International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 - 5161

Available at http://inpressco.com/category/ijcet

Research Article

Performance Analysis of a Selected System in a Process Industry

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Accepted 11 January 2014, Available online 01 February 2014, **Special Issue-2, (February 2014)**

Abstract

This paper discusses the performance analysis of a selected system in a process industry. The selected plant comprises of various systems. One of the most important functionaries of the selected plant is ball mill system. It has five subsystems arranged in series. We purpose a mathematical model. We use probalistic approach and derive differential equations based on Markov-Death process. These equations are solved using normalizing conditions to determine the steady state availability of the ball mill system. The performance of each subsystem of ball mill system is analyzed and a decision support system is developed. The results of the proposed model of this paper are useful to the management for the timely execution of proper maintenance decisions and hence enhance the system performance.

Keywords: *Process Industry, Performance Analysis etc.*

1. Introduction

The Concept of reliability has been known for a number of years. But it has assumed greater significance and importance during the past decade. In Today-Competitive environment, main concern of the industrialist is to cut down the manufacturing cost and improving the productivity as well as delivery performance. The industries must be in upstate i.e. availability for the long duration to meet the ever increasing customer demand at lower cost. Advance technology makes the industrial system more complex. The risk associated with the failure of complex system is very high and the main objective is to make this complex production system reliable i.e. they work without failure but failure is an unavoidable phenomenon associated with these advanced technological system. The ever increasing needs of modern society i.e. applications of automation, embedded technology, software and hardware interfaces, application of advanced technology, multiple functions and many other features have made the engineering systems more complicated

The complexities of industrial systems as well as their products are increasing day-by-day. Safety concern, environment, product cost and uninterrupted services also play a vital role in decision-making process. Globalization of market and availability of products in many varieties have thrown a great challenge before the industries to achieve the target. The manufacturers of highly complex equipments have served to focus greater attention on reliability. Their products should be available to consumers to their satisfaction at reasonable cost. The products should also provide satisfactory performance with minimum failures to consumers during the entire life of products. The improvements in effectiveness of such complex systems have therefore acquired special importance in recent years.

1.1 Literature Review

Ghosh and Majumdar (2010) modeled the occurrences of successive failure types and time to failure of the two repairable machine systems. A Markov chain model was used to characterize the occurrences of failures. Gupta and Tewari (2010) discussed about the availability predictive modeling of a thermal plant using Markov process and probabilistic approach. Garg et al. (2010) developed a decision support system for a tab manufacturing plant. The Markov birth – death process has been used to generate differential equations which were further solved for steady state availability in order to develop the decision matrices. Kumar et al. (2010) discussed the availability optimization of CO shift conversion system of a fertilizer plant using GA. The mathematical formulation of the problem was done using probabilistic approach and differential equations were developed on the basis of Markov birth-death process. The performance of each subsystem of CO shift conversion system has also been optimized using genetic algorithm. Vatn and Aven (2010) discussed a traditional approach for maintenance optimization where an object function is used for optimizing maintenance intervals. A framework has also been presented which opens up for a broader decision basis, covering considerations on the potential for gross accidents, the type of uncertainties and lack of knowledge of important risk influencing factors. Rao and Naikan (2011) proposed a hybrid approach called as Markov System Dynamics

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approach which combines the Markov model with system dynamics simulation for the time dependent availability analysis. The proposed method could be capable of computing the repairable system steady state time. Gupta (2011) demonstrated a mathematical model of a repairable spinning solution preparation system, a part of an acrylic yarn manufacturing plant with an effort to improve its availability. The proposed derived methodology relied on Markov Modeling. Zhigang and Haitao (2011) investigated the condition based maintenance of multi-component systems. A numerical algorithm was developed for the exact cost evaluation. Examples using real-world condition monitoring data were provided to demonstrate the proposed methods. Vasili et al. (2011) presented a brief review of existing maintenance optimization models. Several reliable models and methods in this area were discussed and future prospects were investigated. Kumar and Tewari (2011) developed a mathematical model of CO_2 cooling system of a fertilizer plant considering exponential distribution for the probable failures and repairs. The steady state availability expression for CO_2 cooling system was derived using normalizing conditions. The performance of each subsystem of CO_2 cooling system was also optimized using GA.

Lisnianski (2012) presented a multi-state Markov model for a coal power generating unit. The paper proposed a technique for the estimation of transition rates between the various generating capacity levels of the unit based on field observation.Adhikarya et al. (2012) concluded that RAM analysis is very much efficient in finding critical subsystems and deciding their preventive maintenance program for enhancing the availability of the power plant as well as the power supply. Twum et al. (2012) presented a multi-criteria optimization model and methodology for the Pareto optimal assignment of reliability to the components of a series-parallel system in order to maximize its reliability. Chouairi et al. (2012) introduced a practical method for reliability modeling of wire ropes. In order to optimize the relation reliability-maintainability and availability of metallic wire ropes, an extensive analytical modeling study has been performed in order to estimate the reliability-related to damage in the case of mixed systems, series-parallel or parallel-series configuration with symmetrical applied

2. Ball Mill System Description

1. **Subsystem (A):** This subsystem consists of single Rolling press unit. It is used to roll the metal sheet. Failure of this unit leads to system failure.
2. **Subsystem (B):** This subsystem consists of two Drilling machine units in parallel. When one unit fails system goes into reduced state. Complete failure occurs when both the units fail.
3. **Subsystem (C):** This subsystem consists of two Simple Lathe machine units in parallel. When one unit fails system goes into reduced state. Complete failure occurs when both the units fail.
4. **Subsystem (D):** This subsystem is single Vertical turret lathe unit. Failure of which leads to system failure.
5. **Subsystem (E):** There is one Plano miller unit in the plant. The failure of the unit leads to system failure

3. Assumptions and Notations

The transition diagram (figure 1) of the ball mill system shows three states, the system can acquire i.e. full working state, reduced state and failed state. Based on th transition diagram a performance evaluating model has been developed. The following assumptions and notations are used in developing the probalistic models for the ball mill system of the concerned plant:

3.1 Assumptions

1. Repair rates and failure rates are assumed to be constant and independent of each other.
2. Not more than one failure occurs at a time.
3. A repaired unit is, performance wise, as good as new.
4. The subsystem B and C fails through reduced states.
5. Switch-over devices are perfect.
6. Repair facility is always available

3.2 Notations

A, B, C, D, E: Subsystems in good operating state.
$\bar{B}$, $\bar{C}$: Indicates that B and C are working in reduced capacity.
a, b, c, d ,e : Indicates the failed state of A,B,C,D,E.
λ_i : Mean constant Failure rates [$\lambda_1(A \rightarrow a)$, $\lambda_2(B \rightarrow \bar{B})$, $\lambda_2(\bar{B} \rightarrow b)$, $\lambda_3(C \rightarrow \bar{C})$, $\lambda_3(\bar{C} \rightarrow c)$, $\lambda_4(D \rightarrow d)$, $\lambda_5(E \rightarrow e)$]
μ_i : Mean constant Repair rates [μ_1 $(a \rightarrow A)$, μ_2 $(\bar{B} \rightarrow B)$, μ_2 $(b \rightarrow \bar{B})$, $\mu_3(\bar{C} \rightarrow C)$, $\mu_3(c \rightarrow \bar{C})$, μ_4 $(d \rightarrow D)$, μ_5 $(e \rightarrow E)$]
P_i (t) : Probability that at time't' all units are good and the system is in i^{th} state.

: Full capacity working state

: Reduced capacity working state

: Failed State

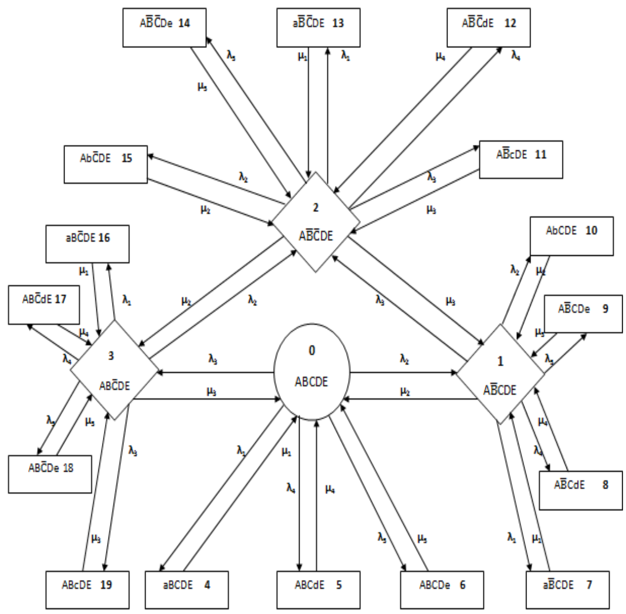

Fig.1 Transition Diagram of Ball Mill System

4. Mathematical modeling of ball mill system

Mathematical modeling has been developed for the prediction of steady state availability of the individual components as well as entire system. The failure and repair rates of different subsystems taken from the maintenance sheets of the plant are used as input information for the analysis. The state of the system defines the condition at any instant of time and information is useful in analyzing the current state and in the prediction of the failure state of the system. If the state is probability based then the model is a Markov probability model. The probability considerations lead into the following differential equations associated with the transition diagram.

$P_0'(t)+(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5)P_0(t) = \mu_1 P_4(t) + \mu_4 P_5(t) + \mu_5 P_6(t) + \mu_2 P_1(t) + \mu_3 P_3(t)$ (1)

$P_1'(t)+(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \mu_2)P_1(t) = \mu_1 P_7(t) + \mu_4 P_8(t) + \mu_5 P_9(t) + \mu_2 P_{10}(t) + \mu_3 P_2(t) + \lambda_2 P_0(t)$ (2)

$P_2'(t)+(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \mu_2 + \mu_3)P_2(t) = \mu_3 P_{11}(t) + \mu_4 P_{12}(t) + \mu_1 P_{13}(t) + \mu_5 P_{14}(t) + \mu_2 P_{15}(t) + \lambda_2 P_3(t) + \lambda_3 P_1(t)$ (3)

$P_3'(t)+(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \mu_3)P_3(t) = \mu_1 P_{16}(t) + \mu_4 P_{17}(t) + \mu_5 P_{18}(t) + \mu_3 P_{19}(t) + \lambda_3 P_0(t) + \mu_2 P_2(t)$ (4)

$P_4'(t) + \mu_1 P_4 = \lambda_1 P_0(t)$ (5)
$P_5'(t) + \mu_4 P_5 = \lambda_4 P_0(t)$ (6)
$P_6'(t) + \mu_5 P_6 = \lambda_5 P_0(t)$ (7)
$P_7'(t) + \mu_1 P_7 = \lambda_1 P_1(t)$ (8)
$P_8'(t) + \mu_4 P_8 = \lambda_4 P_1(t)$ (9)
$P_9'(t) + \mu_5 P_9 = \lambda_5 P_1(t)$ (10)
$P_{10}'(t) + \mu_2 P_{10} = \lambda_2 P_1(t)$ (11)
$P_{11}'(t) + \mu_3 P_{11} = \lambda_3 P_2(t)$ (12)
$P_{17}'(t) + \mu_4 P_{17} = \lambda_4 P_3(t)$ (13)
$P_{13}'(t) + \mu_1 P_{13} = \lambda_1 P_2(t)$ (14)
$P_{14}'(t) + \mu_5 P_{14} = \lambda_5 P_2(t)$ (15)
$P_{15}'(t) + \mu_2 P_{15} = \lambda_2 P_2(t)$ (16)
$P_{16}'(t) + \mu_1 P_{16} = \lambda_1 P_3(t)$ (17)
$P_{18}'(t) + \mu_5 P_{18} = \lambda_5 P_3(t)$ (18)
$P_{12}'(t) + \mu_4 P_{12} = \lambda_4 P_2(t)$ (19)
$P_{19}'(t) + \mu_3 P_{19} = \lambda_3 P_3(t)$ (20)

The steady state availability of each subsystem is obtained by putting d/dt = 0 at $t \rightarrow \infty$ into differential equations.

$(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5)P_0 = \mu_1 P_4 + \mu_4 P_5 + \mu_5 P_6 + \mu_2 P_1 + \mu_3 P_3$ (21)

$(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \mu_2)P_1 = \mu_1 P_7 + \mu_4 P_8 + \mu_5 P_9 + \mu_2 P_{10} + \mu_3 P_2 + \lambda_2 P_0$ (22)

$(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \mu_2 + \mu_3)P_2 = \mu_3 P_{11} + \mu_4 P_{12} + \mu_1 P_{13} + \mu_5 P_{14} + \mu_2 P_{15} + \lambda_2 P_3 + \lambda_3 P_1$ (23)

$(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \mu_3)P_3 = \mu_1 P_{16} + \mu_4 P_{17} + \mu_5 P_{18} + \mu_3 P + \lambda_3 P_0 + \mu_2 P_2$ (24)

$\mu_1 P_4 = \lambda_1 P_0$ (25)
$\mu_4 P_5 = \lambda_4 P_0$ (26)
$\mu_5 P_6 = \lambda_5 P_0$ (27)
$\mu_1 P_7 = \lambda_1 P_1$ (28)
$\mu_4 P_8 = \lambda_4 P_1$ (29)
$\mu_5 P_9 = \lambda_5 P_1$ (30)
$\mu_2 P_{10} = \lambda_2 P_1$ (31)
$\mu_3 P_{11} = \lambda_3 P_2$ (32)
$\mu_4 P_{12} = \lambda_4 P_2$ (33)
$\mu_1 P_{13} = \lambda_1 P_2$ (34)
$\mu_5 P_{14} = \lambda_5 P_2$ (35)
$\mu_2 P_{15} = \lambda_2 P_2$ (36)
$\mu_1 P_{16} = \lambda_1 P_3$ (37)
$\mu_4 P_{17} = \lambda_4 P_3$ (38)
$\mu_5 P_{18} = \lambda_5 P_3$ (39)
$\mu_3 P_{19} = \lambda_3 P_3$ (40)

Solving these equations recursively yields all values of P in terms of P_0

$P_1 = \frac{\lambda_2}{\mu_2} P_0$ (41)

$P_2 = \frac{\lambda_2 \lambda_3}{\mu_2 \mu_3} P_0$ (42)

$P_3 = \frac{\lambda_3}{\mu_3} P_0$ (43)

The probability of full working capacity P_0 is determined using normalizing condition i.e. sum of the probabilities of all states is equal to one.

$$P_0 = \left[1 + \frac{\lambda_2}{\mu_2} + \frac{\lambda_2\lambda_3}{\mu_2\mu_3} + \frac{\lambda_3}{\mu_3} + \frac{\lambda_1}{\mu_1} + \frac{\lambda_4}{\mu_4} + \frac{\lambda_5}{\mu_5} + \frac{\lambda_1\lambda_2}{\mu_1\mu_2} + \frac{\lambda_4\lambda_2}{\mu_4\mu_2} + \frac{\lambda_5\lambda_2}{\mu_5\mu_2} + \left(\frac{\lambda_2}{\mu_2}\frac{\lambda_2}{\mu_2}\right) + \frac{\lambda_2\lambda_3\lambda_3}{\mu_2\mu_3\mu_3} + \frac{\lambda_2\lambda_3\lambda_4}{\mu_2\mu_3\mu_4} + \frac{\lambda_1\lambda_2\lambda_3}{\mu_1\mu_2\mu_3} + \frac{\lambda_2\lambda_3\lambda_5}{\mu_2\mu_3\mu_5} + \frac{\lambda_2\lambda_2\lambda_3}{\mu_2\mu_2\mu_3} + \frac{\lambda_1\lambda_3}{\mu_1\mu_3} + \frac{\lambda_4\lambda_3}{\mu_4\mu_3} + \frac{\lambda_5\lambda_3}{\mu_5\mu_3} + \frac{\lambda_3\lambda_3}{\mu_3\mu_3}\right]^{-1}$$

Steady state availability for the system (A_v) of the system is given by summation of probabilities of all full working and reduced capacity states.

$$A_v = \sum_{i=0}^{3} P_i$$

$$A_v = P_0 + P_1 + P_2 + P_3$$

5. Performance Analysis

Performance analysis forms the foundation for all other performance improvement activities. From maintenance history sheet of ball mill system of the selected plant and through discussions with the plant personnel appropriate failure and repair rates of all five subsystems are taken and availability matrix for different availability values are prepared accordingly by putting the values in A_v.Table 1 to 5 depicts the availability levels for various subsystems of the ball mill system. The availability values are then plotted.

Table 1 Effect of Failure and Repair Rates of Rolling Press on Availability

μ_1 \ λ_1	0.0004	0.0008	0.0012	0.0016	0.0020	Constant Values
0.033	0.9429	0.9317	0.9221	0.9057	0.9015	$\lambda_2 = 0.0020, \mu_2 = 0.033$ $\lambda_3 = 0.0002, \mu_3 = 0.311$ $\lambda_4 = 0.001, \mu_4 = 0.055$ $\lambda_5 = 0.001, \mu_5 = 0.033$
0.066	0.9482	0.9428	0.9324	0.9320	0.9268	
0.099	0.9496	0.9463	0.9427	0.9391	0.9356	
0.132	0.9509	0.9482	0.9455	0.9427	0.9401	
0.165	0.9514	0.9492	0.9474	0.9449	0.9427	

Table 2: Effect of Failure and Repair Rates of Drilling Machine on Availability

λ_2 / μ_2	0.0020	0.0040	0.0060	0.0080	0.0100	Constant Values
0.311	0.9429	0.9423	0.9421	0.9419	0.9416	$\lambda_1 = 0.0004, \mu_1 = 0.033$ $\lambda_3 = 0.0002, \mu_3 = 0.311$ $\lambda_4 = 0.001, \mu_4 = 0.055$ $\lambda_5 = 0.001, \mu_5 = 0.033$
0.622	0.9443	0.9428	0.9424	0.9420	0.9419	
0.933	0.9451	0.9446	0.9441	0.9436	0.9430	
1.244	0.9463	0.9452	0.9448	0.9443	0.9436	
1.555	0.9480	0.9461	0.9453	0.9449	0.9444	

Table 3: Effect of Failure and Repair Rates of Lathe Machine on Availability

λ_3 / μ_3	0.0002	0.0004	0.0006	0.0008	0.0010	Constant Values
0.011	0.9429	0.9416	0.9402	0.9393	0.9360	$\lambda_1 = 0.0004, \mu_1 = 0.033$ $\lambda_2 = 0.0020, \mu_2 = 0.311$ $\lambda_4 = 0.001, \mu_4 = 0.055$ $\lambda_5 = 0.001, \mu_5 = 0.033$
0.022	0.9432	0.9419	0.9408	0.9398	0.9374	
0.033	0.9447	0.9421	0.9416	0.9402	0.9382	
0.044	0.9460	0.9440	0.9436	0.9421	0.9401	
0.055	0.9482	0.9456	0.9440	0.9431	0.9424	

Table 4: Effect of Failure and Repair Rates of VTL Machine on Availability

λ_4 / μ_4	0.001	0.002	0.003	0.004	0.005	Constant Values
0.055	0.9429	0.9266	0.9129	0.8964	0.8820	$\lambda_1 = 0.0004, \mu_1 = 0.033$ $\lambda_2 = 0.0020, \mu_2 = 0.311$ $\lambda_3 = 0.0002, \mu_3 = 0.011$ $\lambda_5 = 0.001, \mu_5 = 0.033$
0.110	0.9508	0.9425	0.9344	0.9266	0.9189	
0.165	0.9531	0.9479	0.9425	0.9371	0.9318	
0.220	0.9548	0.9506	0.9446	0.9427	0.9385	
0.275	0.9586	0.9523	0.9490	0.9457	0.9424	

Table 5: Effect of Failure and Repair Rates of Plano miller Machine on Availability

λ_5 / μ_5	0.001	0.002	0.003	0.004	0.005	Constant Values
0.033	0.9429	0.9162	0.8912	0.8564	0.8458	$\lambda_1 = 0.0004, \mu_1 = 0.033$ $\lambda_2 = 0.0020, \mu_2 = 0.311$ $\lambda_3 = 0.0002, \mu_3 = 0.011$ $\lambda_4 = 0.001, \mu_4 = 0.055$
0.066	0.9560	0.9424	0.9291	0.9162	0.9037	
0.099	0.9604	0.9515	0.9424	0.9355	0.9248	
0.132	0.9630	0.9560	0.9492	0.9428	0.9357	
0.165	0.9644	0.9588	0.9533	0.9478	0.9424	

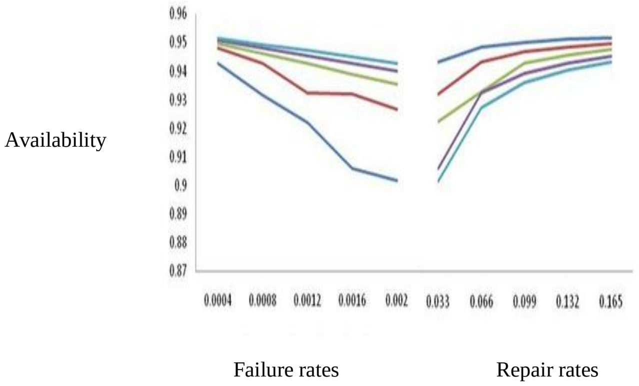

Fig 2.Effect of Failure and Repair Rates of Subsystem A on system Availability

Figure 2, 3, 4 and 6 represent the plot for various subsystems of ball mill system, depicting the effect of failure and repair rates of various subsystems on ball mill system availability. Various availability levels may be computed for different combinations of failure and repair rates .On the basis of analysis a decision support system is generated. This helps to build optimal maintenance strategies.

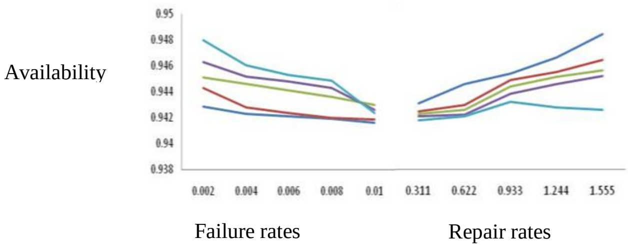

Fig 3.Effect of Failure and Repair Rates of Subsystem B on system Availability

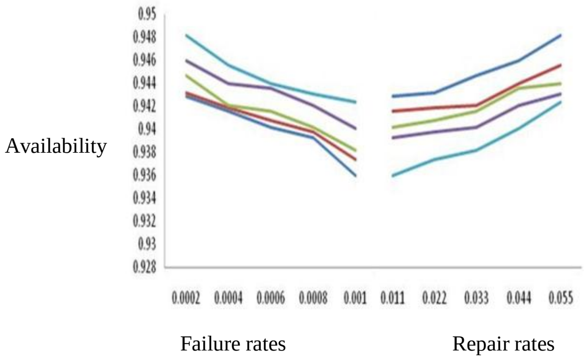

Fig 4.Effect of Failure and Repair Rates of Subsystem C on system Availability

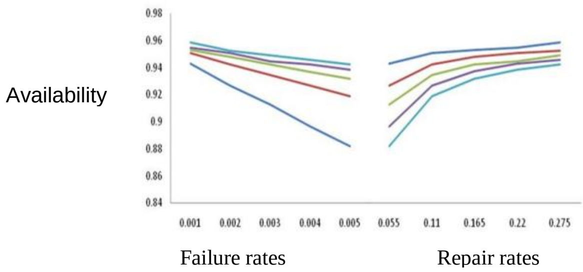

Fig 5.Effect of Failure and Repair Rates of Subsystem D on system Availability

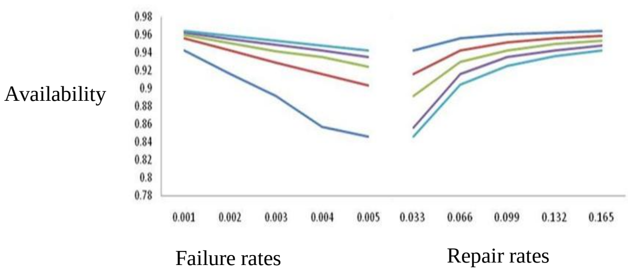

Fig 6. Effect of Failure and Repair Rates of Subsystem E on system Availability

The decision matrices as given by tables 1 to 5 depict the variation of system availability with the change in failure and repair rates of different subsystems. These matrices help to develop the decision support system for the maintenance department to look insight the criticality of various subsystems. The developed DSS for Ball Mill system is presented in table 6.

Table 6: Decision Support System for Ball mill System

Subsystem	Increase in Failure Rates	Decrease in Availability	Increase in Repair Rates	Increase in Availability	Rank/ Repair Priority
Rolling press	0.0004-0.0020	4.14%	0.165-0.033	0.85%	III
Drilling	0.0020-0.01	0.13%	0.1555-0.311	0.51%	V
Simple lathe	0.0002-0.0010	0.69%	0.055-0.011	0..53%	IV
VTL	0.001-0.005	6.09%	0.275-0.55	1.57%	II
Plano miller	0.0010-0.005	0.97%	0.165-0.033	2.15%	I

6. Results

Table 1 and figure 2 shows the effect of failure rates (λ_1) and repair rates (μ_1) of subsystem A on the availability of the Ball mill system. It is observed that as failure rates (λ_1) of subsystem A increase from 0.0004 to 0.0020, the system availability decreases drastically by 4.14%. Similarly, as the repair rates (μ_1) increase from 0.033 to 0.165, the system availability increases marginally by 0.85%.

From table 2 and figure 3, it is observed that as failure rates (λ_2) of subsystem B increase from 0.0020 to 0.0100, the system availability decreases only by 0.13%. Similarly, when repair rates (μ_2) of subsystem B increase from 0.311 to 1.555, the system availability increases merely by 0.51%.

Table 3 and figure 4 reveal the variation of system availability with change in failure rates (λ_3) and repair rates (μ_3) of the subsystem C. As failure rates (λ_3) increase from 0.0002 to 0.0010, the system availability reduces appreciably by 0.69%. Similarly, when repair rates (μ_3) increase from 0.011 to 0.055, then the system availability increases only by 0.53%.

Table 4 and figure 5 show the variation in availability of ball mill system with change in failure and repair rates of subsystem D (λ_4, μ_4). As failure rates (λ_4) increase from 0.001 to 0.005, the system availability reduces by 6.09%. Similarly, when repair rates (μ_4) increase from 0.055 to 0.275, the system availability increases by 1.57%.

Table 5 and figure 6 reveal the variation of system availability with change in failure rates (λ_5) and repair rates (μ_5) of the subsystem E. As failure rates (λ_5) increase from 0.001 to 0.005, the system availability reduces marginally by 0.97%. Similarly, when repair rates (μ_5) increase from 0.033 to 0.165, then the system availability increases appreciably by 2.15%.

7. Conclusion

The Decision Support System for Ball mill system has been developed with the help of mathematical modeling using probabilistic approach. The decision matrices are also developed. These matrices facilitate the maintenance decisions to be made at critical points where repair priority should be given to some particular subsystem of Ball mill system. DSS as shown in table 6 clearly indicates that the subsystem E is most critical subsystem as far as maintenance aspect is concerned. So, subsystem E should be given top priority as the effect of its failure and repair rates on the system availability is much higher than that of other subsystems. The findings of this paper are discussed with the concerned plant management. These results are found to be highly beneficial for performance analysis of ball mill system and hence to decide the maintenance priorities of various subsystem.

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