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Profit analysis of a two-unit similar cold standby system with endurance time and preventive maintenance

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Abstract
The current study examines the profit analysis of a similar cold standby system with endurance time and preventive maintenance. In order to achieve this goal, we consider two categories of repair facilities in this model: primary repair facilities and specialized repair facilities. Primary repairers are usually referred to as general repairers and have usually stayed at the restoration facility, if it is not able to complete the repair in time, then specialist repairmen are called for complex repair. The system is sent for preventive maintenance once the maximum operation time has elapsed. Using the Semi-Markov process and Markov regenerative point approach, reliability characteristics such as MTSF, availability and busy period of repairmen are obtained. Further, the profit analysis is performed. The tabular and graphical representations are also done concerning the failure rate.

Keywords: Availability, patience time, Weibull distribution, profit analysis, cold standby

1. Introduction

"Weibull Distribution" is among the most used distributions in reliability engineering. It is a kind of versatile distribution that can take the values from the other distributions using the parameter called the shape parameter. The Weibull Distribution is a continuous probability distribution that is used to analyze life data, model failure times and assess product reliability. It can also fit a vast range of data from other fields like economics, hydrology, biology and engineering. It is an extreme value of probability distribution that is frequently used to model reliability, survival, wind speeds and other data. The only reason to use the Weibull distribution is because of its flexibility as it can simulate various distributions like normal and exponential distributions. Ashish Kumar and Monika Saini [1] discussed the concept of fuzzy reliability used for the analysis of the fuzzy availability of a sugar plant. The effect of coverage factor, failure and repair rates of subsystems on the system's fuzzy availability had been analyzed. Chapman–Kolmogorov differential equations have been derived with the help of the Markov birth-death process. In another study by Ashish Kumar, S. K. Chhillar and S C. Malik [2] single-unit system is analyzed by considering the concepts of degradation and maintenance subjected to random shocks. Naveen Kumar *et al.*, [3] has proposed work with a motto to develop a stochastic framework for the e-waste management plant to optimize its availability integrated with reliability, availability, maintainability and dependability (RAMD) measures and Markovian analysis to estimate the steady-state availability of the E-waste management plant. Monika Saini *et al.*, [4] proposed a novel stochastic model by considering a condenser as a system consisting of seven subsystems. All the time-dependent random variables associated with failure rates followed exponential distribution while repair rates are arbitrarily distributed. Monika Saini *et al.*, [5] done a case study of load haul dump (LHD) machines that considers the optimization of failure and repair rate parameters using two well-established metaheuristic approaches, namely, genetic algorithm (GA) and particle swarm optimization (PSO). Ashish Kumar *et al.*, [6] approached a reliability model of a redundant system having one original and one duplicate unit developed with an immediate repair facility.

Repairman conducts the preventive maintenance of the unit after a pre-specific time to enhance the performance and efficiency of the system. All random variables follow the Weibull distribution. Ashish Kumar and Monika Saini [7] carried out their work to perform RAMD analysis and Failure Modes and Effects Analysis (FMEA) unified with the development of a novel stochastic model using Markovian approach to estimate the Steady-State Availability (SSA) of the TIUP. Nivedita Gupta *et al.*, [8] investigate various reliability measures of generators used in STP through the RAMD approach at the component level. For this purpose, mathematical models using the Markovian birth-death process have been developed for all subsystems of the generator. Hemant Kumar saw and V K Pathak [9] developed a stochastic model of the single-unit system in a manufacturing plant. The system has been investigated under the assumption that the unit works in three different states: normal state, partially failed state and totally failed state. The system suffers three types of failures: *viz*; Hardware failure, Critical human failure and Non-critical human failure. In this field, a large number of papers such as performance analysis of a redundant system of non-identical units with Weibull densities for failure and repair were discussed by Ashish Kumar *et al.*, [10]. Similarly, Gupta and Gupta [11] estimated Stochastic analysis of a reliability model of the one-unit system with post-inspection, post-repair, preventive maintenance and replacement. Kadyan, Mukender Singh [12] evaluated the Reliability and profit analysis of a single-unit system with preventive maintenance subject to the maximum operation time of the system.

In the present paper, we develop a stochastic model for profit analysis of a two-unit similar cold standby system with endurance time and preventive maintenance for the evaluation of system reliability, mean time to system failure, steady-state availability, a busy period of the server, expected number of repairs, expected number of visits by the server and profit function of the system by considering all time random variables as Weibull distributed. The possible states of the proposed model have been discussed under the system description. Two types of repair persons have been provided to do repair and maintenance activities. After maximum operation time, the system undergoes preventive maintenance. All random variables are statistically independent. Semi-Markov process and regenerative point techniques are used to draw recurrence relations for various reliability characteristics. All time random variables are Weibull distributed.

2 The modelling of the system was based on the following assumptions

1. The systems consist of two units of similar (same) type, the primary being in operation and the second being stored as a cold standby that will not fail until it is going into operation.
2. The system is provided with preventive maintenance after the maximum operating time.
3. Unit failure is detected and attended to by a primary repair person.
4. Endurance time is applied when one can wait while the primary repair person is undergoing repair for the failed unit. The expert repair person is called to the system when a primary repair person is not able to do some complex repairs.
5. The specialist leaves the system after completing the recovery of the failed unit, and the other unit can be attended to by the primary repairer.
6. The units are new after each restoration and preventive maintenance.
7. At time 't' one unit is simply online (working mode) and another unit is in standby mode.
8. As each unit fails, the machine becomes inoperable.
9. Failures, repairs and downtime are randomly distributed. The repairer does not harm the unit in any way.
10. All random variables are independent together.
11. There is a single recovery facility serviced by a repairer, namely the primary and the specialized repair person.

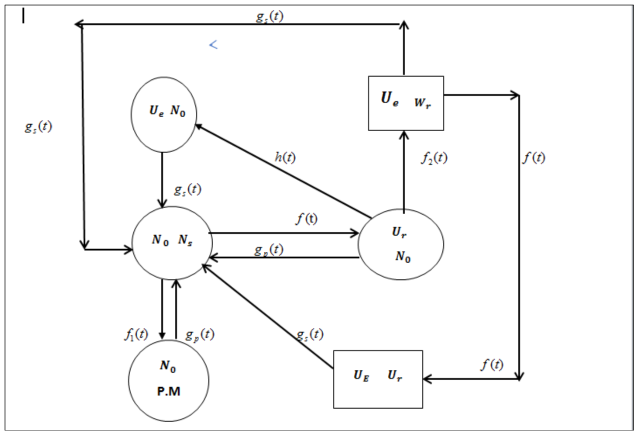

Fig 1: Transition diagram

3 Notation and States of the System

Modes of the units (parts) N_0 - Normal unit when it is operative, N_s - normal unit when it is kept in cold standby, P.M - preventive maintenance, W_r - waiting for repair, U_r - under repair, U_e - failed unit repair by a specialist repair person.

States of the System are

S_0 - (N_0, N_s), $S_1 - (U_r, N_0)$, $S_2 - (P.M, N_0)$, $S_3 - (U_e, U_r)$, $S_4 - (U_e, U_R)$, $S_5 - (U_E, U_r)$

$q_{ij}(t), Q_{ij}(t)$: pdf and cdf of first passage time from "i" regenerative state to a regenerative or failed state "j" without visiting other regenerative states in (0,t].

$q_{ij}^{k}(t), Q_{ij}^{k}(t)$: pdf and cdf of first passage time from "i" regenerative state to a regenerative or failed state "j" without visiting "k" state once in (0,t].

p_{ij}, p_{ij}^{k} : Probability of transition from an "i" regenerative state to "j" regenerative state without/ with visiting "k" state once in (0,t].

$**/*$: Laplace - Stieltjes/ Laplace transform symbol.

O - initial stage of the system (i.e at time t=0, one unit starts operating and the other has been kept on cold standby),

$h(t), H(t)$: $h\eta t^{n-1}e^{-(ht^{\eta})}$ = pdf of the patience time.

G(t), g(t) : cdf and pdf of repair time.

$f(t)$: $\beta\eta t^{n-1}e^{-(\beta t^{\eta})}$ = pdf of the failure rate of first unit repair by a primary repair person.

$f_2(t)$: $\chi\eta t^{n-1}e^{-(\chi t^{\eta})}$ = pdf of the failure rate of standby unit repair by a primary repair person.

$g_m(t), G_m(t)$: probability density function of repair time of repair person (m= p,s), where $g_p(t) = \gamma\eta t^{n-1}e^{-(\gamma t^{\eta})}$ and $g_s(t) = \alpha\eta t^{n-1}e^{-(\alpha t^{\eta})}$

$f_1(t)$: $\delta\eta t^{n-1}e^{-(ht^{\delta})}$ = pdf of maximum operation time.

$g_2(t): l\eta t^{n-1}e^{-(lt^{\eta})}$ = pdf of preventive maintenance rate of first unit.
$\eta > 0$, which is common shape parameter.
$\chi, \alpha, \beta, \delta, h, l > 0$ are scale parameter.

4 Equations

Transition Probabilities and Mean Sojourn Times

Simple probabilistic concerns yield the subsequent expressions for the non-zero elements

$$P_{ij} = Q_{ij}(\infty) = \int q_{ij}(t)dt \quad (1)$$

$$Q_{01}(t) = \int_0^{\infty} f(t)\overline{F_1(t)}dt = \int_0^{\infty} \beta\eta t^{n-1}e^{-(\beta t^{\eta})}.e^{-(\delta t^{\eta})}dt(2)$$

$$Q_{02}(t) = \int_0^{\infty} f_1(t)\overline{F(t)}dt = \int_0^{\infty} \delta\eta t^{n-1}e^{-(\delta t^{\eta})}.e^{-(\beta t^{\eta})}dt \quad (3)$$

$$Q_{10}(t) = \int_0^{\infty} g_p(t)\overline{H(t)}.\overline{F_2(t)}dt = \int_0^{\infty} \gamma\eta t^{n-1}e^{-(\gamma t^{\eta})}.e^{-(ht^{\eta})}.e^{-(\chi t^{\eta})}dt \quad (4)$$

$$Q_{13}(t) = \int_0^{\infty} h(t).\overline{G_p(t)}.\overline{F_2(t)}dt = \int_0^{\infty} h\eta t^{n-1}e^{-(ht^{\eta})}.e^{-(\gamma t^{\eta})}.e^{-(\chi t^{\eta})}dt \quad (5)$$

$$Q_{14}(t) = \int_0^{\infty} f_2(t).\overline{H(t)}.\overline{G_p(t)}dt = \int_0^{\infty} \chi\eta t^{n-1}e^{-(\chi t^{\eta})}.e^{-(\gamma t^{\eta})}.e^{-(ht^{\eta})}dt \quad (6)$$

$$Q_{30}(t) = \int_0^{\infty} g_s(t)dt = \int_0^{\infty} \alpha\eta t^{n-1}e^{-(\alpha t^{\eta})}dt = p_{30} = 1 \quad (7)$$

$$Q_{40}(t) = \int_0^{\infty} g_s(t).\overline{F(t)}dt = \int_0^{\infty} \alpha\eta t^{n-1}e^{-(\alpha t^{\eta})}.e^{-(\beta t^{\eta})}dt \quad (8)$$

$$Q_{45}(t) = \int_0^{\infty} f(t).\overline{G_s(t)}dt \quad (9)$$

$$Q_{50}(t) = \int_0^{\infty} g_s(t)dt = \int_0^{\infty} \alpha\eta t^{n-1}e^{-(\alpha t^{\eta})}dt \quad (10)$$

$$Q_{20}(t) = \int_0^{\infty} g_2(t)dt(11)$$

$$\lim_{t\to\infty} Q_{01}(t) = P_{01}P_{01} = \frac{\beta}{\beta+\delta} \quad (12)$$

$$\lim_{t\to\infty} Q_{02}(t) = P_{02}P_{02} = \frac{\delta}{\delta+\beta} \quad (13)$$

$$P_{01} + P_{02} = \frac{\beta}{\delta+\beta} + \frac{\delta}{\delta+\beta} = 1 \quad (14)$$

$$P_{10} = \frac{\gamma}{\gamma+h+\chi}, P_{13} = \frac{h}{\gamma+h+\chi}, P_{14} = \frac{\chi}{\gamma+h+\chi} \quad (15)$$

$$P_{10} + P_{13} + P_{14} = \frac{\gamma}{\gamma+h+\chi} + \frac{h}{\gamma+h+\chi} + \frac{\chi}{\gamma+h+\chi} = 1 \quad (16)$$

$$P_{20} = 1 \quad (17)$$

$$\lim_{t\to\infty} Q_{40}(t) = P_{40}P_{40} = \frac{\alpha}{\alpha+\beta} \quad (18)$$

$$P_{40} + P_{45} = 1 \quad (19)$$

$$P_{50} = 1. \quad (20)$$

Let T denote the time to system failure then the mean sojourn times (μ_i)in the state S_i are given by

$$(\mu_i) = E(t) = \int_0^{\infty} P[T > t]dt \quad (21)$$

Therefore, the mean sojourn times (μ_i) at regenerative states S_i are as follows:

$$\mu_0(t) = \int_0^{\infty} \overline{F(t)F_1(t)}dt \quad (22)$$

$$= \frac{\Gamma(1+\frac{1}{\eta})}{(\beta+\delta)^{\frac{1}{\eta}}}(23)$$

$$\mu_1(t) = \frac{\Gamma(1+\frac{1}{\eta})}{(\gamma+h+\chi)^{\frac{1}{\eta}}} \quad (24)$$

$$\mu_0(t) = \frac{\Gamma(1+\frac{1}{\eta})}{(\beta+\delta)^{\frac{1}{\eta}}} \quad (25)$$

$$\mu_2(t) = \frac{\Gamma(1+\frac{1}{\eta})}{(l)^{\frac{1}{\eta}}} \quad (26)$$

similarly,

$$\mu_3(t) = \frac{\Gamma(1+\frac{1}{\eta})}{(\alpha)^{\frac{1}{\eta}}} \quad (27)$$

5 Mean Time to System Failure:

Let $\pi_i(t)$ be the c.d.f of first passage time from the regenerative state S_i to a failed state. The obtained recursive relations for $\pi_i(t)$

$$\pi_0(t) = Q_{01}(t)©\pi_1(t) + Q_{02}(t)©\pi_2(t)x \quad (28)$$

$$\pi_1(t) = Q_{10}(t)©\pi_0(t) + Q_{13}(t) + Q_{14}©\pi_4(t) \quad (29)$$

$$\pi_2(t) = Q_{20}(t)©\pi_0(t) \quad (30)$$

We are taking Laplace Steiltjes transform of the above equation:

$$(\pi_0^{**}, \pi_1^{**}, \pi_2^{**}) = Q^{**^{-1}}(0, Q_{13}^{**} + Q_{14}^{**}, 0). \quad (31)$$

Where,

$$Q^{**-1} = \begin{bmatrix} 1 & -Q_{01}^{**} & -Q_{02}^{**} \\ -Q_{10}^{**} & 1 & 0 \\ -Q_{20}^{**} & 0 & 1 \end{bmatrix} \begin{bmatrix} \pi_0^{**} \\ \pi_1^{**} \\ \pi_2^{**} \end{bmatrix} = \begin{bmatrix} 0 \\ Q_{13}^{**} \\ 0 \end{bmatrix}. \quad (32)$$

Now, by solving the above equation for $\pi_0^{**}(s)$, we get the mean time to system failure when the system starts from the state S_0 given by

$$D^*(S) = 1 - Q_{0,1}^{**}(s)Q_{1,0}^{**}(s) - Q_{0,2}^{**}(s)Q_{2,0}^{**}(s) \quad (33)$$

$$N(s) = Q_{01}(Q_{13}^{**}(s) + Q_{14}^{**}(s)) \quad (34)$$

6 Availability

Let $M_i(t)$ denote the probability that the system is initially in regenerative state $S_i \in E$ is up at time t without passing through any other regenerative state or returning to itself through one or more non-regenerative states.

The steady state of the availability of both the repair person is given by

$$A_0^*(s) = \frac{N_2(s)}{D_1(s)}, \quad (35)$$

$$where, D_1(s) = \mu_0 + \mu_1 p_{01} + \mu_2 p_{02} + \mu_3 p_{01} p_{13} + \mu_4 p_0 p_{14} + \mu_5 p_{50} \quad (36)$$

7. Busy Period Analysis Busy period for Primary Repair person: Let U_i be the probability that the given system is going under repair with the help of a regular repair facility which is in state $S_i \in E$ at a time 't' without transiting to any regenerative state. Therefore,

$$U_1 = \overline{G_p(t)}. \quad (37)$$

Taking Laplace-Transform and solving for $B_0^*(s)$

$$B_p^*(s) = \frac{N_3(S)}{D_1(S)}, \quad (38)$$

Hence, we get

$$U_1^*(0) = \int_0^\infty t g_p(t) dt = U_1 = \mu_1 \quad (39)$$

$$N_3 = \mu_1 p_{01}. \quad (40)$$

Busy Period of the server due to Specialist Repair Person

Let U_i be the probability that the system is going under repair by a specialist repair person in the given state $S_i \in E$ at a given time 't' without moving to any regenerative state. Therefore,

$$U_i = \overline{G_s(t)}. \quad (41)$$

Taking Laplace-Transform and solving for $S_0^*(s)$

$$B_s^*(t) = \frac{N_4(S)}{D_1(S)}, \quad (42)$$

therefore,

$$N_4 = \mu_3 p_{01} p_{13} + \mu_4 p_{01} p_{14} + \mu_5 p_{01} p_{14} p_{45}. \quad (43)$$

8 Due To Preventive Maintenance

Let $P_i^{pm}(t)$ be the expected number of preventive maintenance by the server in $(0, t]$, given that the system entered the regenerative state S_i at t=0. Taking Laplace-Transform of above equation and solving for $P_0^*(s)$

$$P_0^*(s) = \frac{N_5(S)}{D_1(S)}, \quad (44)$$

we have

$$N_5 = \mu_2 p_{02}. \quad (45)$$

9 Expected No. of Visits By the Server

Eventually, we get a steady state, the function of time for which the expected number of visits by the server is given by

$$V_0 = \lim_{s \to 0} \frac{N_6(S)}{D_1(S)}, \quad (46)$$

$$N_6 = p_{10}. \quad (47)$$

10 Profit Analysis

The Expected total P(t) per unit time incurred to the system is given by:

$$P(t) = K_0 A_0 - K_1 B_0^R - K_2 B_0^s - K_3 p_0^{pm} - K_4 N_0 \quad (48)$$

K_0 = Revenue per unit up-time of the system
K_1 = Cost per unit time for which primary repair person is busy in repair
K_2 = Cost per unit time for which specialist repair person is busy in repair
K_3 = Cost per preventive maintenance
K_4 = Cost per visit by the server

11. particular cases

1. If we take shape parameter $\eta = 0.5$ then the given maximum operation time/failure of Main unit/failure of standby unit/preventive maintenance/repair of Main unit/repair of the standby unit time distributions reduce to:-

$$g_2(t) = \frac{l}{2\sqrt{t}} e^{-l\sqrt{t}}, f(t) = \frac{\beta}{2\sqrt{t}} e^{-\beta\sqrt{t}}, f_1(t) = \frac{\delta}{2\sqrt{t}} e^{-\delta\sqrt{t}}, h(t) = \frac{h}{2\sqrt{t}} e^{-h\sqrt{t}} \quad (49)$$

$$f_2(t) = \frac{\chi}{2\sqrt{t}} e^{-\chi\sqrt{t}}, g_p(t) = \frac{\gamma}{2\sqrt{t}} e^{-\gamma\sqrt{t}}, g_s(t) = \frac{\alpha}{2\sqrt{t}} e^{-\alpha\sqrt{t}} \quad (50)$$

2. If we take shape parameter $\eta = 2.0$ then the given reliability characteristics reduce to Rayleigh with the pdf

$$g_2(t) = 2le^{-lt^2}, f(t) = 2\beta e^{-\beta t^2}, f_1(t) = 2\delta e^{-\delta t^2}, h(t) = 2he^{-ht^2} \quad (51)$$

$$f_2(t) = 2\chi e^{-\chi t^2}, g_p(t) = 2\gamma e^{-\gamma t^2}, g_s(t) = \alpha e^{-\alpha t^2} \quad (52)$$

$$t \geq 0 \; and \; \eta, \beta, \gamma, \alpha, `l, h, k, `\chi` > 0$$

12 Tables

For shape parameter $\eta = 2, \alpha = 1.2, \gamma = 5, h = 0.009, \delta = 2, \chi = 1.5, l = 1.4$			
Particular values of (β)	**MTSF**	**Availability**	**Profit**
0.01	133.08	0.5208	4999.2
0.02	682.13	0.5189	4179.9
0.03	438.58	0.5172	3570.4
0.04	329.2	0.5154	3060.2
0.05	262.84	0.5134	2804.5
0.06	218.2	0.5110	2700.6
0.07	186.44	0.5099	2689.5
0.08	164.20	0.5068	2676.6

0.09	144.97	0.5062	2663.3
0.1	131.04	0.5046	2652.2

For shape parameter $\eta = 2, \alpha = 1.2, \gamma = 5, h = 0.009, \delta = 2, \chi = 1.5, l = 1.4$			
Particular values of (β)	**MTSF**	**Availability**	**Profit**
0.01	1208.6	2.1592	5798.6
0.02	1205.4	2.1244	5069.9
0.03	1202.4	2.0926	4334.4
0.04	1199.4	2.0593	3900.1
0.05	1196.2	2.0282	3696.8
0.06	1193.3	2.0256	3556.6
0.07	1178.4	2.0242	3545.5
0.08	1093.4	1.1656	3534
0.09	1067.3	1.1667	3519.7
0.1	1032.2	1.1656	3500.4

13 Figures

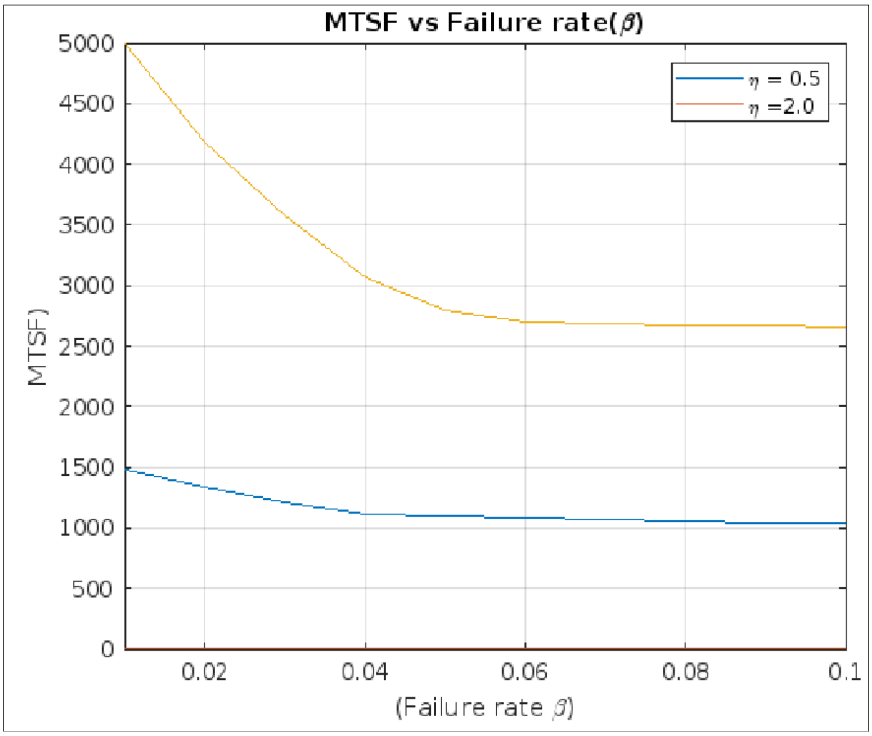

Fig 2: MTSF vs Failure rateβ

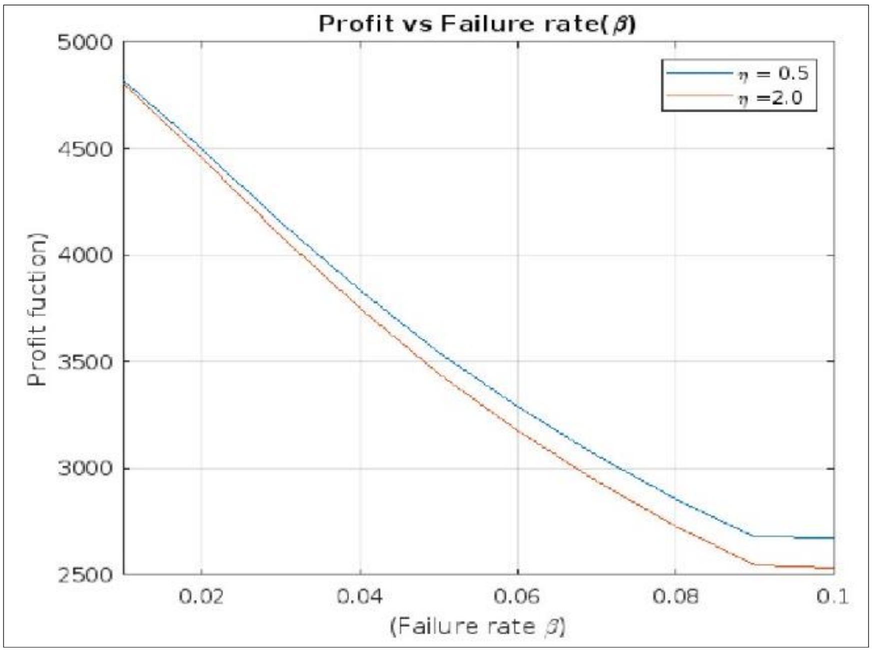

Fig 3: Profit vs Failure rateβ

Graphical analysis

The curve for MTSF and Failure rate have been drawn for different values of shape parameters and repair rate of both the repair person, preventive maintenance, and patience time has been taken. The variation in MTSF about the failure rate is seen in Fig.1 and Figure 2 shows the profit pattern relative to the failure rate for various shapes parameter values. The data in the tables as mentioned above show that as the shape parameter rises (i.e., as the system ages) the values of MTSF, availability as well as profit decreases.

Summary and Conclusions

It is challenging to analyze failures in complex systems with many interdependent system components, especially when unpredictable events can affect the system's performance. So, there are many ways to represent engineering complex systems. However, the shape parameter of the Weibull distribution is frequently used to evaluate product reliability and its capacity to analyze failure trends is useful in identifying the key contributing factors to system failure. Additionally enhanced MTSF, availability, and profit for higher rates of repair and maintenance and helped decrease the system's downtime. This could be helpful throughout the planning, running or decision-making phases.

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