PERFORMANCE MODELING OF CRYSTALLIZATION SYSTEM IN SUGAR PLANT USING RAMD APPROACH

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Abstract

The aim of the present study is to investigate reliability, availability, maintainability, and dependability (RAMD) of crystallization system of a sugar production plant. Previous studies attentive on the reliability and availability analysis of sugar plants specially its subsystems like evaporation units. This study is focus on the RAMD analysis of the crystallization system of sugar plant having four subsystems with different number of components. Failure and repair rates of all subsystems are taken as exponentially distributed. The transition diagram and Chapman-Kolmogorov differential equations for each subsystem are derived by using Markov birth-death process. For all four subsystems, reliability, availability, mean time between failure (MTBF), mean time to repair (MTTR), and dependability ratio are computed using simple probabilistic concepts. The effect of change in failure rates of subsystem in system performance is also observed. It is shown that the crystallization subsystem found to be more sensitive among four subsystems from reliability point of view. This study can be helpful to system designer for further modeling/designing of reliable systems and enhancement in system's performance through planning efficient maintenance strategies.

Keywords: Mean Time Between Failures, Reliability, Availability, Maintainability, Dependability

I. Introduction

India's economy is primarily agrarian. Agriculture accounts for roughly 20% of the GDP. Agriculture encompasses activities such as cultivating crops, raising poultry, fishing, breeding cattle, and practicing animal husbandry. These actions are critical to our country's survival. The Indian economy has expanded significantly in recent decades. The improvement of agriculture and allied operations to meet international standards has also resulted in a rise in the export of various food products, which has fuelled economic growth. One of the most well-known industries is sugar, of which India is now the world's largest producer, consumer, and exporter. In India, the sugar industry is an agriculture-based industry that has a big influence on the rural economy. Millions of workers and farmers who cultivate sugarcane are impacted by this industry. The sugar manufacturing process involves multiple stages such as extraction, clarification, boiling, crystallization, centrifuging, grading, weighing, and bagging. Achieving maximum production levels and ensuring high system availability are crucial in the manufacturing sector. Industries are configured with several different types of heavy machinery. The primary concern of manufacturing industries is the reliability of these machines. RAMD techniques are widely used by researchers to evaluate the systems performance. This technique effectively assesses the reliability and availability of individual components in complex systems. Nowadays, systems are becoming increasingly complex in structure. So, it became very necessary to identify the most critical component and carry forward the maintenance strategies on time for a flawless process of production.

Bradley and Dawson [1] Rolls-Royce study discovered that most PC components failed more frequently early in life, resulting in higher beginning operating costs, and suggested a rolling replacement approach to spread costs fairly. Blischke and Murthy [2] investigated dependability, maintenance, maintainability, and quality, focusing on practical challenges within these domains. Each example emphasized reliability and practical project implications. Bhamare et al. [3] evaluated historical achievements in reliability engineering, investigated statistical and fuzzy logic methodologies, and indicated limitations and potential for future research in reliability analysis. Sharma and Kumar [4] highlighted the significance of the RAM approach in modeling engineering systems and enhancing performance. Adhikary et al. [5] investigated RAM indices of 210-megawatt coal-fired thermal power stations to improve the availability of power plants. Sharma and Sharma [6] proposed a MSDM (multi-stage decision-making) model to incorporate a framework for optimizing RAM and cost decisions in a process plant. Kumar [7] created many stochastic computer system models based on the notion of maximum operation and maintenance times. Sharma and Khanduja [8] discussed the efficacy and availability of feeding systems in the sugar industry. Sharma and Vishwakarma [9] emphasized the use of Markov processes and optimization in the refining system of the sugar industry to provide maximum system productivity.

Aggarwal et al. [10] developed a performance model utilizing the RAMD approach for manufacturing skim milk powder systems. This research assisted in identifying the crucial subsystem and its impact on the system's performance under actual operating conditions. Kadyan and Kumar [11] used the SVA (supplementary variable approach) and the Markov process to analyze the availability and profitability of a feeding system in the sugar sector. Ram and Kumar [12] investigated the performability of a system using the 1-out-of-2: G strategy and evaluated the reliability measures for each subsystem. Parida et al. [13] conducted a thorough evaluation of the literature on performance measurement and management in maintenance. Kumar and Saini [14] suggested a sugar plant mathematical model to assess availability using a fuzzy reliability technique. Kadyan and Kumar [15] analyzed the operational behavior of availability and expected profit analysis of a B-Pan crystallization system by using the Markovian technique. Tsarouhas and Besseris [16] provided comprehensive maintainability analysis of the shaving blade section of a high-tech razor manufacturing plant and focused on identifying the areas for improvement. Tsarouhas [17] developed RAM analysis to improve the performance of the wine packaging line by using datasets from the production system. Choudhary et al. [18] examined the effectiveness of RAM analysis for capacity improvement of a cement plant. Dahiya et al. [19] analyzed the performance and profit analysis of the feeding system of sugar plants by using the concept of coverage factor.

Saini et al. [20] derived the reliability, availability, maintainability, and dependability of a microprocessor system made up of seven subsystems, utilizing state transition diagrams and Markov processes to calculate important performance measures. Kumar et al. [21] developed a stochastic model to carry out RAMD analysis and FME (failure mode and effect) analysis of tube-well integrated pipelines. Saini et al. [22] studied failure patterns, best-fit distributions, and suggested maintenance solutions of a sugar plant on the basis of six months data. Gao [23] analyzed a fault-tolerant system with warm standbys, determining its steady-state availability, reliability function, and mean time to first failure using Markov theory and Laplace transforms. Yusuf et al. [24] analyzed two hybrid systems using the RAMD framework and found that evaluating and comparing these systems helped identify improvement opportunities for enhancing operational efficiency and productivity.

This study is focused on the RAMD analysis of the crystallization system of the sugar plant, which has four subsystems with different numbers of components. Failure and repair rates of all subsystems are taken as exponentially distributed. The transition diagram and Chapman-Kolmogorov differential equations for each subsystem are derived by using the Markov birth-death process. For all four subsystems, reliability, availability, mean time between failure (MTBF), mean time to repair (MTTR), and dependability ratio are computed using simple probabilistic concepts. The effect of changes in failure rates of subsystems on system performance is also observed. It is shown that the crystallization subsystem was found to be more sensitive among four subsystems from a reliability point of view. Findings of this study can assist system designers in developing reliable systems and improving performance by implementing efficient maintenance strategies.

The whole manuscript is divided into five sections. An introduction to the system is appended in Section 1. Materials, methods, and system description are presented in Section 2. Section 3 incorporates the mathematical modeling and RAMD analysis of the system, and results are shown in tabular form. Section 4 covers the discussion and conclusion part of the study.

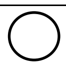
II. Material and Methods

The techniques used for investigation are described as follows:

I. Notations

The following nomenclature is used to develop the state transition diagram and mathematical modeling of system.

Table 1: *Notations for paint manufacturing plant's sub-system*

	System is in working condition with full capacity
	Failure state of system
U, Z, G, W	Fully working states of the subsystems
U_1, U_2, Z_1, Z_2	States where one or two failed unit of subsystem A and B goes under repair
u, z, g, w	Completely failed states of subsystems
$\alpha_1, \alpha_2, \alpha_3, \alpha_4$	Constant failure rates of subsystems A, B, C and D respectively
$\beta_1, \beta_2, \beta_3, \beta_4$	Constant repair rates of subsystems A, B, C and D respectively
$P_1(t)$	Probability of the initial state of the system working with full capacity
P_i ; i=1, 2, 3, 4	Steady state probability of i[th] state of the system
$f(x) = \begin{cases} \theta e^{-\theta x} & 0 \le x \le \infty \\ 0 & otherwise \end{cases}$	PDF of exponential distribution Here θ =constant rate in failure per unit of measurement
$R(t) = P(T < t) = \int_t^\infty f(x)dx \;\; or \;\; R(t) = e^{-\alpha t}$	Reliability function, here α = failure rate
$\frac{MTTF}{MTTF+MTTR} = \frac{Life\ time}{Life\ time+Repair\ time}$	Availability function
$M(t) = P(T < t) = 1 - e^{\frac{-t}{MTTR}}$	Maintainability function
$MTBF = \int_0^\infty R(t)dt = \int_0^\infty e^{-\alpha t}dt = \frac{1}{\alpha}$	Mean time between failure
$MTTR = \frac{1}{\beta}$	Mean time to repair, here β = Repair rate
$d = \frac{MTBF}{MTTR} = \frac{\beta}{\alpha}$	Dependability ratio
$D_{min} = 1 - \left(\frac{1}{d-1}\right)\left(e^{\frac{-In\, d}{(d-1)}} - e^{\frac{-d\, In\, d}{(d-1)}}\right)$	

II. System Description

This section contains the detailed description of crystallization unit of a sugar production plant. It is a prominent part of process in which raw sugar syrup converted in different size of crystal and impurities are separated by different processes. All subsystems are arranged in a series configuration. The representation of components is in figure 1.

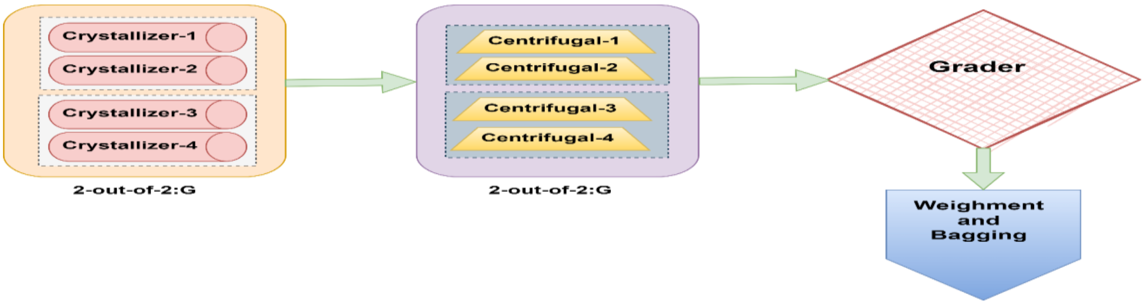


Figure 1: *Configuration block diagram of Crystallization System*

i) Crystallizer (A)

The raw sugar syrup which is produced after evaporation process now transferred to large rotating vessels for cooldown evenly. The next step is seeding, which is done in three steps. The initial crystallization produces crystallized sugar and molasses, or residuals. When the molasses and crystals separate, the liquid is prepared for the next step. This subsystem is configured as 2-out-of-2: G system. It consists of a total of four units, out of which two are in operation and two are in cold standby. The failure and repair rate of all the units are same. The failure of more than two units lead to the complete failure of the system. The differential equations of subsystem crystallizer are calculated by using state transition diagram given in figure 2.

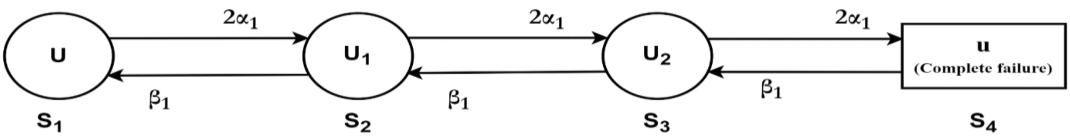


Figure 2: *State transition diagram of crystallizer subsystem*

ii) Centrifugal machine (B)

In this process the liquid syrup is separated from the sugar crystals and then the syrup coating is removed by using fine jet of water. The centrifuged raw sugar contains 97-99% of sucrose and 0.5% of moisture. The amount of molasses left on the crystals determines the type of sugar produced. This can be further stored in bags or bulk. This subsystem is also configured as 2-out-of-2: G system. It consists of a total of four units with same failure and repair rates. Among four units, two are in operation and two are on cold standby. The system faces complete failure if more than two units goes under failure. The differential equations of subsystem centrifugal machine are calculated by using state transition diagram given in figure 3.

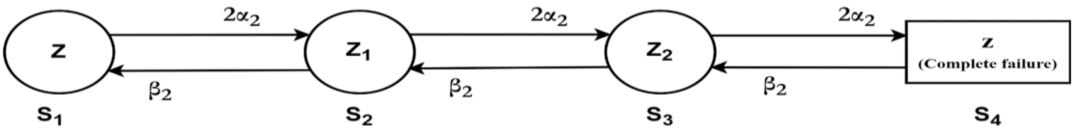


Figure 3: *State transition diagram of centrifugal machine*

iii) Grader (C)

The resulting sugar is made up of heterogeneous crystals and must be sieved and graded before it's packaging. The primary goal is particle size classification, which is accomplished using screens. Typically, classification is accomplished by using wire mesh or perforated plate through which particles smaller than the screen aperture may pass while the biggest fraction is carried over the surface. This subsystem has single unit in operation with constant failure and repair rates. The failure of this unit leads to the failure of entire system. The differential equations of subsystem grader are calculated by using state transition diagram given in figure 4.

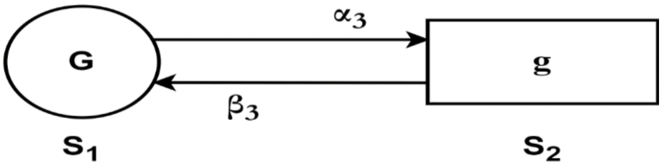


Figure 4: *State transition diagram of grader*

iv) Weighment and bagging (D)

Some of the most difficult aspects of bagging sugar include clean filling, dust reduction, and equipment cleanliness. Raw sugar is carried as both bulk and break-bulk freight. Raw sugar is packaged as break-bulk cargo in bags made of woven natural materials (such as jute) or woven plastic bags with a plastic inner liner that is impermeable to water vapor and provides contamination prevention. This subsystem has single unit in operation with constant failure and repair rates. The failure of this unit leads to the complete failure of system. The differential equations of subsystem grader are calculated by using state transition diagram given in figure 5.

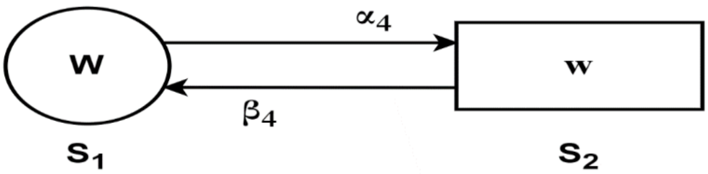


Figure 5: *State transition diagram of weighment and bagging*

III. Assumptions

The system is assumed to worked under the following conditions:

- At time t=0, all subsystems are functioning properly without facing any failure.
- All the failure and repair rates are chosen as arbitrary and distributed exponentially.

- Cold standby redundancy is operated at the component level for subsystem crystallizer and centrifugal machine.
- Repairs are flawless. Failed unit works properly as new after repair.

Table 1: *Failure and repair rates of subsystems*

Sr. No.	Sub-system	Failure-rate (α)	Repair-rate (β)
1	Crystallizer (A)	α_1 = 0.0095	β_1 = 0.53
2	Centrifugal machine (B)	α_2 = 0.0088	β_2 = 0.69
3	Grader (C)	α_3 = 0.0075	β_3 = 0.71
4	Weighment and bagging (D)	α_4 = 0.0091	β_4 = 0.81

III. Mathematical Modeling and RAMD Analysis

In this section, RAMD investigation through development of mathematical models of crystallization subsystem of sugar production plant is investigated. The Markov birth-death process is used to derive the Chapman-Kolmogorov differential equations. Transition diagram for each four subsystems is displayed in figures 2-5. Failure and repair rates of the subsystems are taken as exponential distributed and appended in table 1. The RAMD indices of all four subsystems are shown in table 2. Table 3 shows the variation in reliability with respect of time. The effect of change in failure rates of different subsystems on system's performance, are appended in tables 4-8.

i) RAMD indices for subsystem 1 (SS_1)

This subsystem named crystallizer and is configured as 2-out-of-2: G and has two standby units. If one of the operating units fails, then one standby unite comes in operation and if both working unit goes down then both cold standby units come in operation. Failure of any of the single unit after this leads to complete system failure. The failure and repair rates of units are same. The Chapman-Kolmogorov differential equations are derived by using figure 1 and relations are given below

$$P_1'(t) = -2\alpha_1 P_1(t) + \beta_1 P_2(t) \quad (1)$$

$$P_2'(t) = -(2\alpha_1 + \beta_1)P_2(t) + 2\alpha_1 P_1(t) + \beta_1 P_3(t) \quad (2)$$

$$P_3'(t) = -(2\alpha_1 + \beta_1)P_3(t) + 2\alpha_1 P_2(t) + \beta_1 P_4(t) \quad (3)$$

$$P_4'(t) = -\beta_1 P_4(t) + 2\alpha_1 P_3(t) \quad (4)$$

By using initial condition and $t \to \infty$ we get reduced equations

$$-2\alpha_1 P_1 + \beta_1 P_2 = 0 \quad (5)$$

$$-(2\alpha_1 + \beta_1)P_2 + 2\alpha_1 P_1 + \beta_1 P_3 = 0 \quad (6)$$

$$-(2\alpha_1 + \beta_1)P_3 + 2\alpha_1 P_2 + \beta_1 P_4 = 0 \quad (7)$$

$$-\beta_1 P_4 + 2\alpha_1 P_3 = 0 \quad (8)$$

By using normalization condition

$$P_1 + P_2 + P_3 + P_4 = 1 \quad (9)$$

After putting values of P_2, P_3 and P_4 in terms of P_1 in equation (9), we get

$$P_1 = \frac{1}{1+\frac{2\alpha_1}{\beta_1}+\frac{4\alpha_1^2}{\beta_1^2}+\frac{8\alpha_1^3}{\beta_1^3}} \quad (10)$$

Availability of SS_1 will be

$$A_{ss_1} = P_1 + P_2 + P_3$$

$$A_{ss_1} = \frac{1+\frac{2\alpha_1}{\beta_1}+\frac{4\alpha_1^2}{\beta_1^2}}{1+\frac{2\alpha_1}{\beta_1}+\frac{4\alpha_1^2}{\beta_1^2}+\frac{8\alpha_1^3}{\beta_1^3}} \quad (11)$$

After putting values of failure and repair rates

$$A_{ss_1} = 0.9999556 \quad (12)$$

Reliability of SS_1 is driven by using the formula,

$$R_{ss_1}(t) = e^{-0.057\times t} \tag{13}$$

The maintainability of SS_1 is,

$$M_{ss_1}(t) = 1 - e^{-1283.15\times t} \tag{14}$$

Now some different measures of system effectiveness of SS_1 are derived by using equations mention above in notation section are as follows, MTBF= 17.5438596h, MTTR= 0.0007793h, d=22511.94 and $D_{min}(ss_1)$=0.999956

ii) RAMD indices for subsystem 2 (SS_2)

Subsystem 2 is a centrifugal machine and has two operating unit and two standby units. The failure of more than two unit is considered as the complete failure of system. The differential equations are derived by using figure 2 and different reliability measures are derived.

$$P_1'(t) = -2\alpha_2 P_1(t) + \beta_2 P_2(t) \tag{15}$$

$$P_2'(t) = -(2\alpha_2 + \beta_2)P_2(t) + 2\alpha_2 P_1(t) + \beta_2 P_3(t) \tag{16}$$

$$P_3'(t) = -(2\alpha_2 + \beta_2)P_3(t) + 2\alpha_2 P_2(t) + \beta_2 P_4(t) \tag{17}$$

$$P_4'(t) = -\beta_2 P_4(t) + 2\alpha_2 P_3(t) \tag{18}$$

By using initial condition and $t \to \infty$ we get

$$-2\alpha_2 P_1 + \beta_2 P_2 = 0 \tag{19}$$

$$-(2\alpha_2 + \beta_2)P_2 + 2\alpha_2 P_1 + \beta_2 P_3 = 0 \tag{20}$$

$$-(2\alpha_2 + \beta_2)P_3 + 2\alpha_2 P_2 + \beta_2 P_4 = 0 \tag{21}$$

$$-\beta_2 P_4 + 2\alpha_2 P_3 = 0 \tag{22}$$

By using normalization condition

$$P_1 + P_2 + P_3 + P_4 = 1 \tag{23}$$

After putting values of P_2, P_3 and P_4 in terms of P_1 in equation (23), we get

$$P_1 = \frac{1}{1+\frac{2\alpha_2}{\beta_2}+\frac{4\alpha_2{}^2}{\beta_2{}^2}+\frac{8\alpha_2{}^3}{\beta_2{}^3}} \tag{24}$$

Availability expression for SS_2 will be

$$A_{ss_2} = P_1 + P_2 + P_3 \tag{25}$$

$$A_{ss_2} = \frac{1+\frac{2\alpha_2}{\beta_2}+\frac{4\alpha_2{}^2}{\beta_2{}^2}}{1+\frac{2\alpha_2}{\beta_2}+\frac{4\alpha_2{}^2}{\beta_2{}^2}+\frac{8\alpha_2{}^3}{\beta_2{}^3}} \tag{26}$$

After putting values of failure and repair rates

$$A_{ss_2} = 0.9999838 \tag{27}$$

Reliability of SS_2 is given by

$$R_{ss_2}(t) = e^{-0.0528\times t} \tag{28}$$

The maintainability of SS_2 is,

$$M_{ss_2}(t) = 1 - e^{-3264.81\times t} \tag{29}$$

Now, some different measures of system effectiveness of SS_2 are as follow, MTBF= 18.9394h, MTTR= 0.0003063h, d=61833.4 and $D_{min}(ss_2)$=0.999984

iii) RAMD indices for subsystem 3 (SS_3)

Here, grader machine is taken as a subsystem 3. It has only one unit in operation and failure of this unit leads to complete system failure. The differential equations are derived by using figure 3. The relations are as follows,

$$P_1'(t) = -\alpha_3 P_1(t) + \beta_3 P_2(t) \quad (30)$$
$$P_2'(t) = -\beta_3 P_2(t) + \alpha_3 P_1(t) \quad (31)$$
using initial condition $t \to \infty$ and we get
$$-\alpha_3 P_1 + \beta_3 P_2 = 0 \quad (32)$$
$$-\beta_3 P_2 + \alpha_3 P_1 = 0 \quad (33)$$
using normalization condition
$$P_1 + P_2 = 1 \quad (34)$$
After putting values of P_2 in terms of P_1 in equation (34), we get
$$P_1 = \frac{\beta_3}{\beta_3 + \alpha_3} \quad (35)$$
Availability expression for SS3 will be
$$A_{ss_3} = P_1 \quad (36)$$
$$A_{ss_3} = \frac{\beta_3}{\beta_3 + \alpha_3} \quad (37)$$
After putting values of failure and repair rates
$$A_{ss_3} = 0.989547 \quad (38)$$
Reliability of SS3 is,
$$R_{ss_3}(t) = e^{-0.0075 \times t} \quad (39)$$
The maintainability of SS3 is,
$$M_{ss_3}(t) = 1 - e^{-0.71 \times t} \quad (40)$$

Now some different measures of system effectiveness of SS3 are calculated as follow, MTBF= 133.333h, MTTR= 1.4084507h, d=94.6667 and $D_{min}(ss_3)$=0.990995

iv) RAMD indices for subsystem 4 (SS4)

Weighment and bagging machine are considered as subsystem 4. It consists single unit in operation and failure of this unit leads to complete system failure. The differential equations are derived by using figure 4. The relations are given below,
$$P_1'(t) = -\alpha_4 P_1(t) + \beta_4 P_2(t) \quad (41)$$
$$P_2'(t) = -\beta_4 P_2(t) + \alpha_4 P_1(t) \quad (42)$$
using initial condition $t \to \infty$ and we get,
$$-\alpha_4 P_1 + \beta_4 P_2 = 0 \quad (43)$$
$$-\beta_4 P_2 + \alpha_4 P_1 = 0 \quad (44)$$
using normalization condition
$$P_1 + P_2 = 1 \quad (45)$$
After putting values of P_2 in terms of P_1 in equation (45), we get
$$P_1 = \frac{\beta_4}{\beta_4 + \alpha_4} \quad (46)$$
Availability expression for SS4 will be,
$$A_{ss_4} = P_1 \quad (47)$$
$$A_{ss_4} = \frac{\beta_4}{\beta_4 + \alpha_4} \quad (48)$$
After putting values of failure and repair rates
$$A_{ss_4} = 0.9888902 \quad (49)$$
Reliability of SS4 is driven as,
$$R_{ss_4}(t) = e^{-0.0091 \times t} \quad (50)$$
The maintainability of SS4 is,
$$M_{ss_4}(t) = 1 - e^{-0.81 \times t} \quad (51)$$

Now some different measures of system effectiveness of SS4 are derived as, MTBF= 109.89h, MTTR= 1.234567h, d=89.011 and $D_{min}(ss_4)$=0.9904687

v) System's reliability

The proposed subsystems are connected in series combination and failure of any one of them leads to the complete failure of the system. The overall reliability of the system is derived by,

$$R_{System}(t) = R_{ss_1}(t) \times R_{ss_2}(t) \times R_{ss_3}(t) \times R_{ss_4}(t) \quad (52)$$

By putting values in equation (52), we get system reliability as,

$$R_{System}(t) = e^{-0.1264(t)} \quad (53)$$

The variation in reliability with respect to time is derived and shown in table 3.

vi) System's availability

Here four subsystems are connected in series combination and the availability of each one is calculated separately. Now the availability of the entire system is derived and the expression is as follow

$$A_{System}(t) = A_{ss_1}(t) \times A_{ss_2}(t) \times A_{ss_3}(t) \times A_{ss_4}(t) \quad (54)$$

By putting values in equation (54), we get the availability of the system as below,

$$A_{System}(t) = 0.9784944 \quad (55)$$

vii) System's maintainability

The four subsystems are linked in series and the failure of one cause the entire system to fail. The maintainability of entire system is calculated and is given below

$$M_{System}(t) = M_{ss_1}(t) \times M_{ss_2}(t) \times M_{ss_3}(t) \times M_{ss_4}(t) \quad (56)$$

$$M_{System}(t) = 1 - e^{-2409232.47 \times t} \quad (57)$$

viii) System's dependability

The dependability of entire system is derived by multiplying the dependability of each subsystem. It is given by

$$D_{min(system)}(t) = D_{min(ss_1)}(t) \times D_{min(ss_2)}(t) \times D_{min(ss_3)}(t) \times D_{min(ss_4)}(t) \quad (58)$$

$$D_{min(system)}(t) = 0.981491 \quad (59)$$

Table 2: *RAMD indices for subsystems of sugar plant systems*

Subsystems	**Ss1**	**Ss2**	**Ss3**	**Ss4**	**System**
Reliability	$e^{-0.057 \times t}$	$e^{-0.0528 \times t}$	$e^{-0.0075 \times t}$	$e^{-0.0091 \times t}$	$e^{-0.1264(t)}$
Availability	0.9999556	0.9999838	0.989547	0.9888902	0.9784944
Maintainability	$1 - e^{-1283.15 \times t}$	$1 - e^{-3264.81 \times t}$	$1 - e^{-0.71 \times t}$	$1 - e^{-0.81 \times t}$	$1 - e^{-2409232.47 \times t}$
Dependability	0.999956	0.999984	0.990995	0.9904687	0.981491
MTBF	17.5439h	18.9394h	133.333h	109.89h	279.7059h
MTTR	0.0007793h	0.0003063h	1.408451h	1.234567h	2.644103h
Dependability ratio (d)	d=22511.94	61833.4	94.6667	89.011	

Table 3: *Variation in reliability with respect to time*

Time (days)	**Ss1**	**Ss2**	**Ss3**	**Ss4**	**system**
0	1	1	1	1	1
30	0.7520143	0.7679735	0.7985162	0.7610928	0.3509892

60	0.5655254	0.5897834	0.6376282	0.5792622	0.1231934
90	0.4252832	0.452938	0.5091564	0.4408723	0.0432395
120	0.319819	0.3478444	0.4065697	0.3355447	0.0151766
150	0.2405085	0.2671353	0.3246525	0.2553807	0.0053268

Table 4: *Variation of maintainability with respect time*

Time (days)	M_{ss_1}	M_{ss_2}	M_{ss_3}	M_{ss_4}	M_{system}
0	0	0	0	0	0
30	1	1	0.999999999	1	1
60	1	1	1	1	1
90	1	1	1	1	1
120	1	1	1	1	1
150	1	1	1	1	1

Table 5: *Effect of change in failure rates on subsystem and system reliability*

Time (days)	Subsystem 1				System			
	α_1=0.0075	α_1=0.0085	α_1=0.0095	α_1=0.0105	α_1=0.0075	α_1=0.0085	α_1=0.0095	α_1=0.0105
30	0.7985162	0.7749165	0.7520143	0.7297889	0.3726931	0.3616783	0.3509891	0.3406158
60	0.6376282	0.6004956	0.5655254	0.5325918	0.1389002	0.1308113	0.1231934	0.1160192
90	0.5091564	0.4653339	0.4252832	0.3886796	0.0517671	0.0473116	0.0432396	0.0395180
120	0.4065697	0.3605949	0.319819	0.283654	0.0192933	0.0171116	0.0151766	0.0134604
150	0.3246525	0.279431	0.2405085	0.2070076	0.0071905	0.0061889	0.0053268	0.0045848

Table 6: *Effect of change in failure rates on subsystem and system reliability*

Time (days)	Subsystem 2				System			
	α_2=0.0068	α_2=0.0078	α_2=0.0088	α_2=0.0098	α_2=0.0068	α_2=0.0078	α_2=0.0088	α_2=0.0098
30	0.8154624	0.7913618	0.7679735	0.7452765	0.3726931	0.3616784	0.3509891	0.3406159
60	0.6649789	0.6262535	0.5897834	0.555437	0.1389002	0.1308112	0.1231934	0.1160191
90	0.5422653	0.4955931	0.452938	0.4139542	0.0517671	0.0473116	0.0432395	0.0395180
120	0.4421969	0.3921935	0.3478444	0.3085103	0.0192932	0.0171116	0.0151766	0.0134604
150	0.3605949	0.3103669	0.2671353	0.2299255	0.0071905	0.0061889	0.0053268	0.0045848

Table 7: *Effect of change in failure rates on subsystem and system reliability*

Time (days)	Subsystem 3				System			
	α_3=0.0055	α_3=0.0065	α_3=0.0075	α_3=0.0085	α_3=0.0055	α_3=0.0065	α_3=0.0075	α_3=0.0085
30	0.8478937	0.8228347	0.7985162	0.7749165	0.3726931	0.3616784	0.3509891	0.3406158
60	0.7189237	0.6770569	0.6376282	0.6004956	0.1389001	0.1308112	0.1231934	0.1160191
90	0.6095709	0.5571059	0.5091564	0.4653339	0.0517671	0.0473116	0.0432395	0.0395179
120	0.5168513	0.458406	0.4065697	0.3605949	0.0192933	0.0171116	0.0151766	0.0134604
150	0.438235	0.3771924	0.3246525	0.279431	0.0071905	0.0061889	0.0053268	0.0045848

Table 8: *Effect of change in failure rates on subsystem and system reliability*

Time (days)	Subsystem 4				System			
	α_4=0.0071	α_4=0.0081	α_4=0.0091	α_4=0.0101	α_4=0.0071	α_4=0.0081	α_4=0.0091	α_4=0.0101
30	0.8081561	0.7842715	0.7610928	0.7385991	0.3726931	0.3616783	0.3509891	0.3406158
60	0.6531163	0.6150818	0.5792622	0.5455286	0.1389002	0.1308112	0.1231934	0.1160192
90	0.52782	0.4823911	0.4408723	0.4029269	0.0517671	0.0473116	0.0432395	0.0395180
120	0.426561	0.3783256	0.3355447	0.2976015	0.0192933	0.0171116	0.0151766	0.0134605
150	0.3447279	0.29671	0.2553807	0.2198082	0.0071905	0.0061889	0.0053268	0.0045849

IV. Discussion and conclusion

Reliability analysis of various subsystems and system has been performed for a particular subsystem of sugar production plant. It is observed that the reliability of the system for 60 days is 0.1231934 and its corresponding values for subsystems at time 60 days are R_{SS1}=0.5655254, R_{SS2}=0.5897834, R_{SS3}=0.6376282, and R_{SS4}=0.5792622 respectively. The reliability of subsystem crystallizer is very low at different time point with respect to other subsystems. It needs more attention and maintenance with careful observation. From table 5, 6, 7, and 8, the reliability of subsystems is highly influenced with respect to failure rates. The derived results help maintenance managers, system designers and engineers to properly analyse system performance and plan maintenance strategies

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