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Effect of Weather on Priority Based Redundant System

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Abstract: The influence of weather on the performance measures of two redundant repairable systems are compared. Both system comprises of two non-identical units namely main unit (original unit) and duplicate unit (substandard unit). Both units are capable of performing the same set of activities with different efficiency. The influence of weather is completely ignored for system I, while system II is operating under different weather conditions – normal and abnormal. Effective performance measures for both the system are obtained in steady state by using semi-Markov process and regenerative point technique. For both the systems, initially, one original unit is operative while the other substandard unit is taken as a spare in cold standby. Each unit has direct complete failure from normal mode. A single server is provided immediately to do repair of the failed unit. However, in system II repair is not allowed in abnormal weather while system remains operative. Priority is given to operation and repair of main unit over duplicate unit. The distributions for failure time of the units and time to change of weather conditions are taken as negative exponential while that of repair time of the units are arbitrary. All random variables are statistically independent. Repairs and switch devices are perfect. Graphs are drawn to depict the behavior of MTSF, availability and profit with respect to normal weather rates for arbitrary values of various parameters and costs.

Index Terms - Redundant System, Semi-Markov process, Regenerative Point Technique, Performance Measures

I. Introduction

The influence of weather conditions on the performance of a single unit repairable system has catered the attention of many researchers including Barak and Malik [2007], Pawar [2010], Promila [2012], Kadyan et al.[2014], Barak et al.[2014] and Kumar [2016] by considering various repair mechanisms. It is found the when the system is not allowed to operate or the repair mechanism is stopped in abnormal weather then it increases the downtime of the system. So, in view of this redundancy techniques are used which not only increases the uptime but also improve the efficiency and performance of repairable systems. Baweja [2014] studied the cold standby system with priority. Deswal et al. [2013] and N.Rajni [2016] studied cold standby redundant system with priority under different weather conditions.

MODELS DESCRIPTION

- Both Models comprises of repairable system of two units namely Main and Duplicate. Both are capable of doing same set of activities but with different proficiency. Main unit is the priority unit for operation as well as for repair
- System is subjected to two type of weather conditions-normal and abnormal.
- Initially, main unit is operative and other is kept as cold standby.
- Both units have two modes normal operative, under repair due to failure
- In Model I neither the system is allowed to operate or repaired in abnormal weather but in Model II the is performing in all weather conditions
- The failure time distribution and time to change weather conditions are exponentially distributed while repair times are distributed arbitrarily.
- There is a single server who visits the system immediately as and when required in normal weather conditions.
- The switch devices, repairs are perfect.
- All random variables are statistically independent.

METHODOLOGY

The systems have been analyzed using well known semi-Markov process and regenerative point technique which are briefly described as:

Markov Process:
If {X(t), t∈T} is a stochastic process such that, given the value of X(s), the value of X(t), t>s do not depend on the values of X(u), u<s Then the process {X(t), t∈T} is a Markov process.

Semi-Markov Process:
A semi-Markov process is a stochastic process in which changes of state occur according to a Markov chain and in which the time interval between two successive transitions is a random variable, whose distribution may depend on the state from which the transition take place as well as on the state to which the next transition take place.

Regenerative Process:
Regenerative stochastic process was defined by Smith (1955) and has been crucial in the analysis of complex system. In this, we take time points at which the system history prior to the time points is irrelevant to the system conditions. These points are called regenerative points. Let X(t) be the state of the system of epoch. If t1, t2,... are the epochs at which the process probabilistically restarts, then these epochs are called regenerative epochs and the process {X(t), t = t1, t2.........} is called regenerative process. The state in which regenerative points occur is known as regenerative state.

The goal of the present study is to discuss a two-unit cold standby repairable systems I &II consisting of non-identical units with priority to operation and repair to main unit subjected to different weather conditions. The following measures of reliability for the systems are obtained:

- Transition probabilities
- Mean sojourn times
- Mean time to system failure
- Steady State Availability
- Busy period of the server due to repair
- Expected number of visits by the server
- Expected profit earned by the system in (0, t)
- Comparative analysis of reliability of two systems
- Comparative analysis of Profit earned by two systems

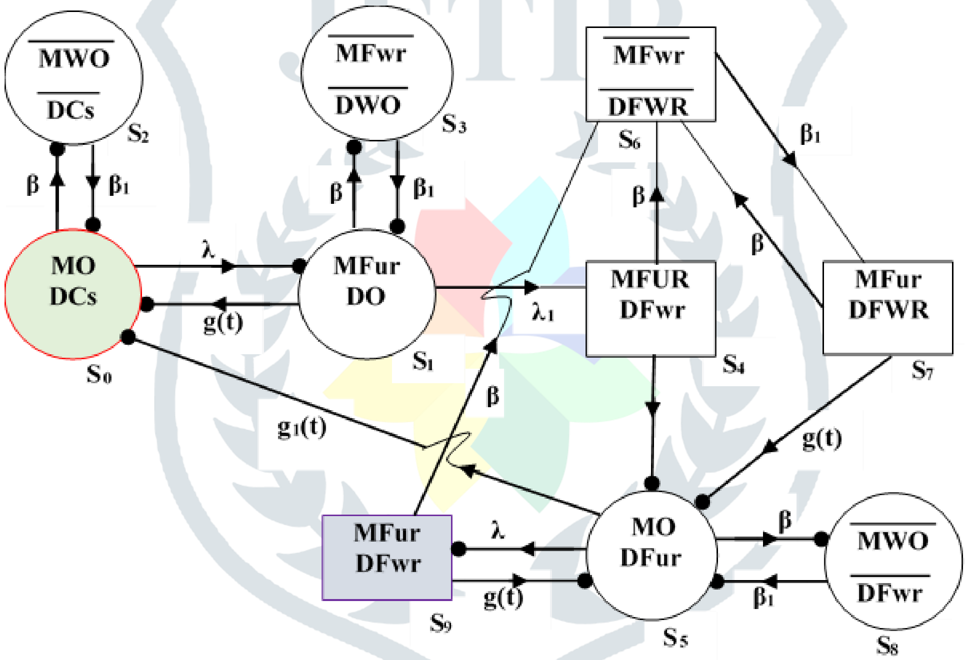
The application of the present work can be visualized in a software industry where application software is run through two different databases-one is initially operative and other is kept in cold standby.

II. NOTATIONS

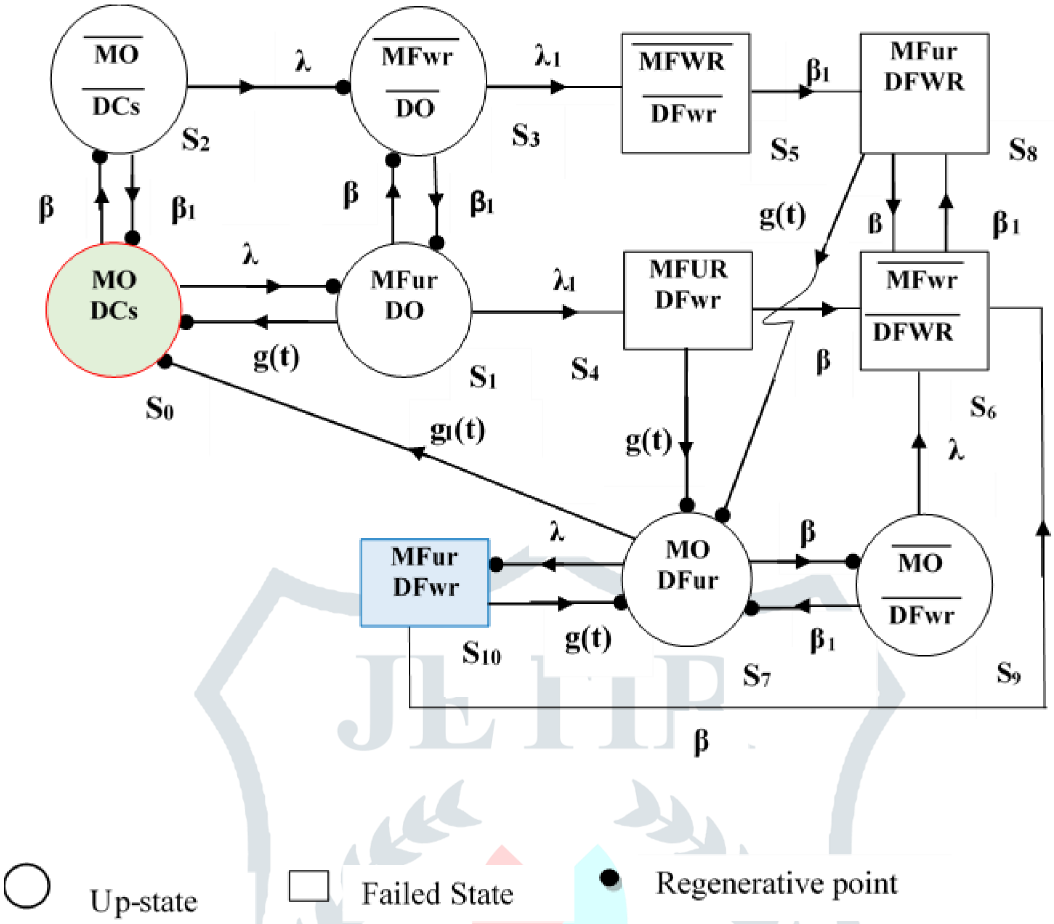
E	The set of regenerative states
MO/DO	Main/Duplicate unit is good and operative
$\overline{MWO}$ / $\overline{DWO}$	Main/Duplicate unit is good and waiting for operation in abnormal weather
$\overline{MO}$ / $\overline{DO}$	Main/Duplicate unit is good and operating in abnormal weather
MFur/DFur	Main/duplicate 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
$\overline{MFwr}$ / $\overline{DFwr}$	Main/Duplicate unit failed and waiting for repair due to abnormal weather
$\overline{MFWR}$ / $\overline{DFWR}$	Main/Duplicate unit failed and waiting for repair continuously from previous state due to abnormal weather
$g_1(t)$/ $G_1(t)$	pdf/cdf of repair time of Duplicate unit
q_{ij} (t)/Q_{ij} (t)	pdf/cdf of passage time from regenerative state i to regenerative state j or to a failed state j without visiting any other regenerative state in (0,t]
$q_{ij.kr}$ (t)/ $Q_{ij.kr}$ (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]
$q_{ij.k,(r,s)}^{n}(t)/Q_{ij.k,(r,s)}^{n}(t)$	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.
$M_i(t)$	Probability that the system is up initially in regenerative state Si at time t without visiting to any other regenerative state

$W_i(t)$	Probability that the server is busy in state Siupto time t without making any transition to any other regenerative state or returning to the same via one or more non-regenerative states
m_{ij}	The conditional mean sojourn time in regenerative state Si when system is to make transition in to regenerative state Sj. Mathematically, it can be written as $m_{ij} = E(T_{ij}) = \int_0^\infty t d[Q_{ij}(t)] = -q_{ij}^{*'}(0)$, where T_{ij} is the transition time from state Si to Sj; Si, Sj ε E.
μ_i	The mean Sojourn time in state Si this is given by $\mu_i = E(T_i) = \int_0^\infty P(T_i > t)dt = \sum_j m_{ij}$, where T_i is the sojourn time in state Si.
Ⓢ/©/©^{n}	Symbol for Laplace Stieltjes convolution/Laplace convolution/Laplace convolution n times
** / *	Symbol for Laplace Steiltjes Transform (L.S.T.)/ Laplace transform (L.T.)

MODEL I



MODEL II



III. TRANSITION PROBABLITIES AND MEAN SOJOURN TIMES

Simple probabilistic considerations yield the following expressions for the non-zero elements

$p_{ij} = Q_{ij}(\infty) = \int_0^\infty q_{ij}(t)dt$, we have

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:

MODEL I

$p_{01}=\frac{\lambda}{\beta+\lambda}$,$p_{02}=\frac{\beta}{\beta+\lambda}$,$p_{10}=\frac{\alpha}{\alpha+\beta+\lambda_1}$,$p_{13}=\frac{\beta}{\alpha+\beta+\lambda_1}$,$p_{14}=\frac{\lambda_1}{\alpha+\beta+\lambda_1}$,$p_{20}=1$,$p_{31}=1$,

$p_{45}=\frac{\alpha}{\alpha+\beta}$,$p_{46}=\frac{\beta}{\alpha+\beta}$,$p_{50}=\frac{\alpha_1}{\alpha_1+\beta+\lambda}$,$p_{58}=\frac{\beta}{\alpha_1+\beta+\lambda}$,$p_{59}=\frac{\lambda}{\alpha_1+\beta+\lambda}$,$p_{67}=1$,

$p_{75}=\frac{\alpha}{\alpha+\beta}$,$p_{76}=\frac{\beta}{\alpha+\beta}$,$p_{85}=1$,$p_{95}=\frac{\alpha}{\alpha+\beta}$,$p_{96}=\frac{\beta}{\alpha+\beta}$,$p_{15.4}=\frac{\lambda_1}{\alpha+\beta+\lambda_1}\frac{\alpha}{\alpha+\beta}$,

$p_{15.4(6,7)^n}=\frac{\lambda_1}{\alpha+\beta+\lambda_1}\frac{\beta}{\alpha+\beta}$,$p_{95.(6,7)^n}=\frac{\beta}{\alpha+\beta}$

$\mu_0=\frac{1}{\beta+\lambda}$,$\mu_1=\frac{1}{\alpha+\beta+\lambda_1}$,$\mu_2=\frac{1}{\beta_1}$,$\mu_3=\frac{1}{\beta_1}$,$\mu_4=\frac{1}{\alpha+\beta}$,$\mu_5=\frac{1}{\alpha_1+\beta+\lambda}$,

$\mu_6=\frac{1}{\beta_1}$, $\mu_7=\frac{1}{\alpha+\beta}$, $\mu_8=\frac{1}{\beta_1}$, $\mu_9=\frac{1}{\alpha+\beta}$, $\mu'_1=\frac{\alpha\beta_1(\alpha+\beta+\lambda_1)+\lambda_1\beta(\alpha+\beta+\beta_1)}{\alpha\beta_1(\alpha+\beta+\lambda_1)(\alpha+\beta)}$, $\mu'_9=\frac{(\beta+\beta_1)}{\alpha\beta_1}$

MODEL II

$p_{01}=\frac{\lambda}{\beta+\lambda}$, $p_{02}=\frac{\beta}{\beta+\lambda}$, $p_{10}=\frac{\alpha}{\alpha+\beta+\lambda_1}$, $p_{13}=\frac{\beta}{\alpha+\beta+\lambda_1}$, $p_{14}=\frac{\lambda_1}{\alpha+\beta+\lambda_1}$, $p_{20}=\frac{\beta_1}{\beta_1+\lambda}$, $p_{23}=\frac{\lambda}{\beta_1+\lambda}$, $p_{31}=\frac{\beta_1}{\beta_1+\lambda_1}$, $p_{35}=\frac{\lambda_1}{\beta_1+\lambda_1}$, $p_{46}=\frac{\beta}{\alpha+\beta}$, $p_{46}=\frac{\alpha}{\alpha+\beta}$, $p_{58}=1$, $p_{68}=1$, $p_{70}=\frac{\alpha_1}{\alpha_1+\beta+\lambda}$, $p_{79}=\frac{\beta}{\alpha_1+\beta+\lambda}$ $p_{7,10}=\frac{\lambda}{\alpha_1+\beta+\lambda}$, $p_{86}=\frac{\beta}{\alpha+\beta}$, $p_{87}=\frac{\alpha}{\alpha+\beta}$, $p_{96}=\frac{\lambda}{\beta_1+\lambda}$, $p_{97}=\frac{\beta_1}{\beta_1+\lambda}$, $p_{10,6}=\frac{\beta}{\alpha+\beta}$, $p_{10,7}=\frac{\alpha}{\alpha+\beta}$

$p_{17.4}=\frac{\lambda_1}{\alpha+\beta+\lambda_1}\,\frac{\alpha}{\alpha+\beta}$, $p_{17.4(6,8)}^{n}=\frac{\lambda_1}{\alpha+\beta+\lambda_1}\,\frac{\beta}{\alpha+\beta}$, $p_{37.58}=\frac{\lambda_1}{\beta_1+\lambda_1}\,\frac{\alpha}{\alpha+\beta}$,

$p_{37.5(8,6)}^{n}=\frac{\lambda_1}{\beta_1+\lambda_1}\,\frac{\beta}{\alpha+\beta}$, $p_{97.(6,8)}^{n}=\frac{\lambda}{\beta_1+\lambda}$, $p_{10,7.(6,8)}^{n}=\frac{\beta}{\alpha+\beta}$

$\mu_0=\frac{1}{\beta+\lambda}$, $\mu_1=\frac{1}{\alpha+\beta+\lambda_1}$, $\mu_2=\frac{1}{\beta_1+\lambda}$, $\mu_3=\frac{1}{\beta_1+\lambda_1}$, $\mu_4=\frac{1}{\alpha+\beta}$, $\mu_5=\frac{1}{\beta_1}$, $\mu_6=\frac{1}{\beta_1}$,

$\mu_7=\frac{1}{\alpha_1+\beta+\lambda}$, $\mu_8=\frac{1}{\alpha+\beta}$, $\mu_9=\frac{1}{\beta_1+\lambda}$, $\mu_{10}=\frac{1}{\alpha+\beta}$

$\mu'_1=\frac{(\alpha\beta_1+\beta_1\lambda_1+\beta\lambda_1)}{\alpha\beta_1(\alpha+\beta+\lambda_1)}$, $\mu_3'=\frac{\alpha\beta_1+\lambda_1(\alpha+\beta+\beta_1)}{\alpha\beta_1(\beta_1+\lambda_1)}$,

$\mu_9'=\frac{\alpha\beta_1+\lambda(\alpha+\beta+\beta_1)}{\alpha\beta_1(\beta_1+\lambda)}$, $\mu'_{10}=\frac{(\beta+\beta_1)}{\alpha\beta_1}$

IV. RELIABILITY AND MEAN TIME TO SYSTEM FAILURE (MTSF)

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

$\emptyset_i(t)=\sum_j Q_{i,j}(t)Ⓢ\emptyset_j(t)+\sum_k Q_{i,k}\,(t)$

Where S_j is the un failed regenerative state and $S_k$is the absorbed state

Taking L.S.T. of above relations and solving for $\emptyset_0^{**}(s)$,we get

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

Where

MODEL I:$N_1=p_{01}(p_{13}\mu_3+\mu_1)+(1-p_{13})(\mu_0+p_{02}\mu_2)$, $D_1=p_{01}p_{14}$

MODEL II:$N_1=(1-p_{13}p_{31})\,(p_{02}\mu_2+\mu_0)+p_{01}\,(\mu_1+p_{13}\mu_1)+p_{02}p_{23}\,(\mu_1p_{31}+\mu_3)$,

$D_1=(1-p_{13}p_{31})\,(1-p_{02}p_{20})-p_{10}\,(p_{01}+p_{02}p_{23}p_{31})$

V. STEADY 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 S_i at t = 0. The recursive relations for $A_i(t)$ are given as

$A_i(t)=M_i(t)+\sum_j q_{i,j}^{(n)}(t)©A_j(t)$ where S_j is any successive regenerative state to which regenerative state S_i can transits through n transitions.

MODEL I: $M_0(t)=e^{-(\beta+\lambda)t}$, $M_1(t)=e^{-(\beta+\lambda_1)t}\ \overline{G(t)}$, $M_5(t)=e^{-(\beta+\lambda)t}\ \overline{G_1(t)}$

MODELII: $M_0(t)=e^{-(\beta+\lambda)t}$,$M_1(t)=e^{-(\beta+\lambda_1)t}\ \overline{G(t)}$,$M_2(t)=e^{-(\beta_1+\lambda)t}$,$M_3(t)=e^{-(\beta_1+\lambda_1)t}$,
$M_7(t)=e^{-(\beta+\lambda)t}\ \overline{G_1(t)}$,$M_9(t)=e^{-(\beta_1+\lambda)t}$

Taking L.T. of above relations and solving for $A_0*(s)$,we obtain $A_0(\infty)=\lim_{s\to 0} sA_0^*(s)=\frac{N_2}{D_2}$

MODEL I:

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

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

MODEL II:
$N_2= ((\mu_0+\mu_2p_{02})((1-p_{13}p_{31})+\mu_3(p_{02}p_{23}+p_{01}p_{13})+\mu_1(p_{01}+p_{02}p_{23}p_{31}))p_{70}+(p_{14}(p_{01}+p_{02}p_{23}p_{31})+p_{35}(p_{02}p_{23}+p_{01}p_{13}))(\mu_7+p_{79}\mu_9)$
$D_2= ((\mu_0+\mu_2p_{02})((1-p_{13}p_{31})+\mu_3'(p_{02}p_{23}+p_{01}p_{13})+\mu_1'(p_{01}+p_{02}p_{23}p_{31}))p_{70}+(p_{14}(p_{01}+p_{02}p_{23}p_{31})+p_{35}(p_{02}p_{23}+p_{01}p_{13}))(\mu_7+p_{79}\mu_9'+p_{7,10}\mu_{10}')$

VI. BUSY PERIOD ANALYSIS OF THE 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 S_i at t=0.The recursive relations for $B_i(t)$ are as follows:

$B_i(t) = W_i(t) + \sum_j q_{i,j}^{(n)}(t)©B_j(t)$

MODEL I: $W_1(t)=e^{-(\beta+\lambda_1)t}\ \overline{G(t)}\ +(\lambda_1 e^{-(\beta+\lambda_1)t}©1)\ \overline{G(t)}$, $W_5(t)=e^{-(\beta+\lambda)t}\ \overline{G_1(t)}\ +(\lambda e^{-(\beta+\lambda)t}©1)\ \overline{G_1(t)}$,$W_9(t)=e^{-\beta t}\ \overline{G(t)}$

MODEL II: $W_1(t)=e^{-(\beta+\lambda_1)t}\ \overline{G(t)}\ +(\lambda_1 e^{-(\beta+\lambda_1)t}©1)\ \overline{G(t)}$,$W_7(t)=e^{-(\beta+\lambda)t}\ \overline{G_1(t)}$,
$W_{10}(t)=e^{-\beta t}\ \overline{G(t)}\ +(\beta e^{-\beta t}©1)\ \overline{G(t)}$

Taking L.T. of above relations and solving for $B_0^*(s)$, $B_0*(\infty)=\lim_{s\to 0} sB_0^*(s) =\frac{N_3}{D_2}$

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

MODELII: $N_3=(W_7*(0)+p_{7,10}W_{10}*(0))(p_{14}(p_{01}+p_{02}p_{23}p_{31})+p_{35}(p_{01}p_{13}+p_{02}p_{23}))+p_{70}W_1*(0)(p_{01}+p_{02}p_{23}p_{31})$

VII. EXPECTED 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 S_i at t=0. The recursive relations for $N_i(t)$ are given as:

$N_i(t) = \sum_j Q_{i,j}^{(n)}(t)\ Ⓢ[\delta_i + N_j(t)]$

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

$$N_0(\infty)=\lim_{s\to 0} sN_0^{**}(s)=\frac{N_4}{D_2}$$

MODEL I:$N_4=p_{01}(1+p_{14}p_{46})p_{50}+p_{14}(p_{58}+p_{59}p_{96}))$

MODEL II: $N_4=p_{70}p_{01}(1-p_{13}p_{31})-p_{14}(p_{70}p_{47}+1-p_{77.10})(p_{01}+p_{02}p_{23}p_{31})+(p_{70}+p_{35})(p_{02}p_{23}+p_{01}p_{13})$

VIII. PROFIT ANALYSIS

The profit incurred to the system Model in steady state can be obtained as

$P_i=K_0A_0-K_1B_0-K_2N_0$;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.

IX. CONCLUSION

MODEL I:

The stochastic behavior of the mean time to system failure (MTSF), availability and profit function has been observed on the basis graphs drawn for a particular case, it is analyzed the MTSF goes on decreasing with the increase of normal weather rate (β_1) and failure rates (λ and λ_1).However, MTSF increases with increase of abnormal weather rate (β) and repair rate (α) of the main unit.The values of availability and profit 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.

MODEL II:

it is analyzed that MTSF, availability and profit go on increasing with the increase of normal weather rate (β_1) and repair rate (α) of the main unit. Also, there is an upward trend in availability and profit when repair rate (α_1) of duplicate unit increases. The values these measures decrease with the increase of abnormal weather rate (β) and failure rates (λ and λ_1).

COMPARATIVE STUDY

I. Comparison of MTSF

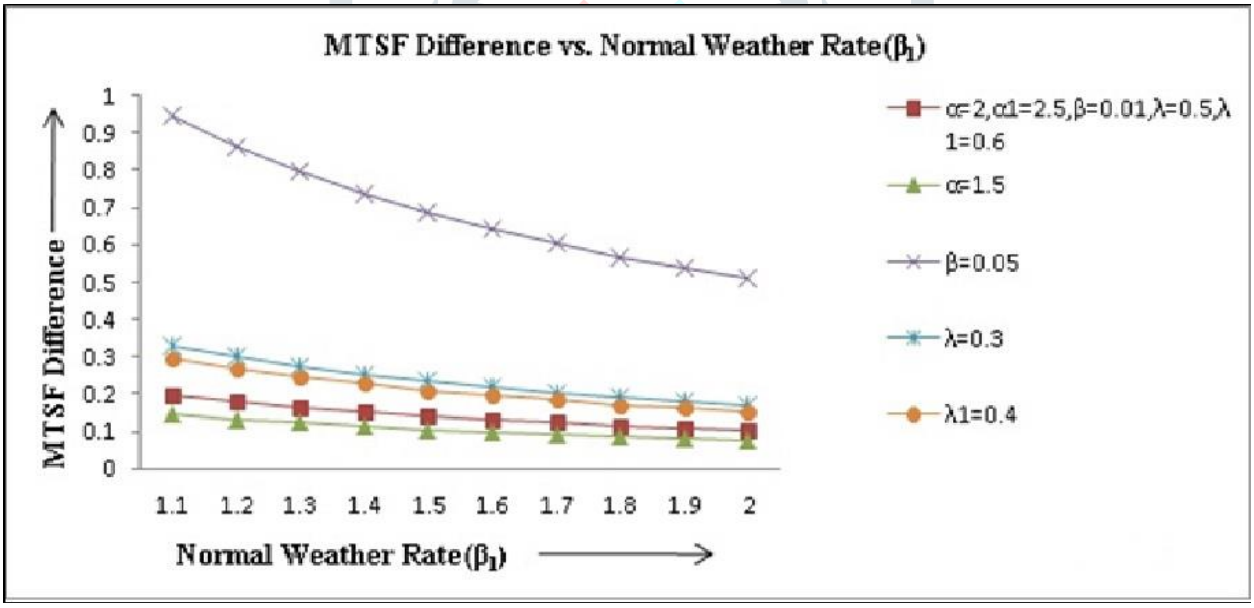
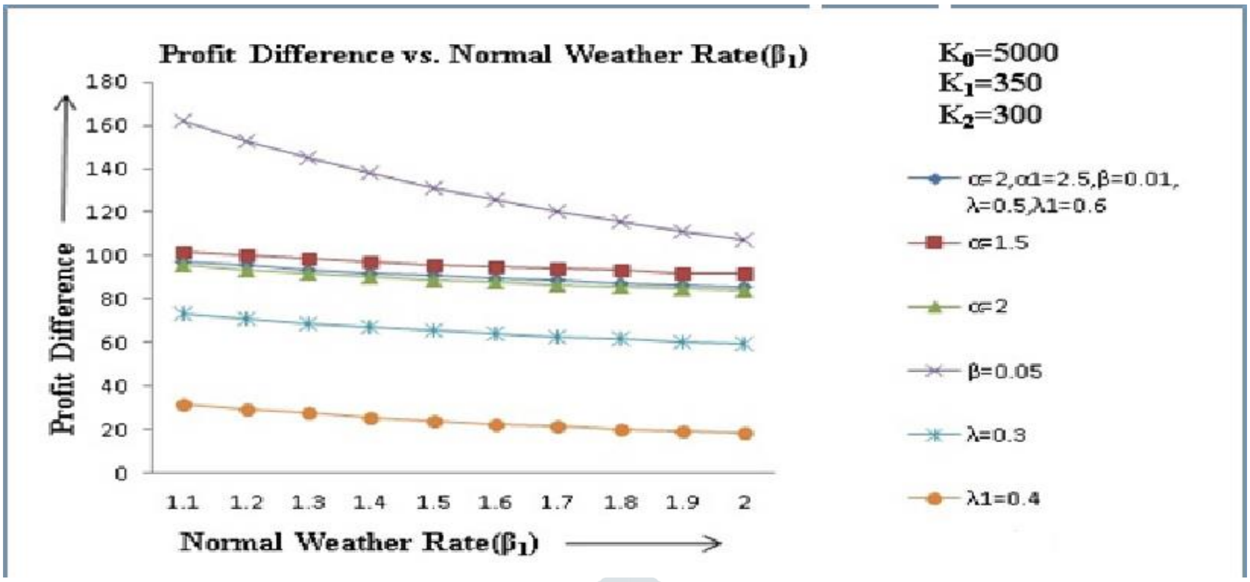


Figure indicates that MTSF difference (MODEL I-MODEL II) decreases with increase of normal weather rate (β_1) and failure rates (λ and λ_1) of the units. But, it increases with the increase of abnormal weather rate (β) and repair rate (α) of the main unit. Thus, the study reveals that the idea to allow operation of the system in abnormal weather is not useful in improving reliability of the system.

II. Comparison of Profit (Availability)



Above figure shows that the profit difference of the Models (Model II-Model I) goes on decreasing with increase of normal weather rate (β_1) and repair rate (α) of the main unit. On the other hand, profit difference follows an upward trend with the increase of repair rate (α_1) of the duplicate unit, abnormal weather rate (β) and failure rates (λ and λ_1) of the units. Thus, a system of non-identical units with priority for operation and repair to main unit over duplicate unit would be more profitable if it is allowed to operate in abnormal weather.

X. MAIN FINDINGS OF THE STUDY

The stochastic modeling of a system of non-identical units operating under different weather conditions has been done by considering different operation and repair policies. The expressions for various reliability and economic measures of the system models have been derived in steady state using semi-Markov process and regenerative point technique. The results for performance measures of the system of vital significance have been obtained for arbitrary values of the parameters and costs.
The main findings of the study are follows:

- The mean time to system failure (MTSF) increases with the increase of abnormal weather rate and repair rates of the units, provided system is not allowed to operate in abnormal weather.
- The profit of the system models go on increasing as normal weather rate and repair rates increase.
- The system cannot be made more reliable and profitable to use by giving priority for operation to main unit over the duplicate unit provided system does not work in abnormal weather.
- The concept of priority for operation and repair to main unit over duplicate unit should be used when failure rate of the main unit is less than that of duplicate unit provided operation is not allowed in abnormal weather.
- The reliability measures keep on increasing with the increase of normal weather rate and repair rates of units provided operation of the system is allowed in abnormal weather also.
- The concept of priority for operation and repair to main unit over the duplicate unit is not helpful in improving the reliability of the system if operation is allowed in abnormal weather.
- The system which operates in different weather conditions can be made more profitable by giving priority for operation and repair to main unit over duplicate unit.

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