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Stochastic Analysis of a Repairable System of Non-identical Units with Priority for Operation and Repair Subject to Weather Conditions

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ABSTRACT
A repairable system of two non-identical units - one is an original (called main unit) and other is a substandard (called duplicate unit) is investigated stochastically under different weather conditions – normal and abnormal. The system starts its operation with original unit keeping duplicate unit in cold standby. There is a direct failure of each unit from normal mode. Both units are capable in performing the system functions well. A single server is called immediately to do repair of the unit whenever needed. The operation and repair of the units are stopped in abnormal weather. And, in normal weather, priority is given for operation and repair to the original unit over duplicate unit. After repair unit works as new. All random variables are statistically independent and uncorrelated. The failure time of the units and time to change of weather conditions follow negative exponential distributions while repair times of the units are arbitrarily distributed. Various reliability and performance measures are obtained in steady state using semi-Markov process and regenerative point technique. The graphical behavior of MTSF, availability and profit function with respect to normal weather rate has also been observed for a particular case.

KEYWORDS
Repairable system, Non-identical units, Different weather conditions, Priority, Reliability measures and Stochastic analysis.

1. INTRODUCTION
It is a common knowledge that redundancy can be used to improve the performance and reliability of repairable systems. Therefore, stochastic models of cold standby repairable systems with identical units have widely been studied by the researchers including Naidu and Gopalan [1] , Goyal and Sharma [2] and Singh [3] under strict control of weather conditions. In fact, it is very difficult to afford an identical unit in spare in case its cost is high. In such a situation, a substandard unit might be kept as spare in cold standby not only to improve the reliability but also to protect the operation of the system for a considerable time. Mokkadis et al. [4] analyzed stochastically the redundant systems of non-identical units under different sets of assumption on failure and repair.
Also, sometimes it becomes necessary to give priority in operation and repair to one unit over the other in order to make the system more profitable. A good example of the situation is that of a system consisting of one unit as power supply through electric transformer and other unit generator. The priority is obviously given to the power supply coming through electric transformer rather than generator. The generator will be used only when supply through electric transformer is discontinued. Further, due to costly operation of generator, the priority for repair may be given to transformer over generator. Chander [5] discussed reliability models with priority for operation and repair.
Further, the weather conditions cannot be controlled easily by human beings. The conditions may change due to changing climate, earthquake, vibrations and other unforeseen reasons. Therefore, Malik and Barak [6] evaluated reliability and economic measures of a single -unit system with no operation and repair in abnormal weather. It is also pointed out here that not much work related to stochastic analysis of repairable systems of non-identical units with priority for operation and repair subject to different weather conditions has been reported so far in the literature of reliability.
In view of the above, the present paper deals with the stochastic analysis of a repairable system of two non-identical units – one is original (called main unit) and other is substandard (called a duplicate unit). The system performs under two weather conditions – normal and abnormal. Initially, the main unit is operative and duplicate unit is kept as spare in cold standby. Each unit has direct complete failure from normal mode. Both units are capable of performing the system functions well with different degree of reliability and desirability. There is a single server who visits the system immediately whenever needed. The operation and repair of the units are stopped in abnormal weather. And, in normal weather, priority is given for operation and repair of the main unit over duplicate unit. After repair, each unit works as new. All random variables are statistically independent and uncorrelated. The switch devices are perfect. The failure times of the units and time of change of weather conditions follow negative exponential distributions. And, repair times of the units are arbitrarily distributed. Various reliability and performance measures such as transition probabilities, mean sojourn times, mean time to system failure (MTSF), steady state availability, busy period of the server, expected no of visits by the server and profit function are obtained using semi-Markov process and regenerative point technique. The graphical behavior of MTSF, availability and profit functions with respect to normal weather rate has also been examined for a particular case.

2.NOTATIONS

E : The set of regenerative states

MO/DO : Main/Duplicate unit is good and operative

$\overline{\text{MWO}}$ / $\overline{\text{DWO}}$: Main/Duplicate unit is good but waiting for operation due to abnormal weather

DCs : Duplicate unit is in cold standby mode

λ / $\lambda 1$: Constant failure rate of Original /Duplicate unit

β / $\beta 1$: Constant rate of change of weather from normal to abnormal/abnormal to normal weather

MFur/DFur : Main/duplicate unit failed and under repair

MFUR/DFUR: Main/duplicate unit failed and under repair continuously from previous state

MFwr/DFwr : Main/duplicate unit failed and waiting for repair

MFWR/DFWR : Main/duplicate unit failed and waiting for repair continuously from previous state

$\overline{\text{MFwr}}$ / $\overline{\text{DFwr}}$: Main/Duplicate unit failed and waiting for repair due to abnormal weather

$\overline{\text{MFWR}}$ / $\overline{\text{DFWR}}$: Main/Duplicate unit failed and waiting for repair continuously from previous state due to abnormal weather

g(t)/G(t) : pdf/cdf of repair time of Original unit

g1(t) / G1(t) : pdf/cdf of repair time of Duplicate unit

qij (t) / Qij (t) : pdf/cdf of passage time from regenerative state i to a regenerative state j or to a failed state j without visiting any other regenerative state in (0,t]

qij.kr (t) / Qij.kr (t) : pdf/cdf of direct transition time from Regenerative state i to a regenerative state j or to a failed state j visiting state k,r once in (0,t]

q ij.k,(r,s)n(t) /Qij.k,(r,s)n(t) : pdf/cdf of direct transition time from regenerative state i to a regenerative state j or to a failed state j visiting state k once and n times states r and s.

Mi(t) : Probability that the system is up initially in regenerative state Si at time t without visiting to any other regenerative state

Wi(t) : Probability that the server is busy in state Si upto time t without making any transition to any other regenerative state or returning to the same via one or more non-regenerative states

mij : The unconditional mean time taken by the system to transits from any regenerative state Si Є S when time is counted from epoch of entrance into that state Sj. Mathematically, it can be written as mij= ∫tQij(t)=-qij *'(0)

μ_i : The mean sojourn time in state Si this is given by μ_i =E(t)=∫P(T>t)dt=∑jmij,where T denotes the time to system failure

Ⓢ/©/©n : Symbol for Laplace Stieltjes Convolution / Laplace convolution / Laplace convolution n times

~ / * : Symbol for Laplace Steiltjes Transform (LST)/ Laplace Transform (LT)

' (desh) : Used to represent derivative

The following are the possible transition states of the system

S0 = (MO, DCs), S1 = (MFur, DO),

S2 = ($\overline{\text{MWO}}$, $\overline{\text{DCs}}$), S3 = ($\overline{\text{MFwr}}$, $\overline{\text{DWO}}$),

S4 = (MFUR, DFwr), S5 = (MO, DFur),

S6 = ($\overline{\text{MFwr}}$, $\overline{\text{DFWR}}$), S7 = (MFur, DFWR),

S8 = ($\overline{\text{MWO}}$, $\overline{\text{DFwr}}$), S9 = (MFur,DFwr)

The states S0, S1, S2, S3, S5, S8, S9 are regenerative while the states S4, S6, S7 are non regenerative as shown in figure1.

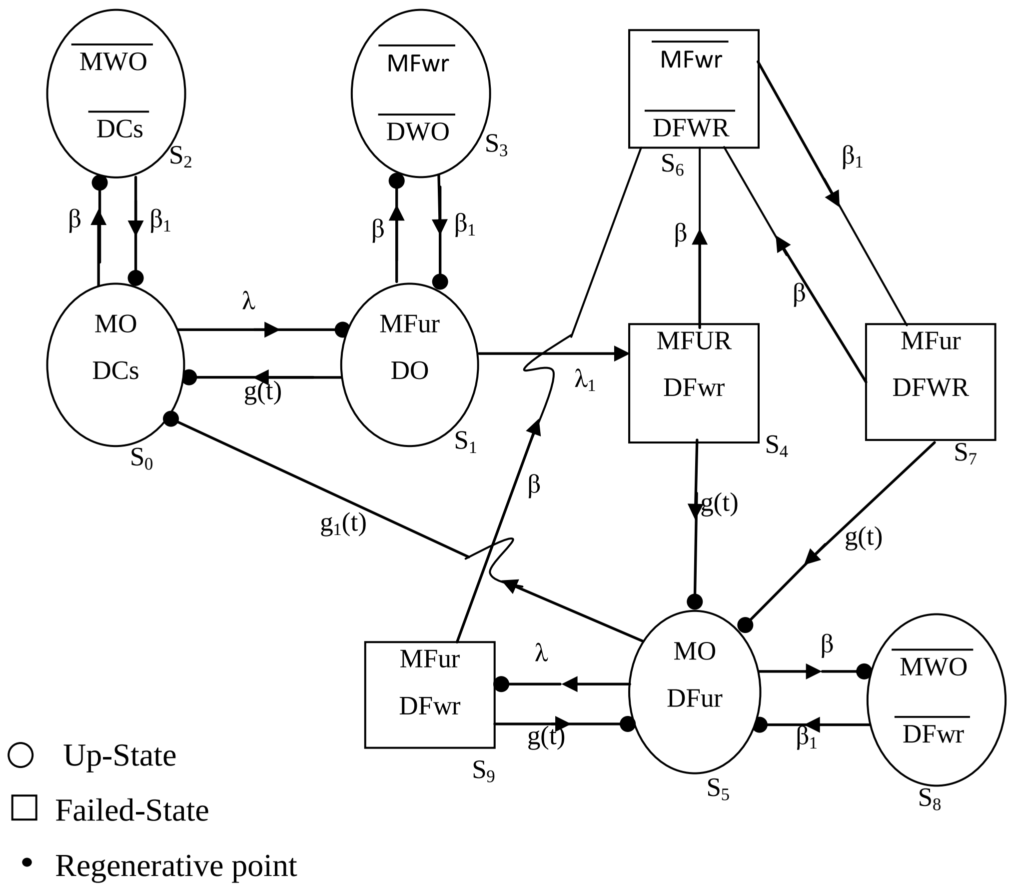

Fig. 1 State Transition Diagram

3. RELIABILITY INDICES

3.1Transition Probabilities and Mean Sojourn Times

Simple probabilistic considerations yield the following expressions for the non-zero elements $p_{ij}=Q_{ij}(\infty)=\int q_{ij}(t)dt$ we have

$p_{01}=\frac{\lambda}{\beta+\lambda}$, $p_{02}=\frac{\beta}{\beta+\lambda}$, $p_{10}=g^*(\beta+\lambda_1)$,

$p_{13}=\frac{\beta}{\beta+\lambda_1}(1-g^*(\beta+\lambda_1)$, $p_{14}=\frac{\lambda_1}{\beta+\lambda_1}(1-g^*(\beta+\lambda_1)$, $p_{20}=1$,

$p_{31}=1$, $p_{45}=g^*(\beta)$, $p_{46}=1-g^*(\beta)$, $p_{50}=g_1^*(\beta+\lambda)$,

$p_{58}=\frac{\beta}{\beta+\lambda}(1-g_1^*(\beta+\lambda))$, $p_{59}=\frac{\lambda}{\beta+\lambda}(1-g_1^*(\beta+\lambda))$,

$p_{67}=1$, $p_{75}=g^*(\beta)$, $p_{76}=1-g^*(\beta)$, $p_{85}=1$, $p_{95}=g^*(\beta)$,

$p_{96}=1-g^*(\beta)$ (1)

It can be easily verified that

$$p_{01}+p_{02}=p_{10}+p_{13}+p_{14}=p_{20}=p_{31}=p_{45}+p_{46}=$$
$$p_{50}+p_{58}+p_{59}=p_{67}=p_{75}+p_{76}=p_{85}=p_{95}+p_{96}=1 \quad (2)$$

The mean sojourn times (μ_i) in the state S_i are

$\mu_0=\frac{1}{\beta+\lambda}$, $\mu_1=\frac{1}{\beta+\lambda_1}(1-g^*(\beta+\lambda_1))$,

$\mu_2=\frac{1}{\beta_1}$, $\mu_3=\frac{1}{\beta_1}$, $\mu_4=\frac{1}{\beta}(1-g^*(\beta)$,

$\mu_5=\frac{1}{\beta+\lambda}(1-g_1^*(\beta+\lambda))$, $\mu_6=\frac{1}{\beta_1}$,

$\mu_7=\frac{1}{\beta}(1-g^*(\beta)$, $\mu_8=\frac{1}{\beta_1}$, $\mu_9=\frac{1}{\beta}(1-g^*(\beta))$ (3)

Also

$m_{01}+m_{02}=\mu_0$, $m_{10}+m_{13}+m_{14}=\mu_1$, $m_{20}=\mu_2$, $m_{31}=\mu_3$,
$m_{45}+m_{46}=\mu_4$, $m_{50}+m_{58}+m_{59}=\mu_5$, $m_{67}=\mu_6$, $m_{75}+m_{76}=\mu_7$,
$m_{85}=\mu_8$, $m_{95}+m_{96}=\mu_9$ (4)

and

$\mu'_1=m_{10}+m_{13}+m_{15.4}+m_{15.4,(6,7)}{}^n\mu'_9=m_{95}+m_{95.(6,7)}{}^n$ (5)

3.2Reliability and Mean Time to System Failure (MTSF)

Let $\phi_i(t)$ be the cdf of first passage time from regenerative state i to a failed state. Regarding the failed state as absorbing state, we have the following recursive relations for $\phi_i(t)$:

$\phi_0(t) = Q_{01}(t)Ⓢ\phi_1(t) + Q_{02}(t)Ⓢ\phi_2(t)$

$\phi_1(t) = Q_{10}(t)Ⓢ\phi_0(t)+Q_{13}(t)Ⓢ\phi_1(t)+Q_{14}(t)$

$\phi_2(t) = Q_{20}(t)Ⓢ\phi_0(t)$, $\phi_3(t) =Q_{31}(t)Ⓢ\phi_1(t)$ (6)

Taking LST of above relation (6) and solving for $\tilde{\phi}_0(s)$

We have

$$R^*(s) = \frac{1-\tilde{\phi}_0(s)}{s} \quad (7)$$

The reliability of the system model can be obtained by taking Laplace inverse transform of (7).

The mean time to system failure (MTSF) is given by

$$MTSF = \lim_{s\to o}\frac{1-\tilde{\phi}_0(s)}{s} = \frac{N_1}{D_1} \quad (8)$$

where

$N_1=p_{01}(p_{13}\mu_3+\mu_1)+(1-p_{13})(\mu_0+p_{02}\mu_2)$

$D_1=p_{01}p_{14}$ (9)

3.3Steady State Availability

Let $A_i(t)$ be the probability that the system is in up-state at instant 't' given that the system entered regenerative state i at t = 0.The recursive relations for $A_i(t)$ are given as

$A_0(t) =M_0(t) +q_{01}(t) © A_1(t) + q_{02}(t) © A_2(t)$

$A_1(t) = M_1(t) +q_{10}(t)©A_0(t)+ q_{13}(t) © A_3(t) +(q_{15.4}(t)+q_{15.4,(6,7)}{}^n(t)) ©A_5(t)$

$A_2(t) = q_{20}(t) © A_0(t)$,$A_3(t)=q_{31}(t)©A_1(t)$

$A_5(t)= M_5(t)+q_{50}(t)©A_0(t)+q_{58}(t)©A_8(t)+q_{59}(t)©A_9(t)$

$A_8(t)=q_{85}(t) ©A_5(t)$,$A_9(t)=(q_{95}(t)+q_{95.(6,7)}{}^n)(t) ©A_5(t)$ (10)

where $M_i(t)$ is the probability that the system is up initially in state $S_i\in E$ is up at time t without visiting to any other regenerative state, we have

$M_0(t)=e^{-(\beta+\lambda)t}$, $M_1(t)=e^{-(\beta+\lambda_1)t}\overline{G(t)}$, $M_5(t)=e^{-\beta t}\overline{G(t)}$ (11)

Taking LT of above relations (10) and solving for $A_0^*(s)$.

The steady state availability is given by

$$A_0(\infty)=\lim_{s\to 0}sA_0^*(s)=\frac{N_2}{D_2} \quad (12)$$

where

$N_2=p_{50}(\mu_0(1-p_{13})+\mu_1p_{01})+\mu_5p_{01}p_{14}$

and

$D_2=p_{01}p_{14}(\mu_5+\mu_8p_{58}+p_{59}\mu'_9)+p_{50}(p_{01}(\mu'_1+p_{13}\mu_3)+ (1-p_{13})(\mu_0+p_{02}\mu_2))$

3.4Busy period analysis for server

Let $B_i(t)$ be the probability that the server is busy in repairing the unit at an instant't' given that the system entered regenerative state i at t=0.The recursive relations for $B_i(t)$ are as follows:

$B_0(t)=q_{01}(t)©B_1(t)+q_{02}(t)©B_2(t)$

$B_1(t)=W_1(t)+q_{10}(t)©B_0(t)+q_{13}(t)©B_3(t) +(q_{15.4}(t)+q_{15.4,(6,7)}{}^n(t))©B_5(t)$

$B_2(t)=q_{20}(t)©B_0(t)$,$B_3(t)=q_{31}(t)©B_1(t)$

$B_5(t)=W_5(t)+q_{50}(t)©B_0(t)+q_{58}(t) ©B_8(t)+q_{59}(t)©B_9(t)$

$B_8(t)=q_{85}(t) ©B_5(t)$,

$B_9(t)=W_9(t)+(q_{95}(t)+q_{95.(6,7)}{}^n(t)) ©B_5(t)$ (14)

where $W_i(t)$ be the probability that the server is busy in state S_i due to failure upto time t without making any transition to any other regenerative state or returning to the same via one or more non regenerative states so,

$W_1(t)=e^{-(\beta+\lambda_1)t}\overline{G(t)} +(\lambda_1e^{-(\beta+\lambda_1)t}©1)\overline{G(t)}$,

$W_5(t)=e^{-(\beta+\lambda)t}$,$W_9(t)=e^{-\beta t}\overline{G(t)}$ (15)

Taking LT of above relations (14) and solving for $B_0^*(s)$.The time for which server is busy due to repair is given by

$B_0^*(\infty) = \lim_{s\to 0} sB_0^*(s) = \frac{N_3}{D_2}$

where

$N_3 = p_{01}p_{50}W_1^*(0) + p_{01}p_{14}(W_5^*(0) + W_9^*(0)p_{59})$

and D_2 is already mentioned.

3.5Expected number of visits by the server

Let $N_i(t)$ be the expected number of visits by the server in (0,t] given that the system entered the regenerative state i at t=0. The recursive relations for $N_i(t)$ are given as

$N_0(t) = Q_{01}(t)$ Ⓢ$[1+N_1(t)] + Q_{02}(t)$ Ⓢ$N_2(t)]$

$N_1(t) = Q_{10}(t)$Ⓢ$N_0(t)+Q_{13}(t)$Ⓢ$N_3(t)$

$+(Q_{15.4}(t)+Q_{15.4,(67)^n})$Ⓢ$N_5(t)$

$N_2(t) = Q_{20}(t)$ Ⓢ$N_0(t)$,$N_3(t) = Q_{31}(t)$ Ⓢ$N_1(t)$

$N_5(t) = Q_{50}(t)$Ⓢ$N_0(t)+Q_{58}(t)$Ⓢ$N_8(t)+Q_{59}(t)$ Ⓢ$N_9(t)$

$N_8(t) = Q_{85}(t)$Ⓢ$N_5(t)$,

$N_9(t)=Q_{95}(t)+Q_{95.(6,7)^n}(t))$Ⓢ$N_5(t)$ (16)

Taking LST of relations (16) and solving for $\tilde{N}_0(s)$.

The expected numbers of visits per unit time by the server are given by

$$N_0(\infty) = \lim_{s\to 0} s\tilde{N}_0(s) = \frac{N_4}{D_2}$$

where

$N_4 = p_{01}p_{50}(1-p_{13})$

and D_2 is already specified.

3.6Profit Analysis

The profit incurred to the system model in steady state caN be obtained as

$P_i = K_0A_0 - K_1B_0 - K_2N_0$

where

K_0=Revenue per unit up-time of the system

K_1=Cost per unit for which server is busy

K_2= Cost per unit visit by the server

and A_0, B_0, N_0 are already defined.

Particular Case

Suppose $g(t) = \alpha e^{-\alpha t}$,$g_1(t) = \alpha_1 e^{-\alpha_1 t}$

By using the non zero elements p_{ij},we can obtain the following results:

$p_{01} = \frac{\lambda}{\beta+\lambda}$, $p_{02} = \frac{\beta}{\beta+\lambda}$, $p_{10} = \frac{\alpha}{\alpha+\beta+\lambda_1}$, $p_{13} = \frac{\beta}{\alpha+\beta+\lambda_1}$,

$p_{14} = \frac{\lambda_1}{\alpha+\beta+\lambda_1}$, $p_{20}=1$, $p_{31}=1$, $p_{45} = \frac{\alpha}{\alpha+\beta}$, $p_{46} = \frac{\beta}{\alpha+\beta}$,

$p_{50} = \frac{\alpha_1}{\alpha_1+\beta+\lambda}$, $p_{58} = \frac{\beta}{\alpha_1+\beta+\lambda}$, $p_{59} = \frac{\lambda}{\alpha_1+\beta+\lambda}$,

$p_{67}=1$, $p_{75} = \frac{\alpha}{\alpha+\beta}$, $p_{76} = \frac{\beta}{\alpha+\beta}$, $p_{85}=1$,

$p_{95} = \frac{\alpha}{\alpha+\beta}$, $p_{96} = \frac{\beta}{\alpha+\beta}$

also

$\mu_0 = \frac{1}{\beta+\lambda}$, $\mu_1 = \frac{1}{\alpha+\beta+\lambda_1}$, $\mu_2 = \frac{1}{\beta_1}$, $\mu_3 = \frac{1}{\beta_1}$, $\mu_4 = \frac{1}{\alpha+\beta}$,

$\mu_5 = \frac{1}{\alpha_1+\beta+\lambda}$, $\mu_6 = \frac{1}{\beta_1}$, $\mu_7 = \frac{1}{\alpha+\beta}$, $\mu_8 = \frac{1}{\beta_1}$, $\mu_9 = \frac{1}{\alpha+\beta}$

$\mu'_1 = \frac{\alpha\beta_1(\alpha+\beta+\lambda_1)+\lambda_1\beta(\alpha+\beta+\beta_1)}{\alpha\beta_1(\alpha+\beta+\lambda_1)(\alpha+\beta)}$, $\mu'_9 = \frac{(\beta+\beta_1)}{\alpha\beta_1}$

MTSF $(T_0) = \frac{N_1}{D_1}$,

Steady state availability $(A_0) = \frac{N_2}{D_2}$,

Busy period analysis for server$(B_0) = \frac{N_3}{D_2}$, (17)

Expected number of visits by the server$(N_0) = \frac{N_4}{D_2}$

Where

$N_1 = (\alpha+\lambda+\lambda_1)(\beta+\beta_1)$

$D_1 = \lambda\lambda_1\beta_1$

$N_2 = \alpha\beta_1(\alpha_1(\alpha+\lambda)+\lambda_1(\alpha_1+\lambda))$

$D_2 = (\beta+\beta_1)(\alpha+\lambda)(\lambda\lambda_1+\alpha_1(\alpha+\lambda_1))$

$N_3 = \frac{\beta_1\lambda(\alpha_1(\alpha+\lambda_1)(\beta+\lambda)+\alpha\lambda_1(\alpha+\beta+\lambda))}{(\alpha+\beta)}$

$N_4 = \alpha\beta_1\lambda\alpha_1(\alpha_1+\lambda)$

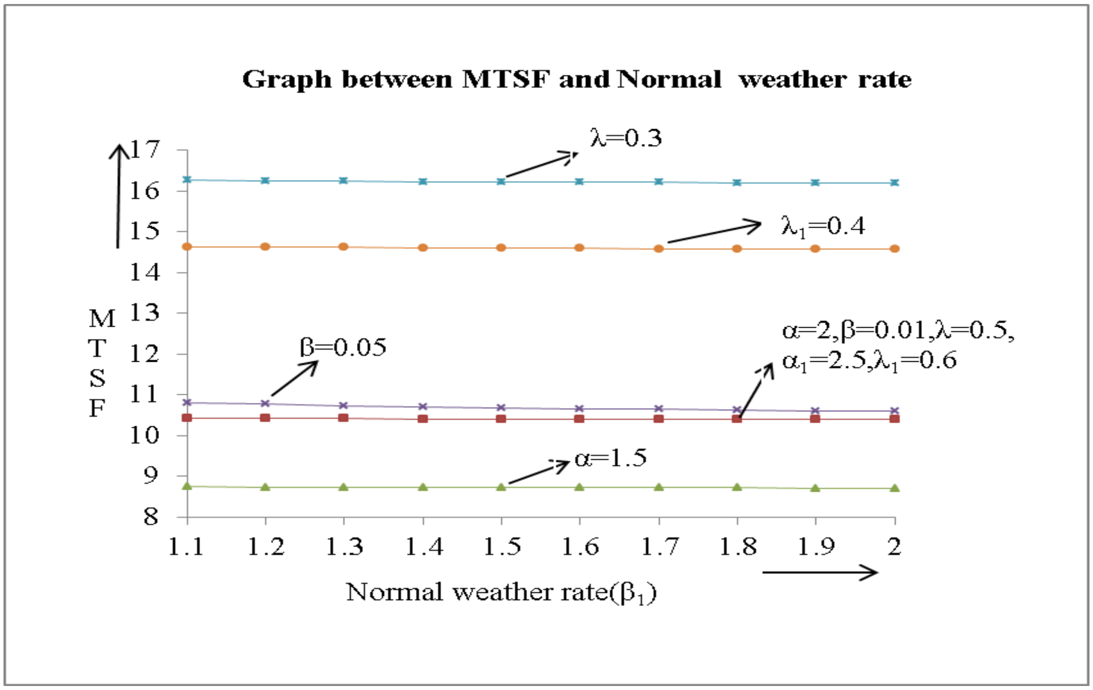

Fig : 2

Table: 1

Normal Weather Rate (β_1)	α=2,β=0.01, λ=0.5λ_1=0.6	α=1.5	β=0.05	λ=0.3	λ_1=0.4
1.1	10.42727	8.745455	10.80303	16.25758	14.63182
1.2	10.41944	8.738889	10.76389	16.24537	14.62083
1.3	10.41282	8.733333	10.73077	16.23504	14.61154
1.4	10.40714	8.728571	10.70238	16.22619	14.60357
1.5	10.40222	8.724444	10.67778	16.21852	14.59667
1.6	10.39792	8.720833	10.65625	16.21181	14.59063
1.7	10.39412	8.717647	10.63725	16.20588	14.58529
1.8	10.39074	8.714815	10.62037	16.20062	14.58056

1.9	10.38772	8.712281	10.60526	16.19591	14.57632
2	10.385	8.71	10.59167	16.19167	14.5725

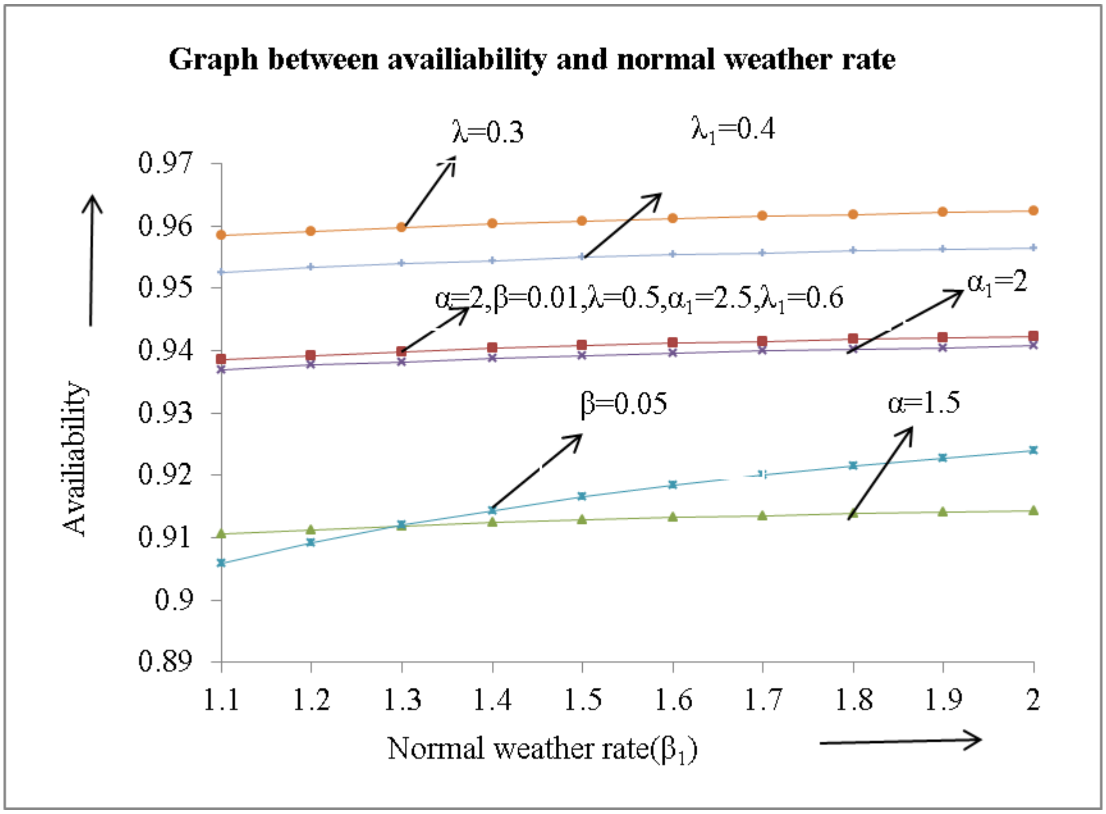

Fig.3

Table: 2

Normal weather Rate(β_1)	$\alpha=2,\beta=0.01,\lambda=0.5,$ $\alpha_1=2.5,\lambda_1=0.6$	$\alpha=1.5$	$\alpha_1=2$	$\beta=0.05$	$\lambda=0.3$	$\lambda_1=0.4$
1.1	0.93853	0.91064	0.93694	0.90588	0.95848	0.95263
1.2	0.93923	0.91132	0.93764	0.90918	0.9592	0.95335
1.3	0.93983	0.9119	0.93824	0.91198	0.95981	0.95395
1.4	0.94034	0.9124	0.93875	0.9144	0.96034	0.95447
1.5	0.94079	0.91283	0.93919	0.91651	0.96079	0.95492
1.6	0.94118	0.91321	0.93958	0.91836	0.96119	0.95532
1.7	0.94152	0.91355	0.93993	0.92	0.96154	0.95567
1.8	0.94183	0.91384	0.94023	0.92146	0.96185	0.95598
1.9	0.9421	0.91411	0.9405	0.92278	0.96213	0.95626
2	0.94235	0.91435	0.94075	0.92396	0.96238	0.95651

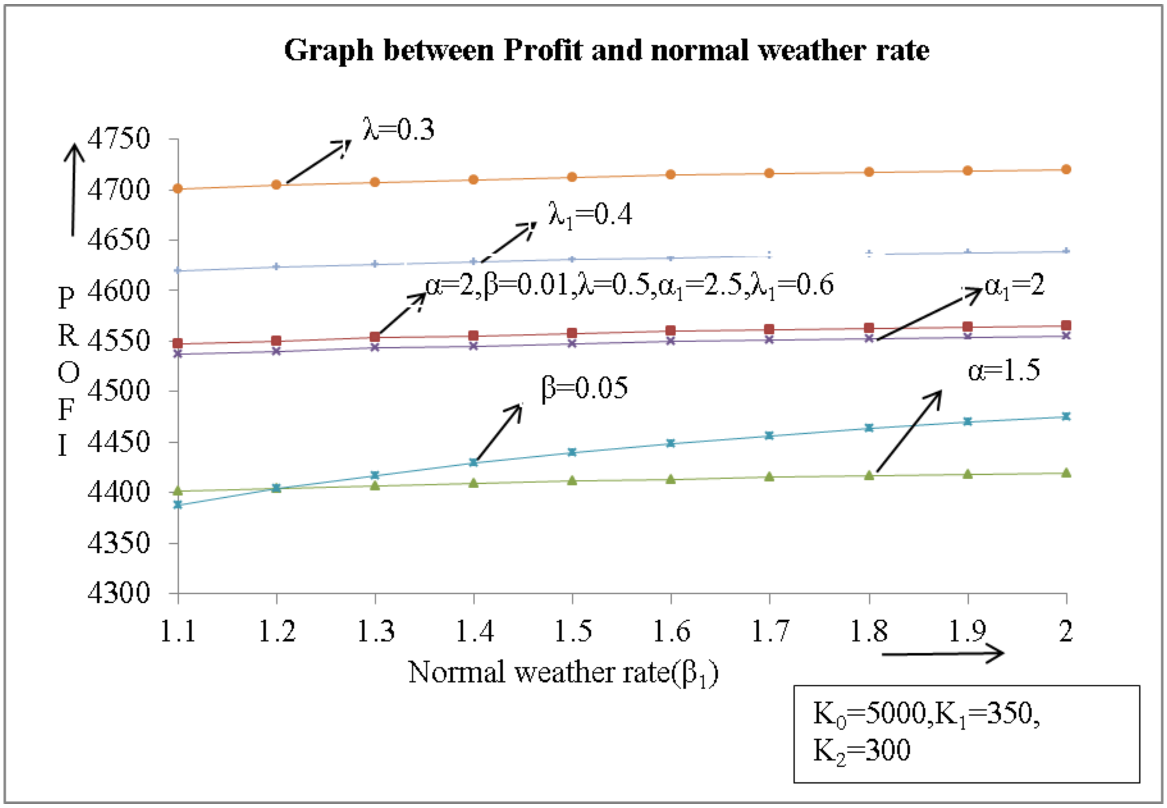

Fig: 4

Table:3

Normal weather rate(β_1)	α=2,β=0.01λ=0.5, α_1=2.5,λ_1=0.6, K_0=5000,K_1=350, K_2=300	α=1.5	α_1=2	β=0.05	λ=0.3	λ_1=0.4
1.1	4546.85	4401.32	4536.71	4387.82	4700.82	4619.86
1.2	4550.27	4404.63	4540.12	4403.78	4704.35	4623.33
1.3	4553.16	4407.43	4543.01	4417.37	4707.34	4626.27
1.4	4555.64	4409.83	4545.49	4429.09	4709.91	4628.79
1.5	4557.8	4411.92	4547.64	4439.29	4712.14	4630.98
1.6	4559.69	4413.75	4549.52	4448.26	4714.09	4632.9
1.7	4561.35	4415.36	4551.18	4456.21	4715.81	4634.59
1.8	4562.84	4416.79	4552.66	4463.29	4717.34	4636.1
1.9	4564.16	4418.08	4553.99	4469.65	4718.72	4637.45
2	4565.36	4419.24	4555.18	4475.39	4719.95	4638.66

4. CONCLUSION

The stochastic behavior of mean time to system failure (MTSF), availability and profit function has been observed on the basis of graphs obtained for a particular case as shown in figures 2, 3 and 4 respectively. From figure 2, it is analyzed that MTSF goes on decreasing with the increase of normal weather rate (β_1) and failure rate (λ and λ_1). However, MTSF increases with increase of abnormal weather rate (β) and repair rate (α) of the main unit. Figures 3 and 4 indicate that the values of availability and profit keep on increasing with the increase of normal weather rate (β_1) and repair rates (α and α_1). But their values decline as and when abnormal weather rate (β) and failure rates (λ and λ_1) increase. Hence, the graph reveals that a system of non-identical unit working under different weather conditions can be made more profitable by increasing repair rates of the main unit as well as by providing normal weather as much as possible for operation of the system.

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