3)	**Vacuum pan** (ψ_4)	**Evaporator** (γ_1)	**Pump** (γ_3)	**Vacuum pan** (γ_4)
30	0.2557	6.8677	0.5936	0.0159	4.2684	0.0539
60	0.3588	10.3530	1.5109	0.0404	12.8801	0.2222
90	0.1612	11.8610	2.3440	0.0179	21.6062	0.3944
120	0.1255	12.4327	3.1065	0.0505	28.6711	0.4991
150	0.3267	12.6371	3.8659	0.1330	33.8280	0.5245
180	0.3609	12.7261	4.6692	0.2009	37.4461	0.4882
210	0.2108	12.7879	5.5370	0.2370	39.9864	0.4239
240	0.1091	12.8421	6.4762	0.2386	41.8130	0.3670

270	0.5675	12.8823	7.4835	0.2113	43.1595	0.3513
300	1.1258	12.8952	8.5481	0.1652	44.1547	0.4047
330	1.7439	12.8696	9.6548	0.1127	44.8596	0.5460
360	2.3840	12.7989	10.7858	0.0659	45.2974	0.7828

Table 6.8.5 Decision matrix for the Evaporator subsystem on the availability of the Evaporation system

ψ_1 γ_1	**0.0007**	**0.0017**	**0.0027**	**0.0037**
0.017	0.594941	0.596335	0.595862	0.593720
0.022	0.595270	0.596181	0.596063	0.594977
0.027	0.596199	0.596250	0.596102	0.595490
0.032	0.596397	0.596413	0.596311	0.595912

Table 6.8.6 Decision matrix for the Pump subsystem on the availability of the Evaporation system

ψ_3 γ_3	**0.0072**	**0.0082**	**0.0092**	**0.0102**
0.009	0.528645	0.499316	0.473070	0.449446
0.014	0.622698	0.596181	0.571830	0.549390
0.019	0.680005	0.656509	0.634582	0.614073
0.024	0.718582	0.697692	0.677983	0.659357

Table 6.8.7 Decision matrix for the Vacuum pan subsystem on the availability of the Evaporation system

ψ_4 γ_4	**0.0022**	**0.0032**	**0.0042**	**0.0052**
0.030	0.602744	0.590725	0.578675	0.566344
0.035	0.606536	0.596181	0.585754	0.575370
0.040	0.609422	0.600326	0.591077	0.581766
0.045	0.611700	0.603610	0.595316	0.586888

Table 6.8.8 Optimal values of failure and repair rates of the subsystems for the maximum availability of the Evaporation system

S. N.	**Subsystem**	**Failure rate (ψ)**	**Repair rate (γ)**	**Max. Availability**
1	Pump	0.0072	0.024	0.718582
2	Vacuum pan	0.0022	0.045	0.611700
3	Evaporator	0.0017	0.032	0.596413

The decision matrices for Evporation system as given in tables (6.8.1 to 6.8.7) indicate that the Pump subsystem is the most critical subsystem as for as maintenance is concerned. So, this subsystem should be given top priority as the effect of its repair rates on the system availability is much higher than other subsystems. On the basis of repair rates, the repair priorities from maintenance point of view for Evaporation system is s under.

Decision criteria for the repair priority of Evaporation system

S. N.	**Subsystem**	**Increase in failure rate (ψ)**	**Decrease in**		**Increase in Repair rate (γ)**	**Increase in**		**Repair Priority**
			Reliabiity	**Availability**		**Reliabiity**	**Availability**	
1	Pump	0.0072-0.0102	11.99613	6.9416	0.009-0.024	33.16421	4.2111	I
2	Vacuum pan	0.0022-0.0052	5.38129	3.0009	0.030-0.040	0.42150	0.3731	II
3	evaporator	0.0007-0.0017	0.64416	0.0677	0.017-0.032	0.12411	0.0248	III

6.8.2 Performance analysis for RAMD of the Evaporation system

The RAMD indices for all the subsystems of Evaporation system are computed and tabulated in table 6.8.9.

Table 6.8.9 RAMD indices for the subsystems of the Evaporation system

RAMD indices of subsystems	**Subsystem (S1)**	**Subsystem (S2)**	**Subsystem (S3)**	**System (S)**
Reliability	$e^{-0.0034t}$	$e^{-0.0082t}$	$e^{-0.0064t}$	$e^{-0.018t}$
Availability	0.9945	0.6306	0.9924	0.6224

Maintainability	$1\text{-}e^{-0.61342t}$	$1\text{-}e^{-0.014t}$	$1\text{-}e^{-0.3335t}$	$1\text{-}e^{-0.01347t}$
Dependability ($D_{min.}$)	0.9960	0.4043	0.9944	0.400
MTBF	294.1176 hr.	121.9512 hr.	156.25 hr.	
MTTR	1.6302 hr.	71.4286 hr.	1.1967 hr.	74.2555
Dependability ratio (d)	180.4152	1.7073	130.5664	

6.8.3 Performance analysis for fuzzy-reliability of the Evaporation system

The effect of the failure rate of the subsystems of the Evaporation system on the fuzzy-reliability of the system is computed by using the equation (4.8.60) for one year (i.e. time, t=30-360 days) and by taking an average value of coverage factor (i.e. *c* =0.5) as the value of system coverage factor (*c*) varies from 0 to 1. The table 6.8.10, 6.8.11, 6.8.12 reveals the effect of the failure rate of each subsystem on fuzzy-reliability of the system while table 6.8.13 reveals the effect of the coverage factor on the fuzzy-reliability of the system.

(a) Effect of the failure rate of the Evaporator subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Evaporator subsystem on the fuzzy reliability of the system is studied by varying their values as: ψ_1=0.0007, 0.0017, 0.0027 and 0.0037 at constant value of its repair rate i.e. γ_1=0.022. The failure and repair rates of other subsystems were taken as: ψ_3=0.0082, ψ_4=0.0032, $\psi_5=\psi_4$ γ_3=0.014, γ_4=0.035, $\gamma_5=\gamma_4$. The fuzzy-reliability of the system is calculated using these values and the results are shown in table 6.8.10. The table 6.8.10 reveals that the fuzzy-reliability of the system decreases from 3.564 to 1.947% when the failure rate of the evaporator increases from 0.0007 to 0.0037.

(d) Effect of failure rate of Pump on fuzzy-reliability of the system

The effect of the failure rate of the Pump subsystem on the reliability of the system is studied by varying their values as: ψ_3=0.0072, 0.0082, 0.0092 and 0.0102 at constant value of its repair rate i.e. γ_3=0.014. The failure and repair rates of other subsystems were taken as: ψ_1=0.0017, ψ_4=0.0032, $\psi_5=\psi_4$, γ_1=0.022, γ_4=0.035, $\gamma_5=\gamma_4$. The fuzzy-reliability of the system is calculated using these values and the results are shown in table 6.8.11.

The table 6.8.11 reveals that the fuzzy-reliability of the system decreases from 6.8984 to 2.8571 when the failure rate of the Pump subsystem increases from 0.0072 to 0.0102.

(e) Effect of the failure rate of the Vacuum pan subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Vacuum pan subsystem on the reliability of the system is studied by varying their values as: ψ_4=0.0022, 0.0032, 0.0042 and 0.0052 at constant value of its repair rate i.e. γ_4=0.035. The failure and repair rates of other subsystems were taken as: ψ_1=0.0017, ψ_3=0.0082, $\psi_5=\psi_4$ γ_1=0.022, γ_3=0.014, $\gamma_5=\gamma_4$. The fuzzy-reliability of the system is calculated using these values and the results are shown in the table 6.8.12. The table 6.8.12 reveals that the fuzzy-reliability of the system decreases from 5.2721 to 1.6945% when the failure rate of the Vacuum pan subsystem increases from 0.0022 to 0.0052.

Table 6.8.10 Effect of failure rate of the Evaporator subsystem on the fuzzy-reliability of the Evaporation system

Time (days)	**Failure rate of the Evaporator system**			
	0.0007	**0.0017**	**0.0027**	**0.0037**
30	0.902620	0.896743	0.890885	0.885046
60	0.850151	0.841992	0.833852	0.825735
90	0.820258	0.811345	0.802427	0.793517
120	0.802595	0.793577	0.784522	0.775453
150	0.791832	0.782957	0.774018	0.765039
180	0.785034	0.776353	0.767594	0.758779
210	0.780524	0.772002	0.763395	0.754724
240	0.777330	0.768888	0.760361	0.751770
270	0.774882	0.766422	0.757884	0.749289
300	0.772846	0.764263	0.755617	0.746928
330	0.771028	0.762219	0.753369	0.744495
360	0.769314	0.760184	0.751039	0.741896

Table 6.8.11 Effect of failure rate of the Pump subsystem on the fuzzy-reliability of the Evaporation system

Time (days)	**Failure rate of the Pump**			
	0.0072	**0.0082**	**0.0092**	**0.0102**
30	0.905463	0.896743	0.888120	0.879592
60	0.855237	0.841992	0.829013	0.816296
90	0.826978	0.811345	0.796141	0.781354
120	0.810474	0.793577	0.777238	0.761435
150	0.800526	0.782957	0.766037	0.749738
180	0.794296	0.776353	0.759126	0.742581
210	0.790173	0.772002	0.754598	0.737917
240	0.787218	0.768888	0.751362	0.734592
270	0.784881	0.766422	0.748797	0.731954
300	0.782842	0.764263	0.746546	0.729636
330	0.780916	0.762219	0.744413	0.727439
360	0.778997	0.760184	0.742293	0.725259

Table 6.8.12 Effect of failure rate of the Vacuum pan subsystem on the fuzzy-reliability of the Evaporation system

Time (days)	**Failure rate of Vacuum pan**			
	0.0022	**0.0032**	**0.0042**	**0.0052**
30	0.901824	0.896743	0.891649	0.886543
60	0.848642	0.841992	0.835222	0.828343
90	0.818653	0.811345	0.803754	0.795903
120	0.801312	0.793577	0.785378	0.776756
150	0.791074	0.782957	0.774192	0.764844
180	0.784878	0.776353	0.767011	0.756936
210	0.780980	0.772002	0.762050	0.751227
240	0.778370	0.768888	0.758285	0.746686
270	0.776461	0.766422	0.755124	0.742716
300	0.774914	0.764263	0.752226	0.738974
330	0.773533	0.762219	0.749399	0.735269
360	0.772209	0.760184	0.746539	0.731498

Table 6.8.13 Effect of the imperfect fault coverage on the fuzzy-reliability of the Evaporation system

Time (days)	***c*=0**	***c*=0.2**	***c*=0.4**	***c*=0.6**	***c*=0.8**	***c*=1**
30	0.8204	0.8447	0.8701	0.8967	0.9246	0.9537
60	0.7281	0.7629	0.8007	0.8420	0.8870	0.9362
90	0.6807	0.7192	0.7625	0.8113	0.8665	0.9291
120	0.6564	0.6957	0.7411	0.7936	0.8547	0.9262
150	0.6439	0.6830	0.7288	0.7830	0.8474	0.9249
180	0.6374	0.6760	0.7217	0.7764	0.8427	0.9243
210	0.6341	0.6721	0.7173	0.7720	0.8394	0.9240
240	0.6324	0.6699	0.7145	0.7689	0.8368	0.9239
270	0.6316	0.6686	0.7125	0.7664	0.8346	0.9238
300	0.6311	0.6677	0.7110	0.7643	0.8325	0.9238
330	0.6309	0.6671	0.7097	0.7622	0.8304	0.9238
360	0.6308	0.6666	0.7085	0.7602	0.8282	0.9238

6.9 PERFORMANCE ANALYSIS FOR THE CRYSTALLIZATION SYSTEM

The performance analysis for the Crystallization system is analyzed by developing decision support system, RAMD analysis and fuzzy-reliability analysis of the system.

6.9.1 Performance analysis for Decision Support System (DSS) of Crystallization system

The Decision Support System of each subsystem for the reliability of the Crystallization system are developed for one year (i.e. time, t =30-360 days) by solving the equation (4.9.15) with Runge-Kutta method and shown in table 6.9.1, 6.9.2, 6.9.3. 6.9.4. The decision support systems (DSS) on the availability of the Crystallization system are developed by solving the equation (4.9.29) with various combinations of failure and repair rates parameters of subsystems of the system and shown in tables 6.9.5, 6.9.6, 6.9.7, 6.9.8 while the table 6.9.9 reveals the optimal values of failure and repair rates of subsystems for maximum availability of the system.

(a) Effect of the failure and repair rates of the Crystallizer subsystem on the reliability of the system

The effect of the failure rate of the Crystallizer subsystem (δ_1) on the reliability of the system is studied by varying their values as: δ_1=0.0011, 0.0012, 0.0013 and 0.0014 at constant value of its repair rate i.e. ϕ_1=0.023. The failure and repair rates of other subsystems were taken as: δ_3=0.0025, δ_6=0.008, $\delta_4=\delta_3$, $\delta_5=\delta_3$, ϕ_3=0.042, ϕ_6=0.014, $\phi_4=\phi_3$, $\phi_5=\phi_3$. The reliability of the system is calculated using these values and the results are shown in table 6.9.1. This table reveals that the reliability of the system decreases from 22.92 to 22.87% approximately with the increase of time. However, it decreases from 0.082 to 0.020% approximately with the increase in failure rate of the Crystallizer subsystem from 0.0011 to 0.0044 and MTBF decreases from 240.45 days to 240.28 days approximately.

The effect of the repair rate of the Crystallizer (ϕ_1) subsystem on the reliability of the system is studied by varying their values as: ϕ_1=0.018, 0.023, 0.028 and 0.033 at constant value of its failure rate i.e. δ_1=0.0012. The failure and repair rates of other subsystems were taken as: δ_3=0.0025, δ_6=0.008, $\delta_4=\delta_3$, $\delta_5=\delta_3$, ϕ_3=0.042, ϕ_6=0.014, $\phi_4=\phi_3$, $\phi_5=\phi_3$. The reliability of the system is calculated using these values and the results are shown in table 6.9.1. This table reveals that the reliability of the system decreases from 22.96 to 22.83% approximately with the increase of time. However, it increases from 0.011 to 0.177% approximately with the increase in the repair rate of the Crystallizer subsystem from 0.018 to 0.033 and MTBF increases from 240.24 days to 240.55 days approximately.

(b) Effect of the failure and repair rates of the Centrifugal Pump subsystem on the reliability of the system

The effect of the failure rate of the Centrifugal pump (δ_3) subsystem on the reliability of the system is studied by varying their values as: δ_3=0.0024, 0.0025, 0.0026 and 0.0027 at constant value of its repair rate i.e. ϕ_3=0.042. The failure and repair rates of other subsystems were taken as: δ_1=0.0012, $\delta_2=\delta_1$, δ_6=0.008, ϕ_1=0.023, $\phi_2=\phi_1$, ϕ_6=0.014. The reliability of the system is calculated using these values and the results are shown in table 6.9.2. This table reveals that the reliability of the system decreases from 22.889 to 28.886% approximately with the increase of time. However, it decreases from 0.005 to 0.001% approximately with the increase in failure rate of Centrifugal Pump subsystem from 0.0024 to 0.0027 and MTBF decreases from 240.40 days to 240.39 days approximately.

The effect of the repair rate of the Centrifugal pump ($ø_3$) subsystem on the reliability of the system is studied by varying their values as: $ø_3$=0.037, 0.042, 0.047 and 0.052 at constant value of its failure rate i.e. δ_3=0.0025. The failure and repair rates of other subsystems were taken as: δ_1=0.0012, δ_2=δ_1, δ_6=0.008, $ø_1$=0.023, $ø_2$=$ø_1$, $ø_6$=0.014. The reliability of the system is calculated using these values and the results are shown in table 6.9.2. This table reveals that the reliability of the system decreases from 22.891 to 22.883% approximately with the increase of time. However, it increases from 0.011 to 0.001% approximately with the increase in repair rate of the Centrifugal Pump subsystem from 0.037 to 0.052 and MTBF increases from 240.39 days to 240.41 days approximately.

(c) Effect of the failure and repair rates of the Sugar grader subsystem on the reliability of the system

The effect of the failure rate of the Sugar grader (δ_6) subsystem on the reliability of the system is studied by varying their values as: δ_6=0.007, 0.008, 0.009 and 0.01 at constant value of its repair rate i.e. $ø_6$=0.014. The failure and repair rates of other subsystems were taken as: δ_1=0.0012, δ_2=δ_1, δ_3=0.0025, δ_4=δ_3, δ_5=δ_3, $ø_1$=0.023, $ø_2$=$ø_1$, $ø_3$=0.042, $ø_4$=$ø_3$, $ø_5$=$ø_3$. The reliability of the system is calculated using these values and the results are shown in table 6.9.3. This table reveals that the reliability of the system decreases from 25.877 to 21.121% approximately with the increase of time. However, it decreases from 12.5 to 6.87% approximately with the increase in failure rate of the Sugar grader subsystem from 0.007 to 0.01 and MTBF decreases from 251 days to 221.55 days approximately.

The effect of the repair rate of the Sugar grader ($ø_6$) subsystem on the reliability of the system is studied by varying their values as: $ø_6$=0.009, 0.014, 0.019 and 0.024 at constant value of its failure rate i.e. δ_6=0.008. The failure and repair rates of other subsystems were taken as: δ_1=0.0012, δ_2=δ_1, δ_3=0.0025, δ_4=δ_3, δ_5=δ_3, $ø_1$=0.023, $ø_2$=$ø_1$, $ø_3$=0.042, $ø_4$=$ø_3$, $ø_5$=$ø_3$. The reliability of the system is calculated using these values and the results are shown in table 6.9.3. This table reveals that the reliability of the system decreases from 34.74 to 11.46% approximately with the increase of time. However, it increases from 4.154 to 41.3% approximately with the increase in the repair rate of the Sugar grader subsystem from 0.009 to 0.024 and MTBF increases from 211.5 days to 274.2 days approximately.

(d) Effect of failure and repair rates of subsystems on reliability of the system

The table 9.4 reveals the change in reliability (%) of the system with the change in failure and repair rates of subsystems.

(e) Effect of failure and repair rates of the Crystallizer subsystem on the availability of the system

The effect of the failure and repair rates of the Crystallizer subsystem on the availability of the system is studied by varying their values as: δ_1=0.0011, 0.0012, 0.0013, 0.0014 and ϕ_1=0.018, 0.023, 0.028, and 0.033. The failure and repair rates of other subsystems were taken as: δ_3=0.0025, δ_6=0.008, $\delta_4=\delta_3$, $\delta_5=\delta_3$, ϕ_3=0.042, ϕ_6=0.014, $\phi_4=\phi_3$, $\phi_5=\phi_3$.The availability of the system is calculated using these values and results are shown in table 6.9.5.

(f) Effect of the failure and repair rates of the Centrifugal Pump subsystem on the availability of the system

The effect of the failure and repair rates of the Centrifugal Pump subsystem on the availability of the system is studied by varying their values as: δ_3=0.0024, 0.0025, 0.0026, 0.0027 and ϕ_3=0.037, 0.042, 0.047, 0.052 The failure and repair rates of other subsystems were taken as: δ_1=0.0012, $\delta_2=\delta_1$, δ_6=0.008, ϕ_1=0.023, $\phi_2=\phi_1$, ϕ_6=0.014. The availability of the system is calculated using these values and results are shown in table 6.9.6.

(g) Effect of the failure and repair rates of the Sugar grader subsystem on the availability of the system

The effect of failure and repair rates of Sugar grader subsystem on the availability of the system is studied by varying their values as: δ_6=0.007, 0.008, 0.009, 0.01 and ϕ_6=0.009, 0.014, 0.019, and 0.024. The failure and repair rates of other subsystems were taken as: δ_1=0.0012, $\delta_2=\delta_1$, δ_3=0.0025, $\delta_4=\delta_3$, $\delta_5=\delta_3$, ϕ_1=0.023, $\phi_2=\phi_1$, ϕ_3=0.042, $\phi_4=\phi_3$, $\phi_5=\phi_3$. The availability of the system is calculated using these values and results are shown in table 6.9.7.

Table 6.9.1 Decision matrix for the Crystallizer subsystem on the reliability of the Crystallization system

Time (Days)	**Failure rate of Crystallizer subsystem (δ_1)**				**Repair rate of Crystallizer subsystem (ϕ_1)**			
	0.0011	**0.0012**	**0.0013**	**0.0014**	**0.018**	**0.023**	**0.028**	**0.033**
30	0.824016	0.823965	0.823909	0.823849	0.823932	0.823965	0.823994	0.824020
60	0.732864	0.732755	0.732638	0.732511	0.732616	0.732755	0.732868	0.732959
90	0.685742	0.685602	0.685452	0.685290	0.685340	0.685602	0.685796	0.685941
120	0.661405	0.661253	0.661089	0.660913	0.660888	0.661253	0.661504	0.661678
150	0.648842	0.648684	0.648514	0.648332	0.648246	0.648684	0.648965	0.649152
180	0.642359	0.642200	0.642028	0.641843	0.641709	0.642200	0.642498	0.642688
210	0.639008	0.638848	0.638676	0.638491	0.638322	0.638848	0.639157	0.639348
240	0.637274	0.637114	0.636942	0.636757	0.636562	0.637114	0.637429	0.637621
270	0.636376	0.636216	0.636043	0.635857	0.635645	0.636216	0.636535	0.636728
300	0.635910	0.635750	0.635576	0.635390	0.635166	0.635750	0.636072	0.636265
330	0.635669	0.635507	0.635334	0.635147	0.634913	0.635507	0.635832	0.636025
360	0.635543	0.635381	0.635207	0.635020	0.634778	0.635381	0.635707	0.635901
MTBF	240.45	240.40	240.34	240.28	240.24	240.40	240.49	240.55

Table 6.9.2 Decision matrix for the Centrifugal Pump subsystem on the reliability of the Crystallization system

Time (Days)	**Failure rate of Centrifugal Pump subsystem (δ_3)**				**Repair rate of Centrifugal Pump subsystem (ϕ_3)**			
	0.0024	**0.0025**	**0.0026**	**0.0027**	**0.037**	**0.042**	**0.047**	**0.052**
30	0.823967	0.823965	0.823962	0.823959	0.823962	0.823965	0.823967	0.823969
60	0.732762	0.732755	0.732748	0.732740	0.732743	0.732755	0.732765	0.732773
90	0.685611	0.685602	0.685593	0.685583	0.685579	0.685602	0.685620	0.685634
120	0.661262	0.661253	0.661244	0.661234	0.661223	0.661253	0.661276	0.661292
150	0.648694	0.648684	0.648674	0.648664	0.648654	0.648684	0.648706	0.648722
180	0.642209	0.642200	0.642190	0.642179	0.642167	0.642200	0.642220	0.642235

210	0.638857	0.638848	0.638838	0.638828	0.638814	0.638848	0.638870	0.638884
240	0.637123	0.637114	0.637104	0.637094	0.637079	0.637114	0.637136	0.637150
270	0.636225	0.636216	0.636206	0.636196	0.636181	0.636216	0.636238	0.636253
300	0.635759	0.635750	0.635740	0.635730	0.635715	0.635750	0.635772	0.635787
330	0.635516	0.635507	0.635498	0.635487	0.635472	0.635507	0.635530	0.635544
360	0.635390	0.635381	0.635371	0.635361	0.635346	0.635381	0.635403	0.635418
MTBF	240.40	240.40	240.40	240.39	240.39	240.40	240.41	240.41

Table 6.9.3 Decision matrix for the Sugar grader subsystem on the reliability of the Crystallization system

Time (Days)	**Failure rate of Sugar grader subsystem (δ_6)**				**Repair rate of Sugar grader subsystem ($\o_6$)**			
	0.007	**0.008**	**0.009**	**0.01**	**0.009**	**0.014**	**0.019**	**0.024**
30	0.843842	0.823965	0.804629	0.785821	0.811656	0.823965	0.835165	0.845372
60	0.760429	0.732755	0.706429	0.681379	0.698383	0.732755	0.761567	0.785856
90	0.715985	0.685602	0.657170	0.630545	0.630422	0.685602	0.728752	0.762938
120	0.692334	0.661253	0.632487	0.605827	0.589683	0.661253	0.714131	0.754099
150	0.679757	0.648684	0.620119	0.593803	0.565264	0.648684	0.707617	0.750683
180	0.673069	0.642200	0.613927	0.587961	0.550626	0.642200	0.704715	0.749354
210	0.669508	0.638848	0.610821	0.585117	0.541845	0.638848	0.703414	0.748825
240	0.667610	0.637114	0.609260	0.583730	0.536574	0.637114	0.702828	0.748610
270	0.666598	0.636216	0.608475	0.583052	0.533408	0.636216	0.702562	0.748519
300	0.666058	0.635750	0.608079	0.582719	0.531506	0.635750	0.702440	0.748479
330	0.665770	0.635507	0.607879	0.582555	0.530363	0.635507	0.702384	0.748460
360	0.665615	0.635381	0.607777	0.582474	0.529676	0.635381	0.702357	0.748451
MTBF	251.00	240.40	230.61	221.55	211.48	240.40	260.04	274.19

Table 6.9.4 Decision matrix for the subsystems on the reliability of the Crystallization system

Time (Days)	Change in reliability of the system with failure rate of subsystems (% negative)			Change in reliability of the system with repair rate of subsystems (% positive)		
	Crystallizer subsystem (δ_1)	**Centrifugal pump subsystem (δ_3)**	**Sugar grader subsystem (δ_6)**	**Crystallizer subsystem ($ø_1$)**	**Centrifugal pump subsystem ($ø_3$)**	**Sugar grader subsystem ($ø_6$)**
30	0.020	0.001	6.876	0.011	0.001	4.154
60	0.048	0.003	10.396	0.047	0.004	12.525
90	0.066	0.004	11.933	0.088	0.008	21.020
120	0.074	0.004	12.495	0.120	0.010	27.882
150	0.079	0.005	12.645	0.140	0.010	32.802
180	0.080	0.005	12.645	0.152	0.010	36.091
210	0.081	0.005	12.605	0.161	0.011	38.199
240	0.081	0.005	12.564	0.166	0.011	39.517
270	0.081	0.005	12.533	0.170	0.011	40.328
300	0.082	0.005	12.512	0.173	0.011	40.822
330	0.082	0.005	12.499	0.175	0.011	41.122
360	0.082	0.005	12.491	0.011	0.011	41.303

Table 6.9.5 Decision matrix for the Crystallizer subsystem on the availability of the Crystallization system

δ_1 $ø_1$	**0.0011**	**0.0012**	**0.0013**	**0.0014**
0.018	0.459937	0.458745	0.457648	0.456628
0.023	0.462013	0.460896	0.459879	0.458942
0.028	0.463533	0.462452	0.461477	0.460587
0.033	0.464739	0.463671	0.462716	0.461850

Table 6.9.6 Decision matrix for the Centrifugal Pump subsystem on the availability of the Crystallization system

δ_3 $ø_3$	**0.0024**	**0.0025**	**0.0026**	**0.0027**
0.037	0.459237	0.458293	0.457375	0.456483
0.042	0.461817	0.460896	0.459996	0.459115
0.047	0.464099	0.463214	0.462346	0.461494
0.052	0.466097	0.465253	0.464423	0.463606

Table 6.9.7 Decision matrix for the Sugar grader subsystem on the availability of the Crystallization system

δ_6 $ø_6$	**0.007**	**0.008**	**0.009**	**0.01**
0.009	0.457696	0.453753	0.448628	0.441848
0.014	0.461125	0.457777	0.453428	0.447675
0.019	0.466751	0.464216	0.460896	0.456467
0.024	0.473972	0.472418	0.470330	0.467478

Table 6.9.8 Optimal values of failure and repair rates of subsystems for maximum availability of the Crystallization system

S. No.	**Subsystem**	**Failure rate (δ)**	**Repair rate (ø)**	**Max. Availability**
1	Sugar grader	0.007	0.024	0.473972
2	Centrifugal pump	0.0024	0.052	0.466097
3	Crystallizer	0.0011	0.033	0.464739

The decision matrices for Crystallization system as given in tables (6.9.1 to 6.9.7) indicate that the Centrifugal Pump subsystem is the most critical subsystem as for as maintenance is concerned. So, this subsystem should be given top priority as the effect of its repair rates on the system availability is much higher than other subsystems. On the basis of repair rates, the repair priorities from maintenance point of view for Crystallization system is as under.

Table 6.9.9 Decision criteria for the repair priority of Crystallization system

S. N.	Subsystem	Increase in failure rate (δ)	Decrease in		Increase in Repair rate (ø)	Increase in		Repair Priority
			Reliabiity	Availability		Reliabiity	Availability	
1	Centrifugal pump	0.0024-0.0017	0.00433	0.2638	0.037-0.052	0.009.8	0.2057	I
2	Crystallizer	0.0011-0.0014	0.07133	0.3054	0.018-0.033	0.11783	0.1232	II
3	Sugar grader	0.007-0.01	11.8495	1.1519	0.009-0.024	31.31375	0.11783	III

6.9.2 Performance analysis for RAMD of the Crystallization system

The RAMD indices for all the subsystems of Crystallization system are computed and tabulated in table 6.9.9.

Table 6.9.9 RAMD indices for the subsystems of the Crystallization system

RAMD indices of subsystems	Subsystem (S1)	Subsystem (S2)	Subsystem (S3)	System (S)
Reliability	$e^{-0.0024t}$	$e^{-0.0075t}$	$e^{-0.008t}$	$e^{-0.00148t}$
Availability	0.9974	0.9965	0.6364	0.6993
Maintainability	$1-e^{-0.9276t}$	$1-e^{-2.12t}$	$1-e^{-0.014t}$	$1-e^{-0.0137t}$
Dependability ($D_{min.}$)	0.9981	0.9974	0.4335	0.43155
MTBF	416.6667 hr.	133.3333 hr.	125 hr.	675 hr.
MTTR	1.0780 hr.	0.4716 hr.	71.4286 hr.	72.9782 hr.
Dependability ratio (d)	386.5278	282.7124	1.7500	

6.9.3 Performance analysis for fuzzy-reliability of the Crystallization system

The effect of the failure rate of the subsystems of the Crystallization system on the fuzzy-reliability of the system is computed by using the equation (4.9.72) for one year (i.e. time, t=30-360 days) and by taking an average value of coverage factor (i.e. *c* =0.5) as the value of system coverage factor (*c*) varies from 0 to 1. The table 6.9.10, 6.9.11, 6.9.12 reveals the effect of the failure rate of each subsystem on fuzzy-reliability of the system while table 6.9.13 reveals the effect of coverage factor on fuzzy-reliability of the system.

(a) Effect of the failure rate of the Crystallization subsystem on the fuzzy-reliability of the system

The effect of failure rate of Crystallization system on fuzzy-reliability of the system is studied by varying their values as: $ø_1$=0.001, 0.0012, 0.0013 and 0.0014 at constant value of repair rate i.e. $ø_1$= 0.23. The failure and repair rates of other subsystems were taken as: $ø_3$=0.0023, $ø_6$=0.008, $ø_2$=$ø_1$, $ø_3$=$ø_4$=$ø_5$, $ø_3$=0.042, $ø_6$=0.014, $ø_2$=$ø_1$, $ø_3$=$ø_4$=$ø_5$. The fuzzy-reliability of the system is calculated using these values and the results are shown in table 6.9.10. This table reveals that the fuzzy availability of the system decreases from 22.782 to 1.75% approximately with the increase of time. However, it decreases by 0.6% approximately with the increase in the failure rate of Crystallization subsystem approximately.

(b) Effect of the failure rate of the Centrifugal Pump subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Centrifugal Pump subsystem on fuzzy-reliability of the system is studied by varying their values as: $ø_3$=0.0024, 0.0025, 0.0026 and 0.0027 at constant value of its repair rate i.e.$ø_3$= 0.042. The failure and repair rates of other subsystems were taken as: $ø_1$=0.0012, $ø_6$=0.008, $ø_2$=$ø_1$, $ø_3$=$ø_4$=$ø_5$, $ø_6$=0.014, $ø_2$=$ø_1$, $ø_3$=$ø_4$=$ø_5$. The fuzzy availability of the system is calculated using these values and the results are shown in table 6.9.11. This table reveals that the fuzzy-reliability of the system decreases from 22.782 to 2.0% approximately with the increase of time. However, it decreases by 0.364% approximately with the increase in failure rate of centrifugal subsystem approximately.

(c) Effect of the failure repair rate of the Sugar grader subsystem on the fuzzy-reliability of the system

The effect of the failure rate of the Sugar grader subsystem on the fuzzy-reliability of the system is studied by varying their values as: $ø_6$=0.007, 0.008, 0.009 and 0.01 at repair rate ($ø_6$) 0.014 at different values of coverage factor. The failure and repair rates of other subsystems were taken as: $ø_1$=0.0012, $ø_3$=0.0025, $ø_2$=$ø_1$, $ø_3$=$ø_4$=$ø_5$, $ø_2$=$ø_1$, $ø_3$=$ø_4$=$ø_5$. The fuzzy-reliability of the system is calculated using these values and the results are shown in table 6.9.12. This table reveals that the fuzzy availability of the system decreases from 25.786 to 2.0% approximately with the increase of time. However, it decreases by 6.878 to 12.512% approximately with the increase in the failure rate of the Sugar grader subsystem approximately.

Table 6.9.10 Effect of failure rate of the Crystallization on the fuzzy-reliability of the Crystallization system

Time (days)	**Failure rate of Crystallization**			
	0.0011	**0.0012**	**0.0013**	**0.0014**
30	0.9069	0.9063	0.9057	0.9051
60	0.8569	0.8560	0.8552	0.8544
90	0.8285	0.8276	0.8267	0.8257
120	0.8120	0.8111	0.8101	0.8091
150	0.8023	0.8013	0.8003	0.7993
180	0.7965	0.7955	0.7945	0.7935
210	0.7931	0.7921	0.7910	0.7900
240	0.7910	0.7900	0.7890	0.7879
270	0.7898	0.7888	0.7877	0.7867
300	0.7891	0.7880	0.7870	0.7859
330	0.7886	0.7876	0.7865	0.7855
360	0.7883	0.7873	0.7863	0.7852

Table 6.9.11 Effect of failure rate of the Centrifugal pump on the fuzzy-reliability of the Crystallization system

Time	**Failure rate of Centrifugal pump**			
(days)	**0.0024**	**0.0025**	**0.0026**	**0.0027**
30	0.9067	0.9063	0.9058	0.9054
60	0.8566	0.8560	0.8555	0.8549
90	0.8282	0.8276	0.8270	0.8264
120	0.8116	0.8111	0.8105	0.8099
150	0.8019	0.8013	0.8007	0.8002
180	0.7961	0.7955	0.7949	0.7944
210	0.7926	0.7921	0.7915	0.7909
240	0.7906	0.7900	0.7894	0.7889
270	0.7893	0.7888	0.7882	0.7876
300	0.7886	0.7880	0.7874	0.7869
330	0.7881	0.7876	0.7870	0.7864
360	0.7879	0.7873	0.7867	0.7862

Table 6.9.12 Effect of failure rate of the Sugar grader on the fuzzy-reliability of the Crystallization system

Time	**Failure rate of Sugar grader**			
(days)	**0.007**	**0.008**	**0.009**	**0.01**
30	0.9151	0.9063	0.8975	0.8889
60	0.8695	0.8560	0.8428	0.8299
90	0.8436	0.8276	0.8120	0.7969
120	0.8284	0.8111	0.7943	0.7781
150	0.8193	0.8013	0.7839	0.7672
180	0.8139	0.7955	0.7779	0.7609
210	0.8106	0.7921	0.7743	0.7572
240	0.8087	0.7900	0.7721	0.7550
270	0.8075	0.7888	0.7709	0.7538
300	0.8067	0.7880	0.7701	0.7530
330	0.8063	0.7876	0.7697	0.7526
360	0.8060	0.7873	0.7694	0.7523

CHAPTER 7: CONCLUSION AND SCOPE FOR FUTURE WORK

7.1 INTRODUCTION

This chapter consists of comprehensive summary of the major research contributions made in the area of "**Design and Development of Decision Support Systems for a Process Plant**". It also outlines all the major findings of the research, its managerial implications and recommendations with a purpose to implement them for the dairy and sugar plants concerned. Finally at the end, some suggestions are included which forms the basis for future research.

7.2 RESEARCH WORK: A SUMMARY

The detailed literature on various issues related to reliability, availability, maintainability, dependability and fuzzy-reliability aspects of engineering systems have been studied. The literature available was classified in to various categories such as; literature on availability and reliability analysis using conventional and stochastic methods, literature on system performance optimization using Genetic Algorithm (GA), literature on reliability, availability, maintainability and dependability analysis and literature on performance analysis using fuzzy approach.

The study was carried out at dairy and sugar plants located at district Palwal, Haryana. The nature and behaviour of each system of the plant was monitored and discussed with the plant personnel who helped to provide comprehensive classification of causes related to anomalous performance of the subsystems. After identification of critical subsystems, the data related to failure and maintenance history of these subsystems of the plants was collected from log books/records and by discussion with the maintenance personnel of the plants. The decision support systems (DSS) for the reliability and availability of the systems namely; skim milk production system, Butter oil production system, Steam generation system, Refrigeration system of the dairy plant and Feeding system, Crushing system, Refining system, Evaporation system, Crystallization system of the sugar plant were developed. The performance models for RAMD indices and fuzzy-reliability of each system were also developed to analyze the behaviour and to evaluate their performance characteristics using Markov berth-death process. The performance optimization for each system of the plant was carried out using Genetic Algorithm technique to provide the optimum system availability levels for different combinations of failure and repair rates of the subsystems of all the systems for improving the overall performance of the dairy and sugar plants concerned.

7.3 FINDINGS OF THE PRESENT RESEARCH WORK

The findings that emerged from present research work are as follows:

7.3.1 Development of Decision Support Systems

The Decision Support System deals with the quantitative analysis of all the factors viz. maintenance strategies and states of nature which influence the maintenance decisions associated with the systems of the dairy and sugar plants. The reliability and availability expressions for the systems of the dairy and sugar plants have been derived to develop decision matrices. These decision matrices are developed under the real decision making environment for the purpose of performance evaluation of the system. Besides, a desired level of performance has been established and the feasible combinations of failure and repair rates have also been determined. The most feasible combinations have been concluded as shown in the table 7.1.

Table 7.1 Feasible combinations of the failure and repair rate parameters for the systems of the dairy and sugar plants

S. N.	System	Av (%)	Failure and repair rates
1	Skim milk production system	89.17	$\lambda_1=0.0038$, $\mu_1=0.321$, $\lambda_2=0.0054$, $\mu_2=0.079$, $\lambda_3=0.0073$, $\mu_3=0.281$, $\lambda_4=0.0048$, $\mu_4=0.092$, $\lambda_6=0.00451$, $\mu_6=0.089$
2	Butter oil production system	78.10	$\beta_1=0.0038$, $\alpha_1=0.321$, $\beta_2=0.0057$, $\alpha_2=0.083$, $\beta_3=0.0073$, $\alpha_3=0.281$, $\beta_4=0.0045$, $\alpha_4=0.105$, $\beta_6=0.00431$, $\alpha_6=0.096$, $\beta_7=0.00323$, $\alpha_7=0.036$
3	Steam generation system	84	$\theta_1=0.006$, $\omega_1=0.37$, $\theta_2=0.028$, $\omega_2=0.074$, $\theta_3=0.0045$, $\omega_3=0.074$, $\theta_5 = 0.0054$, $\omega_5=0.38$, $\theta_6=0.0062$, $\omega_6=0.32$
4	Refrigeration system	78	$\boldsymbol{\phi}_1=0.066$, $\boldsymbol{\tau}_1=0.31$, $\phi_3=0.038$, $\boldsymbol{\tau}_3=0.36$, $\boldsymbol{\phi}_5 = 0.0063$, $\boldsymbol{\tau}_5=0.26$, $\boldsymbol{\phi}_6=0.027$, $\boldsymbol{\tau}_6=0.43$, $\boldsymbol{\phi}_7=0.041$, $\boldsymbol{\tau}_7=0.28$.
5	Feeding system	96.8	$\boldsymbol{\varepsilon}_1=0.0086$, $\boldsymbol{\Delta}_1=0.22$, $\boldsymbol{\varepsilon}_3=0.006$, $\boldsymbol{\Delta}_3=0.23$, $\boldsymbol{\varepsilon}_4 = 0.0085$, $\boldsymbol{\Delta}_4=0.17$, $\boldsymbol{\varepsilon}_6=0.0085$, $\boldsymbol{\Delta}_6=0.14$.
6	Crushing system	59.17	$\sigma_1=0.0047$, $\rho_1=0.026$, $\sigma_2=0.0082$, $\rho_2=0.021$, $\sigma_3 = 0.0076$, $\rho_3=0.032$
7	Refining system	86.86	$\eta_1=0.006$, $\xi_1=0.134$, $\eta_4=0.0057$, $\xi_4=0.54$, $\eta_5=0.003$, $\xi_5=0.48$, $\eta_7=0.0076$, $\xi_7=0.061$.
8	Evaporation system	71.85	$\psi_1=0.0017$, $\gamma_1=0.022$, $\psi_3=0.0072$, $\gamma_3=0.024$, $\psi_4=0.0032$, $\gamma_4=0.035$
9	Crystallization system	47.39	$\delta_1=0.0012$, $\varnothing_1=0.023$, $\delta_3=0.0025$, $\varnothing_3=0.042$, $\delta_6=0.007$, $\varnothing_6=0.024$

7.3.2 Performance optimization of the system

The performance models are effectively utilized for the performance optimization of the systems of the dairy and sugar plants. The Genetic Algorithm (GA) has been used for determining the optimum values of the performance (i.e. availability) of each system of the dairy and sugar plant. The effect of GA parameters (i.e. no. of generations, crossover probability, mutation probability and population size) on the system performance has been analyzed and the corresponding optimum values of failure and repair rate parameters are also obtained. It has been done in four ways as given below;

(a) Number of generations is varied keeping crossover probability, mutation probability and population size constant.

(b) Crossover probability is varied keeping number of generations, mutationprobability and population size constant.

(c) Mutation probability is varied keeping number of generation, crossover probability and population size constant.

(d) Population size is varied keeping number of generations, crossover probability and mutation probability constant.

The combination of failure and repair rate parameters with optimum value of availability for each system has been selected for each parameter of Genetic Algorithm (GA) as shown in the table 7.3 while table 7.2 reveals the range of failure and repair rate parameters of the systems of the dairy and sugar plants.

The results concern with the performances of the systems of the dairy and sugar plants as mentioned in table 7.1 were compared with the results of the performance optimization of the systems by using Genetic Algorithm technique as mentioned in the table 7.3. This comparison was discussed with maintenance engineers and it was found that the results with GA will be beneficial to the plant personnel for timely execution of maintenance strategies to enhance the overall performance of the dairy and sugar plants concerned.

7.3.3 Critical component/subsystem of the system

Decision matrices are also used to identify the critical component/subsystem of each system to implement proper maintenance decisions to the plants accordingly. The critical subsystem of each system is also identified by computing RAMD indices and fuzzy-reliability of each system of the plants as shown in table 7.4.

Table 7.2 Range of failure and repair rate parameters of the systems of the dairy and sugar plants

S. N.	System	Failure rate	Repair rate
1	Skim milk production system	λ_1=0.0023 to 0.0082, λ_2=0.0011 to 0.0075, λ_3=0.0031 to 0.0091, λ_4=λ_5=0.0038 to 0.0092, λ_6=λ_7=0.00251 to 0.00821	μ_1=0.31 to 0.89, μ_2=0.021 to 0.095, μ_3=0.23 to 0.72, μ_4= μ_5= 0.032 to 0.097, μ_6= μ_7=0.049 to 0.092
2	Butter oil production system	β_1=0.0028 to 0.0075, β_2=0.0047 to 0.0094, β_3=0.0043 to 0.0087, β_4=β_5=0.0035 to 0.0078, β_6=0.00231 to 0.00621, β_7=0.00128 to 0.00825	α_1=0.221 to 0.782, α_2=0.043 to 0.095, α_3=0.181 to 0.785, α_4=α_5=0.027 to 0.183, α_6=0.046 to 0.179, α_7=0.016 to 0.085
3	Steam generation system	θ_1=0.0028, 0.0087, θ_2=0.012 to 0.073, θ_3= θ_4=0.0018 to 0.0087, θ_5=0.0023 to 0.0083, θ_6= θ_7=0.0018 to 0.0093	ω_1=0.13 to 0.78, ω_2=0.08 to 0.45, ω_3=ω_4=0.012 to 0.097, ω_5=0.16 to 0.83, ω_6=ω_7=0.17to 0.76.
4	Refrigeration system	ϕ_1=ϕ_2=0.025 to 0.078, ϕ_3=ϕ_4=0.015 to 0.078, ϕ_5 =0.0021 to 0.0093, ϕ_6 =0.01 to 0.085, ϕ_7 =0.016 to 0.092	τ_1=τ_2=0.13 to 0.78, τ_3=τ_4=0.15 to 0.78, τ_5 =0.13 to 0.78, τ_6 =0.18 to 0.85, τ_7 =0.1 to 0.69
5	Feeding system	ε_1= ε_2 =0.0025 to 0.0092, ε_3 =0.0031 to 0.0087, ε_4=ε_5=0.0042 to 0.0095, ε_6=ε_7 =0.0018 to 0.0085	Δ_1=Δ_2=0.03 to 0.18, Δ_3=0.091 to 0.19, Δ_4=Δ_5 =0.03 to 0.22, Δ_6=Δ_7 =0.01 to 0.18
6	Crushing system	σ_1=0.0042 to 0.0086, σ_2=0.0063 to 0.0096, σ_3=σ_4=0.0058 to 0.0092	ρ_1=0.012 to 0.021, ρ_2=0.014 to 0.027, ρ_3=ρ_4=0.024 to 0.046
7	Refining system	η_1=η_2=η_3=0.002 to 0.009, η_4=0.0022 to 0.0087, η_5=η_6=0.0012 to 0.0073, η_7=0.031 to 0.0095	ξ_1=ξ_2=ξ_3=0.08 to 0.148, ξ_4=0.21 to 0.68, ξ_5=ξ_6=0.032 to 0.092, ξ_7=0.026 to 0.084
8	Evaporation system	ψ_1=ψ_2=0.0009 to 0.0026 ψ_3=0.0063 to 0.0096, ψ_4=ψ_5=0.0021 to 0.0046	γ_1=γ_2=0.016 to 0.027, γ_3=0.010 to 0.12, γ_4=γ_5=0.024 to 0.12
9	Crystallization system	δ_1=δ_2=0.001 to 0.0075, δ_3=δ_4=δ_5=0.0016 to 0.0085, δ_6 =0.0062 to 0.0098	$\varnothing_1$=$\varnothing_2$=0.010 to 0.287, $\varnothing_3$=$\varnothing_4$=$\varnothing_5$=0.028 to 0.95, $\varnothing_6$ =0.012 to 0.087

Table: 7.3 Performance optimization of the systems of the dairy and sugar plants

S. N.	System	**Performance optimization using GA by varying number of generation**		**Performance optimization using GA by varying crossover probability**		**Performance optimization using GA by varying mutation probability**		**Performance optimization using GA by varying population size**	
		Av (%)	**Failure and Repair rate parameters**	**Av (%)**	**Failure and Repair rate parameters**	**Av (%)**	**Failure and Repair rate parameters**	**Av (%)**	**Failure and Repair rate parameters**
1	Skim milk production system	94.2	$\lambda_1=0.0025, \mu_1=0.88,$ $\lambda_2=0.0015, \mu_2=0.088,$ $\lambda_3=0.0035, \mu_3=0.60,$ $\lambda_4=0.0050, \mu_4=0.035,$ $\lambda_6=0.00363, \mu_6=0.073$	94.73	$\lambda_1=0.0024, \mu_1=0.88,$ $\lambda_2=0.0011, \mu_2=0.092,$ $\lambda_3=0.0071, \mu_3=0.69,$ $\lambda_4=0.0063, \mu_4=0.075,$ $\lambda_6=0.00261, \mu_6=0.088$	94	$\lambda_1=0.0023, \mu_1=0.80,$ $\lambda_2=0.0013, \mu_2=0.081,$ $\lambda_3=0.0040, \mu_3=0.56,$ $\lambda_4=0.0090, \mu_4=0.036,$ $\lambda_6=0.00749, \mu_6=0.082$	94	$\lambda_1=0.0023, \mu_1=0.80,$ $\lambda_2=0.0013, \mu_2=0.081,$ $\lambda_3=0.0040, \mu_3=0.56,$ $\lambda_4=0.0090, \mu_4=0.036,$ $\lambda_6=0.00749, \mu_6=0.082$
2	Butter oil production system	85.83	$\beta_1=0.0059, \alpha_1=0.641,$ $\beta_2=0.0047, \alpha_2=0.091,$ $\beta_3=0.0049, \alpha_3=0.453,$ $\beta_4=0.0046, \alpha_4=0.080,$ $\beta_6=0.00246, \alpha_6=0.056,$ $\beta_7=0.00162, \alpha_7=0.078$	86.7	$\beta_1=0.003, \alpha_1=0.703,$ $\beta_2=0.0055, \alpha_2=0.087,$ $\beta_3=0.0069, \alpha_3=0.652,$ $\beta_4=0.0038, \alpha_4=0.078,$ $\beta_6=0.00246, \alpha_6=0.076,$ $\beta_7=0.00129, \alpha_7=0.082$	85.43	$\beta_1=0.004, \alpha_1=0.448,$ $\beta_2=0.0047, \alpha_2=0.092,$ $\beta_3=0.0068, \alpha_3=0.379,$ $\beta_4=0.0039, \alpha_4=0.069,$ $\beta_6=0.00245, \alpha_6=0.076,$ $\beta_7=0.00218, \alpha_7=0.068$	85.4	$\beta_1=0.039, \alpha_1=0.447,$ $\beta_2=0.0045, \alpha_2=0.095,$ $\beta_3=0.0067, \alpha_3=0.381,$ $\beta_4=0.0041, \alpha_4=0.067,$ $\beta_6=0.00243, \alpha_6=0.075,$ $\beta_7=0.00219, \alpha_7=0.071$
3	Steam generation system	96.2	$\theta_1=0.00300, \omega_1=0.663,$ $\theta_2=0.0120, \omega_2=0.411,$ $\theta_3=0.00228, \omega_3=0.0767,$ $\theta_5 = 0.00237, \omega_5=0.644,$ $\theta_6=0.00836, \omega_6=0.321$	95.73	$\theta_1=0.00337, \omega_1=0.755,$ $\theta_2=0.0147, \omega_2=0.434,$ $\theta_3=0.00209, \omega_3=0.0890,$ $\theta_5=0.00273, \omega_5=0.500,$ $\theta_6=0.00195, \omega_6=0.306.$	96.17	$\theta_1=0.00351, \omega_1=0.664,$ $\theta_2=0.0123, \omega_2=0.443,$ $\theta_3=0.00288, \omega_3=0.0771,$ $\theta_5=0.00287, \omega_5=0.632,$ $\theta_6=0.00842, \omega_6=0.359$	95.96	$\theta_1=0.00412, \omega_1=0.626,$ $\theta_2=0.0124, \omega_2=0.421,$ $\theta_3=0.00317, \omega_3=0.072,$ $\theta_5=0.00255, \omega_5=0.634,$ $\theta_6=0.00842, \omega_6=0.701.$
4	Refrigeration system	95.2	$\phi_1=0.0342, \tau_1=0.748,$ $\phi_3=0.0245, \tau_3=0.711,$ $\phi_5 = 0.0027, \tau_5=0.730,$ $\phi_6=0.0105, \tau_6=0.765,$ $\phi_7=0.0184, \tau_7=0.612.$	95.2	$\phi_1=0.03119, \tau_1=0.746,$ $\phi_3=0.02445, \tau_3=0.767,$ $\phi_5=0.00278, \tau_5=0.730,$ $\phi_6=0.01027, \tau_6=0.749,$ $\phi_7=0.01853, \tau_7=0.610.$	95.12	$\phi_1=0.06803, \tau_1=0.744,$ $\phi_3=0.01669, \tau_3=0.766,$ $\phi_5=0.00253, \tau_5=0.726,$ $\phi_6=0.01004, \tau_6=0.797,$ $\phi_7=0.01635, \tau_7=0.608$	95.3	$\phi_1=0.03325, \tau_1=0.744),$ $\phi_3=0.02344, \tau_3=0.710),$ $\phi_5=0.00262, \tau_5=0.668),$ $\phi_6=0.01026, \tau_6=0.738),$ $\phi_7=0.01731, \tau_7=0.610).$
5	Feeding system	98.11	$\varepsilon_1=0.0028, \Delta_1=0.1726,$ $\varepsilon_3=0.0032, \Delta_3=0.1804,$ $\varepsilon_4 = 0.0056, \Delta_4=0.1913,$ $\varepsilon_6=0.0030, \Delta_6=0.1392.$	98	$\varepsilon_1=0.0037, \Delta_1=0.1172,$ $\varepsilon_3=0.0032, \Delta_3=0.1836,$ $\varepsilon_4 = 0.0054, \Delta_4=0.1960,$ $\varepsilon_6=0.0038, \Delta_6=0.1643.$	98.1	$\varepsilon_1=0.0041, \Delta_1=0.1682,$ $\varepsilon_3=0.0031, \Delta_3=0.1814,$ $\varepsilon_4 = 0.0045, \Delta_4=0.2188,$ $\varepsilon_6=0.0050, \Delta_6=0.1506.$	98	$\varepsilon_1=0.0041, \Delta_1=0.1653,$ $\varepsilon_3=0.0031, \Delta_3=0.1826,$ $\varepsilon_4=0.0051, \Delta_4=0.1758,$ $\varepsilon_6=0.0045, \tau_6=0.0829$
6	Crushing system	86.7	$\sigma_1=0.004257,$ $\rho_1=0.090133,$ $\sigma_2=0.006944,$ $\rho_2=0.09416, \sigma_3 =$ $0.006101, \rho_3=0.90426$	86.5	$\sigma_1=0.005002,$ $\rho_1=0.090685,$ $\sigma_2=0.006547,$ $\rho_2=0.092585, \sigma_3 =$ $0.005852, \rho_3=0.095363$	86.5	$\sigma_1=0.005213,$ $\rho_1=0.094757,$ $\sigma_2=0.006383,$ $\rho_2=0.094262, \sigma_3 =$ $0.006164, \rho_3=0.092657$	86	$\sigma_1=0.004594,$ $\rho_1=0.097348,$ $\sigma_2=0.006324,$ $\rho_2=0.082298, \sigma_3 =$ $0.006518, \rho_3=0.085437$

7	Refining system	95	$\eta_1=0.0023$, $\xi_1=0.1139$, $\eta_4=0.0046$, $\xi_4=0.5636$, $\eta_5=0.0024$, $\xi_5=0.0779$, $\eta_7=0.0033$, $\xi_7=0.0821$.	95	$\eta_1=0.0027$, $\xi_1=0.1084$, $\eta_4=0.0044$, $\xi_4=0.4075$, $\eta_5=0.0018$, $\xi_5=0.0721$, $\eta_7=0.0031$, $\xi_7=0.0813$.	94.6	$\eta_1=0.0020$, $\xi_1=0.0949$, $\eta_4=0.0042$, $\xi_4=0.4439$, $\eta_5=0.0015$, $\xi_5=0.0561$, $\eta_7=0.0033$, $\xi_7=0.0759$.	95.4	$\eta_1=0.0023$, $\xi_1=0.1301$, $\eta_4=0.0025$, $\xi_4=0.5144$, $\eta_5=0.0018$, $\xi_5=0.0830$, $\eta_7=0.0034$, $\xi_7=0.0822$
8	Evaporation system	93	$\psi_1=0.000982$, $\gamma_1=0.016854$, $\psi_3=0.006366$, $\gamma_3=0.109264$, $\psi_4=0.002408$, $\gamma_4=0.11969$	93	$\psi_1=0.001215$, $\gamma_1=0.023182$, $\psi_3=0.006467$, $\gamma_3=0.118381$, $\psi_4=0.00251$, $\gamma_4=0.115457$	93.21	$\psi_1=0.001310$, $\gamma_1=0.024986$, $\psi_3=0.006356$, $\gamma_3=0.119119$, $\psi_4=0.002181$, $\gamma_4=0.108608$	93.2	$\psi_1=0.001503$, $\gamma_1=0.01708$), $\psi_3=0.006351$, $\gamma_3=0.113098$, $\psi_4=0.002215$, $\gamma_4=0.116628$
9	Crystallization system	96.5	$\delta_1=0.006738$, $\phi_1=0.03212$, $\delta_3=0.002191$, $\phi_3=0.94785$, $\delta_6=0.009619$, $\phi_6=0.08690$	96.95	$\delta_1=0.004935$, $\phi_1=0.02305$, $\delta_3=0.001619$, $\phi_3=0.885348$, $\delta_6=0.009780$, $\phi_6=0.08625$	95.25	$\delta_1=0.007217$, $\phi_1=0.02237$, $\delta_3=0.00342$, $\phi_3=0.927002$, $\delta_6=0.009554$, $\phi_6=0.08620$	94	$\delta_1=0.006658$, $\phi_1=0.010847$, $\delta_3=0.007503$, $\phi_3=0.328142$, $\delta_6=0.009247$, $\phi_6=0.08602$

Table 7.4 Critical subsystem of the systems of dairy and sugar plants

S. N.	**System**	**Reliability and availability analysis**		**RAMD analysis**		**Fuzzy-reliability analysis**	
		Critical Subsystem	**Effect on Reliability and Availability of the system**	**Critical subsystem**	**Effect on RAMD indices of the system**	**Critical subsystem**	**Effect on Fuzzy-reliability of the system**
1	Skim milk production system	Cream separator	Change in reliability is max. (i.e. 0.01% approx.), change in availability is max. (i.e. 0.5% approx.)	S1 (Chiller and Cream separator)	RAMD indices are lowest. MTBF is low, MTTR is high, d is low	Cream separator	Change in fuzzy-reliability is max. (i.e. 0.5% approx.) with change in failure rates
2	Butter oil production system	Cream separator	Change in reliability is max. (i.e. 1.286% approx.), change in availability is max. (i.e. 1.65% approx.)	S2 (Cream separator and pasteurizer)	RAMD indices are lowest. MTBF is low, MTTR is high, d is low	Cream separator	Change in fuzzy-reliability is max. (i.e. 0.7% approx.) with change in failure rates
3	Steam generation system	Feed pump	Change in reliability is max. (i.e. 6.50% approx.), change in availability is max. (i.e. 8.65% approx.)	S1 (L.P. heater and feed pump)	RAMD indices are lowest. MTBF is low, MTTR is high, d is low	Feed pump	Change in fuzzy-reliability is max. (i.e. 3% approx.) with change in failure rates
4	Refrigeration system	Evaporator	Change in reliability is max. (i.e. 5.76% approx.), change in availability is max. (i.e. 7.37% approx.)	S4 (Evaporator)	RAMD indices are lowest. MTTR is high, d is low	Evaporator	Change in fuzzy-reliability is max. (i.e. 2.84% approx.) with change in failure rates
5	Feeding system	Crushing unit	Change in reliability is max. (I.e. 2.144% approx.), change in availability is max. (I.e. 3.35% approx.)	S2 (Crushing system)	RAMD indices are lowest. MTTR is high, d is low	Crushing unit	Change in fuzzy-reliability is max. (i.e. 0.88% approx.) with change in failure rates
6	Crushing system	Cane preparation	Change in reliability is max. (i.e. 9.5% approx.), change in availability is max. (i.e. 12.35% approx.)	S1 (cane preparation)	RAMD indices are lowest. MTTR is high,	Cane preparation	Change in fuzzy-reliability is max. (i.e. 3.86% approx.) with change in failure rates
7	Refining system	Heater	Change in reliability is max. (i.e. 4.8% approx.), change in availability is max. (i.e. 5.4% approx.)	S4 (heater)	RAMD indices are lowest. MTTR is high, d is low	heater	Change in fuzzy-reliability is max. (i.e. 2.16% approx.) with change in failure rates
8	Evaporation system	Pump	Change in reliability is max. (i.e. 12.9% approx.), change in availability is max. (i.e. 15% approx.)	S2 (pump)	RAMD indices are lowest. MTBF is low, MTTR is high, d is low	pump	Change in fuzzy-reliability is max. (i.e. 6.9% approx.) with change in failure rates
9	Crystallization system	Sugar grader	Change in reliability is max. (i.e. 2.5% approx.), change in availability is max. (i.e. 2.7% approx.)	S3 (Sugar grader)	RAMD indices are lowest. MTBF is low, MTTR is high, d is low	Sugar grader	Change in fuzzy-reliability is max. (i.e. 3.7% approx.) with change in failure rates

7.3.4 Causes for poor reliability and availability of the system

There are various causes for poor reliability and availability of the system

(a) **Effect of failure and repair rates of components/subsystems of the system**: Sharma and Kumar (Ref. no. 156) and Sharma and Garg (Ref. no. 160) stated the relation between reliability (R) and failure rate (λ) of a component as;

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

The above equation shows that the reliability decreases with the increase in the failure rate of the component. Ertas (1993) and Castro and Cavaka (2003) expressed the availability (A) of the system in terms of failure rate and repair rate (μ) as;

$$A = \frac{\mu}{\mu+\lambda}$$

The above equation shows that the availability of the system increases with the increase in the repair rate and decrease in the failure rate of the system.

(b) **Poor design**: Poor design, incorrect manufacturing techniques and improper selection of materials are the reasons of poor reliability and availability

(c) **Lack of total knowledge and experience**: The insufficient training and insufficient knowledge of operator about the machine also causes poor availability and poor reliability.

(d) **Complexity of the equipment**: The complexity in the machine or equipment causes difficulty in operation and maintenance and hence it causes poor reliability of the system.

(e) **Human errors**: Poor availability and reliability due to human-error may be due to the following

(i)Lack of knowledge about the equipment or process
(ii)Forgetfulness
(iii)Physical inability
(iv)Absence of correct machine operating procedures
(v)Poor skills for judgment

(f) **Poor redundancy and fault tolerance of the components/subsystems**: Redundancy means the duplication or triplication of the equipment that is needed to operate without disruption, if and when the primary equipment fails during the mission. Fault tolerance is the ability of the system to tolerate faults and continue operating properly. Hence, poor redundancy and fault tolerance (i.e. imperfect switch-over devices) causes poor availability/ reliability of the system. Castro and Cavaka (2003) also stated that the use of redundant components in an engineering system results in availability increase. Hence, poor redundancy and fault tolerance causes poor availability/ reliability of the system.

(g) **Poor maintainability of the system**:

The poor maintainability of the system causes poor availability and reliability. The maintainability of a component depends on its failure and repair rates i.e. maintainability of a component considers both the failure and repair rates simultaneously. The factors that affect maintainability includes: Sharma and Kumar (2008) and Ertas (1993) expressed the availability in terms of mean time to failure (MTTF) and mean time to repair (MTTR) as;

$$A = \frac{\mathrm{MTTF}}{\mathrm{MTTF+MTTR}}$$

Castro and Cavaka (2003) stated that the maintainability of a component can be iproved by the increase the availability of the component, Sharma and Garg (2011) stated the relation between maintainability (M) and repair rate of a system to shows that the maintainability improves with the increase in the repair rate of the system.

$$\mathrm{M(t)} = 1 - \exp\left(\frac{-t}{\mathrm{MTTR}}\right) = 1 - e^{-\mu t}$$

(h) **Common root causes of poor equipment performance**: Root causes are the underlying factors that are found to be responsible for poor equipment performance i.e. poor availability and reliability of the system;

(i) **Misapplication**: This can be due to equipment operations outside of the design envelope, poor initial design practices or poor procurement practices.

(ii) **Operating practices**: It is due to inadequate operating procedures, lack of adherence to procedures or inadequate system for follow up.

(iii) **Maintenance practices**: It is due to inadequate maintenance procedures, no adherence to procedures or inadequate frequency of maintenance tasks.

(iv) **Age**: It is due to accelerated wear mechanism by environmental factors or the end of the useful life by normal wear and tear.

(v) **Management system**: It is due to lack of skills or operator training, poor employee involvement, poor recognition of hazard, previously identified hazards were not followed up on and eliminated.

7.3.5. Suggestions for reduction of downtime, improvement of uptime, availability and reliability of systems

The management of industrial systems pushes their production equipment to full capacity and at the same time, tries to reduce downtime. When industrial systems are running at full capacity, downtime becomes a very important issue in production management and planning. There will be a loss of profits and revenue while production targets can't be reached and the system can't produce any output. In many cases, process improvement tools like; lean manufacturing techniques and principles can be used to identify problem areas, maintenance issues and other items which can reduce plant downtime. The following maintenance management practices/concepts are useful for reduction of downtimes, improvement of uptime, availability and reliability of systems

(i) 5-Zero concepts: This concept was introduced by Toyota Motors Works in Japan. It is called for 5 zeros i.e.

- `0' breakdown
- `0' fault
- `0' delays
- `0' stock and
- `0' paper work

(ii) Reliability-Based Maintenance (RBM) or Reliability Centred Maintenance (RCM)
(iii) Creative Maintenance
(iv) Predictive maintenance

- Utilize people skills and all available performance data. Maintenance history, logs and design data to make appropriate and timely decisions about the equipment`s maintenance requirements.
- Analyze trends in all available data to detect and correct a problem before it occurs.
- Analyze the information for equipment depreciation.

(v) Preventive maintenance

- Actively service the plant equipment with the basic and essential maintenance such as cleaning, routine adjustments and lubrication.

- Implement a timely and organized routine maintenance program.
- Replace machinery components based on run hours or a similar factor and their potential to fail in the future such as bearings, shafts, sensors, gears etc.

Billinton and Allen (1992) stated that there are two main ways by which the reliability can be affected. The first relates to quality and the second to redundancy. The first attribute i.e. quality is concern not only the physical materials and components used in the system, but also the quality of manufacture, testing, calibration, transport and operation. These also depend on the quality and experience of the personnel involved, the stress to which they are exposed, the training they have been given, and the ergonomics and environment of the work place. These human factors are known to play a very important role in the reliability of the product and systems.The second attribute accepts that components will always fail from time to time and that there should be sufficient "backup" so that the function of a failed component is absorbed by another; the failed component either remains in the failed state in a non-repairable system or is repaired/replaced in a repairable system. The backup system is known as redundancy.

They suggested some methods for improving the reliability of a system like; stocking spares and performing preventive maintenance. They concluded that the reliability activity should also be concerned with maintainability of the system. Maintainability analysis is used to translate the maintenance requirements of the units and its associated subsystems in to specific items in order to reduce and simplify the maintenance requirement.

7.4 MAJOR CONTRIBUTIONS OF THE PRESENT RESEARCH WORK

The major contributions made through the present research work are as follows

(a) The present research work provides a comprehensive review of literature on availability, reliability, RAM and fuzzy-reliability of industrial systems.

(b) Mathematical model is suggested to compute reliability of the systems.

(c) A method is suggested to compute Reliability, availability, Maintainability and Dependability (RAMD) indices for a system under real conditions.

7.5 LIMITATIONS OF THE PRESENT RESEARCH WORK

Though a lot of efforts have been made in the present research work but this research is not free from the limitations. The limitations of the present work are as

(a) The mathematical modelling of the system has discrete and countable states.

(b) The system must be in only one state at a time.

(c) The system makes a transition from one state to another from time to time.

(d) The transition of the system from working state to failed state or vice versa is instantaneous.

(e) The failure rate of component or subsystem is constant.

(f) The sufficient repair facilities with required maintenance executives are available all the times.

(g) Sufficient inventory of required parts are available all the times.

(h) Sufficient redundancy is provided for smooth function of the system.

7.6 SCOPE FOR FUTURE RESEARCH WORK

The present work can be extended in the following directions as:

(a) Performance models can be developed for various process plants assuming simultaneous failures among various systems of an industrial system

(b) The present research work can be extended with the consideration of time dependent failure and repair rates

(c) The present research work can be extended to arbitrary repairs and failure time distribution

(d) The Genetic Algorithm can be further utilized in optimizing the system’s performance while considering the availability, maintenance cost and life cycle costs as the criteria for optimization

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Appendices

Appendix-1: Probability Distributions

There are two types of probability distributions:

(1) Discrete probability distribution

(2) Continuous probability distribution

(1) **Discrete probability distribution**: It is used when the sampling space is discrete but not countable. Following is a list of discrete probability distributions:

(a) Discrete uniform

(b) Binomial and Multinomial

(c) Hypergeometric

(d) Negative Binomial and Geometric

(e) Poisson

(a) **Discrete uniform distribution**: if a r. v., X, assumes the values x_1, x_2, ..., x_k with equal probabilities, then X conforms discrete uniform distribution and its probability function is given below:

$$f(x,k) = \frac{1}{k}, \quad x = x_1, x_2, \ldots, x_k$$

- The mean and variance:

$$\mu = \frac{1}{k}\sum_{i=1}^{k} x_i$$

$$\sigma^2 = \frac{1}{k}\sum_{i=1}^{k} (x_i - \mu)^2$$

(b) **Binomial and multinomial distributions**: let us introduce the Bernoulli process. If:

- The outcomes of process is either success (X = 1) or fail (X = 0)
- The probability of success is P(X = 1) = p and the probability of fail is P(X = 0) = 1-p = q

Then, the process is a Bernoulli process.

- The probability distribution of the Bernoulli process:

$$p(x) = p^x(1 - p)^{1-x}, x = 0, 1 \text{ and } 0 < p < 1$$

- The mean and the variance:

  E(X) = p

  V(X) = p(1 - p)

Binomial Distribution: The binomial distribution is defined based on the Bernoulli process. It is made up of n independent Bernoulli processes. Suppose that X_1, X_2, ..., X_n are independent Bernoulli random variables, then Y = Σ X_i will conform Binomial distribution. (note that Y is the number of successes among the n trails)

- The probability distribution of binomial distribution is:

$$P(Y = y) = \binom{n}{y} p^y (1-p)^{n-y}, \qquad y = 0,1,...,n$$

- Mean and variance of the binomial distribution:

E(Y) = Σ E(X_i) = Σp = np

V(Y) = Σ V(X_i) = Σp(1 - p) = np(1 - p)

Multinomial distribution: This is an extension of binomial distribution: let x_1, x_2, ..., x_k be independent r. v. with the probability p_1, p_2, ..., p_k, where,

$$\sum_{i=1}^{k} x_i = n, and \sum_{i=1}^{k} p_i = 1$$

then, they conform multinomial distribution with the probability distribution:

$$f(x_1, x_2, ... x_k; p_1, p_2, ... p_k) = \binom{n}{x_1, x_2, ... x_k} p_1^{x1} p_2^{x2} ... p_k^{xk}$$

(c)**Hypergeometric Distribution**: In general, the probability distribution is as follows:

$$P(Y = y) = \frac{\binom{8}{y}\binom{4}{3-y}}{\binom{12}{3}}, \quad y = 0,\ 1,\ 2,\ 3$$

- The general formula of the hypergeometry distribution:

$$P(Y = y) = \frac{\binom{k}{y}\binom{N-k}{n-y}}{\binom{N}{n}}, \quad y = 0,\ 1,\ 2,\ ...,\ n$$

- The mean and the variance of the hypergeometry distribution:

$$\mu = \frac{nk}{N}$$

$$\sigma^2 = \frac{N-n}{N-1}\frac{nk}{N}\left(1-\frac{k}{N}\right)$$

as a special case, let N be infinite, then (k / N) = p, and (N-n) / (N-1) = 1. Hence:

$\mu = np$

$\sigma^2 = np(1 - p)$

i.e., the hypergeometric distribution becomes the binomial distribution

(d) **Negative Binomial and Geometric Distributions**

- The general formula for the negative binomial distribution is as follows:

$$f(X = x) = \binom{x-1}{k-1} p^k (1-p)^{x-k}, \text{ x = k, k+1, k+2, ...}$$

where, x is the number of trails and k is the k^th success.

- The mean of variance of the negative binomial distribution:

E(X) = k(1-p)/p

V(X) = $k(1-p)/p^2$

- The general formula is:

$f(X = x) = (1 - p)^{x-1}p$, x = 1, 2, 3, ...

This is the geometric distribution.

- The mean of variance of the negative binomial distribution and geometric distributions:

E(X) = 1/p

V(X) = $(1-p)/p^2$

(e) **Poisson distribution:** It is a random process representing a discrete event takes place over continuous intervals of time or region. Poisson distribution plays an extremely important role in science and engineering, since it represents an appropriate probabilistic model for a large number of observational phenomena.

- The Poisson distribution can be described by the following formula:

$$p(x,\lambda t) = \frac{e^{-\lambda t}(\lambda t)^x}{x!}, \text{ x = 0, 1, 2, ...}$$

where, λ is the average number of outcomes per unit time or region. Hence, λt represents the number of outcomes. The Poisson process can be considered as an approximation to the Binomial Distribution when n is large and p is small. From a physical point of view, given a time interval of length T, which is divided interval into n equal sub-intervals of length Δt ($\Delta t \to 0$), (note that $T = n\Delta t$), and assume:

- The probability of a success in any sub-interval Δt is given by $\lambda\Delta t$.
- The probability of more than one success in any sub-interval Δt is negligible.
- The probability of a success in any sub-interval does not depend on what happened prior to that time.

Then, we have the Poisson distribution.

- Mean and Variance of Poisson distribution

$\mu = \lambda,\ \sigma^2 = \lambda$

(2) **Continuous probability distribution**: Continuous probability distribution is used when the sample space is continuous. Following is a list of continuous probability distributions.

(a) Uniform
(b) Normal (or Guassian)
(c) Gamma, Exponential and χ^2 distribution
(d) Weibul distribution

(a) **Uniform Distribution**: The uniform distribution is a continuous probability distribution with the assumption that the random event is equally likely in an interval. The probability density function (pdf)

$$f(x) = \begin{cases} \dfrac{1}{b-a} & a \le x \le b \\ 0 & \text{elsewhere} \end{cases}$$

- By integration, we obtain the probability function (pf)

$$F(x) = \begin{cases} 0 & x \le a \\ \dfrac{x-a}{b-a} & a \le x \le b \\ 1 & b \le x \end{cases}$$

A comparison between the discrete distributions and continuous distribution

- the discrete r. v., we have probability function:

  P(X = x) = p(x)

- for continuous r. v.:

F(X = x) = 0

$$F(x) = \int_{-\infty}^{x} f(x)\,dx$$

$$f(x) = \frac{F(x)}{dx}$$

- The mean and the variance:

$E(x) = (a+b)/2$

$V(x) = (b-a)^2/12$

(b) **Normal Distribution**: In the natural world there are more cases where possibilities are not equally likely. Instead there is a most likely value and then the likelihood decreases symmetrically. This leads to the Normal distribution. It is the most widely used probability distribution.

- The probability density function:

$$f(x) = \frac{1}{\sqrt{2\pi}\ \sigma} e^{-(x-\mu)^2/2\sigma^2}$$

It should be noted that probability function does not have analytical form, hence, we rely on numerical calculation. The mean, variance and standard deviation of a normal distributions are:

$E(X) = \mu$

$V(X) = \sigma^2$

(c) **Gamma distribution, Exponential distribution and Chi-Square (χ^2) distribution**: There are cases, for example the failure rate, in which the possibility decreases exponentially. This leads to the exponential distribution.

- The probability density function of the exponential distributions:

$$f(x) = \begin{cases} \frac{1}{\theta}\exp\left(-\frac{x}{\theta}\right) & x > 0, \quad \theta > 0 \\ 0 & \text{elsewhere} \end{cases}$$

- The probability function

$F(x) = 1 - \exp(-x/\theta), x > 0, \theta > 0$

- To calculate mean and variance, we need the Gamma (Γ) function:

$$\Gamma(\alpha) = \int_{0}^{\infty} x^{\alpha-1} e^{-x} dx$$

using integration by part:

(uv)' = u'v + uv'

$$uv = \int u' v + \int uv'$$

or

$$\int uv' = uv - \int u' v$$

let u = $x^{\alpha-1}$, dv = $e^{-x}dx$, it follows that:

$$\Gamma(\alpha) = -e^{-x} x^{\alpha-1} \Big|_0^\infty + \int_0^\infty e^{-x}(\alpha-1)x^{\alpha-2}dx = (\alpha-1)\Gamma(\alpha-1)$$

In particular:

$\Gamma(\alpha+1) = \alpha F(\alpha)$

$\Gamma(n) = (n-1)!$

$\Gamma(1/2) = \sqrt{\pi}$

In general:

$$\int_0^\infty (\beta x)^{\alpha-1} e^{-x/\beta} dx = \beta^\alpha \Gamma(\alpha)$$

for the geometry distribution, since $\alpha = 1$, $\theta = \beta$:

$E(X) = \theta$

$V(X) = \theta^2$

$\sigma = \theta$

- The exponential distribution is correlated to Poisson distribution: given a Poisson distribution with the mean λt, the probability of first time occurrence is exponential.
- Another common case is that the possibility is low when close to zero - this leads to the Gamma distribution. The probability density function of Gamma distribution:

$$f(x) = \frac{1}{\Gamma(\alpha)\beta^\alpha} x^{\alpha-1} e^{-\frac{x}{\beta}}, \ x > 0, \beta > 0.$$

- The mean and variance:

$E(X) = \alpha\beta$

$V(X) = \alpha\beta^2$

- Note that exponential distribution is a special case of Gamma distribution with $\alpha = 1$.

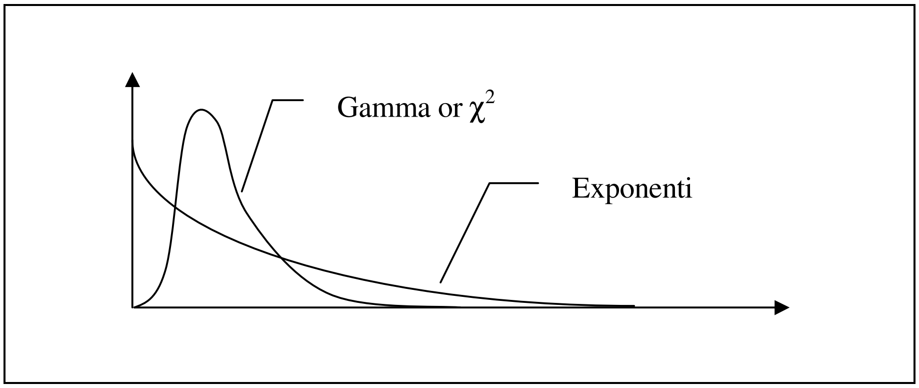
- Another special case of the gamma distribution is the χ^2 distribution. Let $\alpha = \nu/2$ and $\beta = 2$, it
- results in the χ^2 distribution:

$$f(x) = \frac{1}{2^{\nu/2}\Gamma(\nu/2)} x^{\nu/2-1} e^{-x/2}, \ x > 0$$

its mean and variance are as follows:

$\mu = \nu$

$\sigma^2 = 2\nu$



(d) **Weibull distribution**: It has assumption similar to Gamma function.

- The probability density function:

$$f(x) = \frac{\gamma}{\theta} x^{\gamma-1} e^{-x^{\gamma}/\theta}, \quad x > 0$$
$$= 0, \quad \text{otherwise}$$

- The probability function:

$F(x) = 1 - \exp(-x^{\gamma}/\theta), x > 0$

- The mean and variance

$$E(X) = \theta^{1/\gamma}\, \Gamma(1 + \frac{1}{\gamma})$$

$$V(X) = \theta^{2/\gamma} \{\Gamma(1 + \frac{2}{\gamma}) - [\Gamma(1 + \frac{1}{\gamma})]^2\}$$

- Application in reliability, defining:

f(t) - the pdf of failure

F(t) - the pf of failure

R(t) = 1 - F(t) - the probability of no failure (reliability function) r(t) = f(t) / R(t) - the failure rate function

if:

$$r(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1 - F(t)} = \frac{1}{\theta}$$

then f(t) will be exponential.

- Proof: since

$dF(t)/dt = f(t)$

$\theta \bullet F'(t) = 1 - F(t)$

$\theta \bullet F'(t) + F(t) = 1$

solving the above gives:

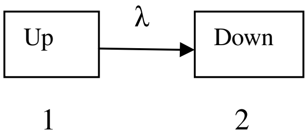
$F(t) = 1 - \exp(-t/\theta), t \geq 0$

or

$f(t) = 1/\theta \exp(-t/\theta), t \geq 0$

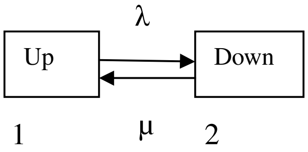
Appendix-2: Basic terms

Reliability, R(t): It is the probability that an item will perform its intended function without failure under stated conditions for a specified period of time.

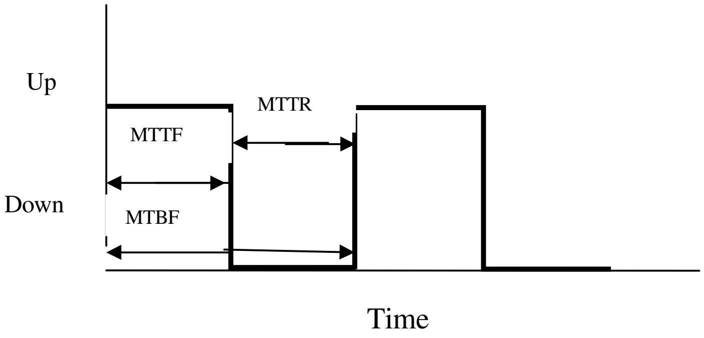


$$R(t) = e^{-\lambda t}$$

Availability: It is the probability of finding system in the operating state at some time in to future.



$$A(t) = \frac{\mu}{\lambda+\mu} + \frac{\mu}{\lambda+\mu} e^{-(\lambda+\mu)t}$$



$$\text{MTTF} = \frac{\text{Total up time}}{\text{No.of failures}} = \frac{1}{\lambda}$$

$$\text{MTBF} = \frac{1}{F_{\text{Failure}}}$$

$$\text{MTTR} = \text{average repair time} = \frac{\text{Total down time}}{\text{No.of failures}} = \frac{1}{\mu}$$

Continuous Markov Process

Many systems exists continuously in a state (i.e. continuous in time) until a transition takes it to another state.

$$\text{Transition Rate} = \frac{\text{No. of transitions from a given state}}{\text{time spent in that state}}$$

$$\lambda = \frac{\text{No. of failures of the component in a given period of time}}{\text{total period of time the component was operating}}$$

$$\mu = \frac{\text{No. of repairs in a given period of time}}{\text{total period of time the component was under repair}}$$

$$\text{MTTF} = \frac{\text{Total up time}}{\text{No.of failures}} = \frac{1}{\lambda}$$

$$\text{MTTR} = \frac{\text{Total down time}}{\text{No.of failures}} = \frac{1}{\mu}$$

Failure: The termination of the ability of an item to perform its required function as specified.

Failure rate: The ratio of the number of failures within a sample to the cumulative operating time.

Hazard rate: The “instantaneous” probability of failure of an item given that it has survived up until that time. Sometimes, called the instantaneous failure rate.

Probability density function (PDF): the frequency distribution and cumulative distribution are calculated from sample measurements. Since samples are drawn from a population, the question is what

MTBF (Mean Time Between Failure)

It is a reliability term used to provide the amount 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. MTBF is more important for industries when equipments such as media converters or switches are installed into mission critical applications. It is the measure of rate of failure within the design life.

MTTF (Mean Time To Failure)

It is a basic measure of reliability for non-repairable systems. It is the mean time expected until the first failure of a component of a system. MTTF is a statistical value and is meant to be the mean over a long period of time and a large number of units. Technically, MTBF should be used only in reference to a repairable item, while MTTF should be used for non-repairable items. It is the ration of the cumulative operating time to the number of failures for a group of items. However, MTBF is commonly used for both repairable and non-repairable items.

Appendix-3: Computation of parameters

The various parameters for skim milk powder production system are computed as:

(a) **Reliability**: The skim milk powder system has twenty states as shown in state transition diagram (Fig. 4.1).

- Each state of the system is represented by an equation as given by eqns. from 4.1.1 to 4.1.8 (i.e. the system of equations carries 20 equations).
- These 20 equations carry 20 unknown parameters (i.e. P_o to P_{19}).
- These 20 equations are solved simultaneously under boundary or initial conditions by applying Rnnga-Kutta fourth order method using MATLAB software (2010 a).
- The reliability of the system is the sum of the reliabilities of system under working and its standby states as given by the equation 4.1.10.

(b) **Availability:** The steady state equations (i.e. eqns from 4.1.11 to 4.1.18) of the system are obtained by imposing the following restrictions; $d/dt \rightarrow 0$, as $t \rightarrow \infty$ to the equations (4.1.1)- (4.1.8).

- The values of P_1, P_2 and P_3 in terms of P_o are expressed by solving them by recursive method.
- The value of P_o is computed under normalized conditions i.e. by using equation 4.1.22.
- The availability of the system is the sum of availabilities of the working and standby states (refer eqn. 4.1.23).

(c) **RAMD:** The skim milk powder production system is divided in to four subsystems; S1, S2, S3 and S4.

- The state transition diagrams are drawn and differential equations are developed similarly as mentioned earlier.
- The equations for availability, reliability and maintainability are developed and shown by equations 4.1.31 to 4.1.33.
- The value of dependability is calculated based on equation 1.4

(d) **Fuzzy Reliability**

- The skim milk powder system has twenty states as shown in state transition diag. 4.4.
- Each state of the system is represented by an equation as given by eqn. from 4.1.62 to 4.1.69 (i.e. the system of equations carries 20 equations).
- These 20 equations carry 20 unknown parameters (i.e. P_1 to P_{20}).
- These 20 equations are solved simultaneously under boundary or initial conditions by applying Rnnga-Kutta fourth order method using MATLAB software (2010 a).
- The reliability of the system is the sum of the reliabilities of system under working and its standby states as given by the equation 4.1.71.

BRIEF POFILE OF THE RESEARCH SCHOLAR

Mr. Anil Kr. Aggarwal is presently working as Director/Principal at Pt. L.R. College of Technology (Technical Campus), Sohna-Samaypur road, Ballabgarh, Faridabad (India). He is the former director of Rattan Institute of Technology and Management, Hodal, Palwal, Haryana and founder director of AERP Institute of Technology and Management (Polytechnic), Hodal, Palwal, Haryana. He received his B.E. (Mech.) from Jamia Millia Islamia (a central university), New Delhi, India and M.Tech. (Production) from GNDEC, Ludhiana, Punjab. He has published approx. 15 papers in reputed journals/conferences. He has about 15 years of teaching experience in reputed engineering colleges. He is perusing his Ph.D. in Mechanical Engineering from Mechanical Engineering deptt., YMCA University of Science &Technology, Faridabad, India.

LIST OF PUBLICATIONS OUT OF THESIS

List of Papers Published in International Journals (09)

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	Anil Kr. Aggarwal, Sanjeev Kumar and Vikram Singh (2015), "Performance modeling of the Skim milk powder production system of a dairy plant using RAMD analysis", International Journal of Quality & Reliability Management, Vol. 32, Issue 2, pp. 167-181.	Emerald	-	Referred	No	Available online at Emerald website
2	Anil Kr. Aggarwal, Sanjeev Kumar and Vikram Singh (2016), "Reliability and availability analysis of the serial processes in Skim milk powder system of a dairy plant: a case study", International Journal of Industrial and Systems Engineering, Vol. 22, No. 1, pp. 36-62.	Inderscience	-	Referred	No	Available online at Inderscience website
3	Anil Kr. Aggarwal, Sanjeev Kumar and Vikram Singh (2016), "Mathematical modeling and fuzzy availability analysis of Skim milk powder system of a dairy plant", International Journal of System Assurance Engineering and Management. Vol. 7, No. 1, pp. 322-334.	Springer	-	Referred	No	Available online at Springer website
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9	Anil Kr. Aggarwal, Sanjeev	YMCAUST	-	Referred	No	Available

	Kumar and Vikram Singh (2016), “Mathematical Modeling and Performance Optimization for Steam Generation System of A Dairy Plant”, YMCAUST International Journal of Research, Vol. 4, Issue 1.					online at YMCAUST website

List of Papers Published in International Conferences (01)

S. N.	Title of the paper	Conference Name	Publisher
1	Anil Kr. Aggarwal, Sanjeev Kumar and Vikram Singh (2013), Performance modeling and availability analysis of Skim milk powder production system of a diary plant	International Conference held on “Chemical, Environmental and Bioprocess Engineering” (Dec. 21-22, 2013)	Krishi Sanskriti, JNU, New Delhi

List of Papers Published in National Conferences (03)

S. No	Title of the paper	Conference Name	Publisher
1	Anil Kr. Aggarwal, Sanjeev Kumar and Vikram Singh (2015), Performance modeling and optimization for the Skim milk powder production system of a dairy plant	National Conference held on Recent trends in mechanical engineering-2015 (Jan. 24, 2015)	Rawal Institute of Engineering and Tech., Faridabad
2	Anil Kr. Aggarwal, Sanjeev Kumar and Vikram Singh (2014), Markov modeling and availability analysis of pasteurized milk production system of a dairy plant	National Conference held on Emerging Technologies 2014 (Aug. 01-02, 2014)	Government Engg. college, Barton hill, Trivandrun-695035
3	Anil Kr. Aggarwal, Sanjeev Kumar and Vikram Singh (2014), A Markov model for performance evaluation of a Butter oil production system of a dairy plant	National Conference held on Emerging Technologies in Mechanical Engineering (Jan. 24-25 2014)	Echelon Institute of Tech., Faridabad

List of Papers communicated in International Journals (01)

S. No	Title of the paper	Publisher	Impact factor	Referred or Non-Referred	Whether you paid any money or not for publication	Remarks
1	Anil Kr. Aggarwal, Sanjeev Kumar and Vikram Singh (2016), “Mathematical modeling and RAM analysis for serial processes in Refrigeration system of a dairy plant”, YMCAUST International Journal of Research	YMCAUST	-	Referred	No	