

INTERNATIONAL JOURNAL OF RESEARCH IN COMMERCE, IT & MANAGEMENT

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THE STOCHASTIC MODELLING AND RELIABILITY ANALYSIS OF A BATTERY PRODUCTION SYSTEM IN AN INDUSTRY

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ABSTRACT

This paper is concerned with stochastic modelling and analysis of battery production system in an industry consisting of a number of units of varying nature. All the units work in sequential manner. Using regenerative point technique, the various reliability characteristics of interest such as reliability, MTSF, steady state availability, busy period and expected profit, which are useful to system managers, engineers, training supervisors and reliability analysts, are obtained. The MTSF and profit function have also been studied through graphs in respect of various parameters in order to have better understanding of the system.

KEYWORDS

Stochastic Modeling, Reliability, MTSF, Steady State Availability, Busy Period and Expected Profit.

INTRODUCTION

Although a lot of work has been done in the field of reliability but most of it is concerned with hypothetical models which are not of much practical utility because they may not exist in real life. Very few authors Sharma and Panigrahi (1990), Singh et al. (1993), Kumar et al. (1996), Singh and Nair (1997), Arora and Kumar (2000), Singh and Singh (2002), Singh (2010), Gupta et al. (2010) have studied the industrial system models with real existing situations. For the purpose of analyzing real existing system, a model of Battery production system is developed for its stochastic analysis by personally visiting the production unit situated at Sidhra in the out-skirts of Jammu city of state Jammu and Kashmir.

The given production system consists of four units of varying nature. The working of different units of the system is described as follows:

1. **BURNER:** Lead or an alloy of lead is melted in the burner and is extracted through an outlet in the form of the grid/plates. Grid is dried and active material is pasted to the grid – brown colored lead dioxide (PbO_2) on positive plates, grey colored sponge lead (Pb) on negative plates. The number and size of the plates determine current capability. Batteries with large plates or many plates produce more current than batteries with small plates or few plates. After drying the plates, plates are charged in the charging room.
2. **CELL MAKER:** It makes the cells by connecting positive and negative plates with separators in between, and then assembles them. Separators are thin sheets of porous, insulating material used as spacers between the positive and negative plates. Fine pores in the separators allow electrical current to flow between the plates while preventing short circuits.
3. **DRILLING MACHINE:** It drills plastic container so that all the cells can be fitted in the plastic container. Plastic containers and their covers are made of polypropylene.
4. **SOLDERING MACHINE:** Heavy, cast alloy metal straps are welded to the negative terminal of one cell and the positive terminal of the adjoining cell until all the cell are connected in the series, and through the railing the container is shifted to the other side of soldering machine and then the cover is welded to the container. After this battery is filled with electrolyte- a mixture of sulphuric acid and water through the holes. The battery is then checked for leaks. The final step is charging. During this step, the battery terminals are connected to a source of electricity and the battery is charged for many hours. When the battery is fully charged it is ready for use.

Using regenerative point technique the following important reliability characteristics of interest are obtained:

1. Reliability and mean time to system failure (MTSF).
2. Point wise and steady-state availabilities of the system.
3. Expected up-time of the system.
4. Expected busy period of the repairman during $(0, t)$.
5. Net expected profit incurred by the system during $(0, t)$ and in steady state.

ASSUMPTIONS

1. Failures and repairs are stochastically independent.
2. All the transitions are stochastically independent.
3. A single repair facility is always available with the system to repair a failed unit and a team of experts is called only in case of emergency repair.
4. A repaired unit is as good as new and is immediately reconnected to the system.
5. A unit fails only after producing certain number of items.
6. On starting of drilling machine, the soldering machine starts automatically as it requires certain time to maintain its pressure.
7. If one unit is already in repair and within this period if some other unit also fails then the whole system is put into emergency repair in order to make the system ready as early as possible.
8. All the failure time distributions are taken to be negative exponential.
9. All the repair time distributions are taken as arbitrary.

NOTATIONS

α	:	Constant failure rate of another unit when one unit has already failed.
α_i	:	Failure rate of the unit B/C/D/S respectively, for $i=1, 2, 3, 4$
$H_i(\cdot)$:	C.d.f of repair time of the units B/C/D/S respectively, for $i=1, 2, 3, 4$

$G_i(\cdot)$:	C.d.f of emergency repair time.
$q_{ij}(t)$:	P.d.f. of time for transition from state S_i to S_j in time $(0, t)$.
$Q_{ij}(t)$:	C.d.f. of time for transition from state S_i to S_j in time $(0, t)$.
p_{ij}	:	Steady state probability of direct transition from the regenerative state S_i to S_j .
μ_i	:	Mean sojourn time in state S_i .
$Z_i(t)$:	Probability that the system sojourns in state S_i upto time t .
*	:	Symbol for Laplace Transform, i.e. $f^*(s) = \int_0^\infty e^{-st} f(t) dt$
\sim	:	Symbol for Laplace -Stieltjes Transform i.e. $\tilde{F}(s) = \int_0^\infty e^{-st} dF(t)$

SYMBOLS FOR THE STATE OF THE SYSTEM

B_o	:	Burner is operative.
B_s	:	Burner is in standby mode.
B_r	:	Burner is under repair.
C_g	:	Cell Maker is good.
C_o	:	Cell Maker is operative.
C_r	:	Cell Maker is under repair.
D_g	:	Drilling Machine is good.
D_o	:	Drilling Machine is operative.
D_r	:	Drilling Machine is under repair.
S_g	:	Soldering Machine is good.
S_o	:	Soldering Machine is operative.
S_r	:	Soldering Machine is under repair.
Emergency repair	:	System is put under emergency repair, when any two units of system are failed.

With the help of the above symbols the possible states of the system are:

$S_0 = [B_o, B_s, C_g, D_g, S_g]$	$S_1 = [B_r, B_o, C_o, D_g, S_g]$	$S_2 = [\text{Emergency Repair}]$
$S_3 = [B_o, B_s, C_o, D_o, S_o]$	$S_4 = [B_r, B_o, C_o, D_o, S_o]$	$S_5 = [B_o, B_s, C_o, D_r, S_o]$
$S_6 = [B_o, B_s, C_o, D_o, S_r]$	$S_7 = [B_o, B_s, C_r, D_o, S_o]$	$S_8 = [B_o, B_r, C_o, D_o, S_o]$
$S_9 = [B_o, B_s, C_o, D_g, S_g]$		

The transition diagram along with all transitions is shown in figure 1.

TRANSITION PROBABILITIES

Let $T_0 (\equiv 0)$, T_1, T_2, \dots denotes the regenerative epochs and X_n denotes the state visited at epoch T_n , i.e just after the transition at T_n . Then $\{X_n, T_n\}$ constitute a Markov-Renewal process with state space E , set of regenerative states and

$$Q_{ij}(t) = P\{X_{n+1} = j, T_{n+1} - T_n \leq t | X_n = i\}$$

is the semi Markov kernel over E .

Then the transition probability matrix of the embedded Markov chain is

$$P = (p_{ij}) = (Q_{ij}(\infty)) = (Q(\infty))$$

The various steady state transition probabilities are as follows:

$p_{01} = 1$	$p_{12} = 1 - \tilde{H}_1(\alpha)$	$p_{13} = \tilde{H}_1(\alpha)$
$p_{23} = 1$	$p_{34} = \frac{\alpha_1}{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4}$	$p_{35} = \frac{\alpha_3}{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4}$
$p_{36} = \frac{\alpha_4}{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4}$	$p_{37} = \frac{\alpha_2}{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4}$	$p_{42} = 1 - \tilde{H}_1(\alpha)$
$p_{43} = \tilde{H}_1(\alpha)$	$p_{52} = 1 - \tilde{H}_3(\alpha)$	$p_{53} = \tilde{H}_3(\alpha)$
$p_{62} = 1 - \tilde{H}_4(\alpha)$	$p_{63} = \tilde{H}_4(\alpha)$	$p_{72} = 1 - \tilde{H}_2(\alpha)$
$p_{73} = \tilde{H}_2(\alpha)$	$p_{82} = 1 - \tilde{H}_1(\alpha)$	$p_{83} = \tilde{H}_1(\alpha)$
$p_{97} = \frac{\alpha_2}{\alpha_1 + \alpha_2}$	$p_{98} = \frac{\alpha_1}{\alpha_1 + \alpha_2}$	

From the obtained steady state probabilities, it can be easily verified that:

$p_{01} = p_{23} = 1$	$p_{12} + p_{13} = 1$	$p_{34} + p_{35} + p_{36} + p_{37} = 1$
$p_{42} + p_{43} = 1$	$p_{52} + p_{53} = 1$	$p_{62} + p_{63} = 1$
$p_{72} + p_{73} = 1$	$p_{82} + p_{83} = 1$	$p_{97} + p_{98} = 1$

MEAN SOJOURN TIME

Mean sojourn time in state S_i is defined as the time of stay of system in state S_i before transiting to any other state. If T_i denotes the sojourn time in state S_i then mean sojourn time state in S_i is:

$$\mu_i = E[T_i] = \int P(T_i > t) dt$$

Thus

$\mu_0 = \int e^{-\alpha_1 t} dt = \frac{1}{\alpha_1}$	$\mu_1 = \frac{1}{\alpha} [1 - \tilde{H}_1(\alpha)]$	$\mu_2 = \frac{1}{\gamma}$
$\mu_3 = \frac{1}{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4}$	$\mu_4 = \frac{1}{\alpha} [1 - \tilde{H}_1(\alpha)]$	$\mu_5 = \frac{1}{\alpha} [1 - \tilde{H}_3(\alpha)]$
$\mu_6 = \frac{1}{\alpha} [1 - \tilde{H}_4(\alpha)]$	$\mu_7 = \frac{1}{\alpha} [1 - \tilde{H}_2(\alpha)]$	$\mu_8 = \frac{1}{\alpha} [1 - \tilde{H}_1(\alpha)]$
$\mu_9 = \frac{1}{\alpha_1 + \alpha_2}$		

Limits of integration are not to be mentioned whenever they are 0 and ∞ .

ANALYSIS OF RELIABILITY AND MTSF

Let ' T_i ' be the time to system failure when system starts functioning from regenerative state S_i at time $t = 0$. Then the reliability of the system is given by

$$R_i(t) = P[T_i > t]$$

Using the basic probabilistic argument recursive relation among $R_i(t)$ can be easily developed and taking L.T of the relations and solving for $R_0^*(s)$, we get

$$R_0^*(s) = \frac{N_1(s)}{D_1(s)} \quad (10)$$

where,

$$N_1(s) = (1 - q_{34}^* q_{43}^* - q_{35}^* q_{53}^* - q_{36}^* q_{63}^* - q_{37}^* q_{73}^*) (Z_0^* + q_{01}^* Z_1^*) + q_{01}^* q_{13}^* (Z_3^* + q_{34}^* Z_4^* + q_{35}^* Z_5^* + q_{36}^* Z_6^* + q_{37}^* Z_7^*)$$

and

$$D_1(s) = 1 - q_{34}^* q_{43}^* - q_{35}^* q_{53}^* - q_{36}^* q_{63}^* - q_{37}^* q_{73}^*$$

Taking the inverse L.T. of (10) we get the reliability of the system.

To get MTSF, we use the well known formula

$$E(T_0) = \int R_0(t)dt = \lim_{s \rightarrow 0} R_0^*(s) = \frac{N_1(0)}{D_1(0)} \quad (11)$$

where

$$N_1(0) = (1 - p_{34}p_{43} - p_{35}p_{53} - p_{36}p_{63} - p_{37}p_{73})(\mu_0 + p_{01}\mu_1) + p_{01}p_{13}(\mu_3 + p_{34}\mu_4 + p_{35}\mu_5 + p_{36}\mu_6 + p_{37}\mu_7)$$

and

$$D_1(0) = 1 - p_{34}p_{43} - p_{35}p_{53} - p_{36}p_{63} - p_{37}p_{73}$$

Here we have used the relations

$$q_{ij}^*(0) = p_{ij} \text{ and } Z_i^*(0) = \mu_i$$

AVAILABILITY ANALYSIS

Let $A_i(t)$ denote the probability that the system is up at epoch t when it initially starts from regenerative state S_i . Using the definition of $A_i(t)$, the recursive relations among $A_i(t)$, can be easily developed, taking their L.T and solving for $A_0^*(s)$, we get

$$A_0^*(s) = \frac{N_2(s)}{D_2(s)} \quad (12)$$

where

$$N_2(s) = [1 - q_{34}^*(q_{43}^* + q_{23}^*q_{42}^*) - q_{35}^*(q_{53}^* + q_{23}^*q_{52}^*) - q_{36}^*(q_{63}^* + q_{23}^*q_{62}^*) - q_{37}^*(q_{73}^* + q_{23}^*q_{72}^*)](Z_0^* + q_{01}^*Z_1^*) \\ + q_{01}^*Z_2^*[q_{12}^*(1 - q_{34}^*q_{43}^* - q_{35}^*q_{53}^* - q_{36}^*q_{63}^* - q_{37}^*q_{73}^*) + q_{13}^*(q_{34}^*q_{42}^* - q_{35}^*q_{52}^* - q_{36}^*q_{62}^* - q_{37}^*q_{72}^*)] \\ + q_{01}^*(q_{13}^* + q_{12}^*q_{23}^*)(Z_3^* + q_{34}^*Z_4^* + q_{35}^*Z_5^* + q_{36}^*Z_6^*) + q_{01}^*q_{37}^*Z_7^*(q_{01}^* + q_{23}^*q_{12}^*)]$$

and

$$D_2(s) = 1 - q_{34}^*(q_{43}^* + q_{23}^*q_{42}^*) - q_{35}^*(q_{53}^* + q_{23}^*q_{52}^*) - q_{36}^*(q_{63}^* + q_{23}^*q_{62}^*) - q_{37}^*(q_{73}^* + q_{23}^*q_{72}^*)$$

The steady state availability of the system is given by

$$A_0 = \lim_{t \rightarrow \infty} A_0(t) = \lim_{s \rightarrow 0} s A_0^*(s) \\ = \lim_{s \rightarrow 0} \frac{s N_2(s)}{D_2(s)} = \lim_{s \rightarrow 0} N_2(s) \lim_{s \rightarrow 0} \frac{s}{D_2(s)} \quad (13)$$

Since, $D_2(0) = 0$, by using L'Hospital rule, we have

$$A_0 = \frac{N_2'(0)}{D_2'(0)}$$

where

$$N_2'(0) = \mu_2[p_{12}(1 - p_{34}p_{43} - p_{35}p_{53} - p_{36}p_{63} - p_{37}p_{73}) + p_{13}(p_{34}p_{42} + p_{35}p_{52} + p_{36}p_{62} - p_{37}p_{72})] + \mu_3 + p_{34}\mu_4 + p_{35}\mu_5 + p_{36}\mu_6 + p_{37}\mu_7$$

and

$$D_2'(0) = (p_{34}p_{42} + p_{35}p_{52} - p_{36}p_{62} - p_{37}p_{72})\mu_2 + \mu_3 + p_{34}\mu_4 + p_{35}\mu_5 + p_{36}\mu_6 + p_{37}\mu_7$$

The expected up time of the system during $(0, t)$ is given by

$$\mu_{up}(t) = \int_0^t A_0(u) du \quad (14)$$

So that

$$\mu_{up}^*(s) = A_0^*(s)/s \quad (15)$$

BUSY PERIOD ANALYSIS

$B_1(t)$ is the probability that the system having started initially from regenerative state $S_1 \in E$ is under repair at time t due to failure of the unit. Using probabilistic arguments, relations among $B_1(t)$ can be set up, taking their L.T and solving for $B_0^*(s)$, we have

$$B_0^*(s) = \frac{N_3(s)}{D_2(s)} \quad (16)$$

$$N_3(s) = [1 - q_{34}^*(q_{43}^* + q_{23}^*q_{42}^*) - q_{35}^*(q_{53}^* + q_{23}^*q_{52}^*) - q_{36}^*(q_{63}^* + q_{23}^*q_{62}^*) - q_{37}^*(q_{73}^* + q_{23}^*q_{72}^*)](Z_0^* + q_{01}^*Z_1^*) + q_{01}^*Z_2^*[q_{12}^*(1 - q_{34}^*q_{43}^* - q_{35}^*q_{53}^* - q_{36}^*q_{63}^* - q_{37}^*q_{73}^*) + q_{13}^*(q_{34}^*q_{42}^* - q_{35}^*q_{52}^* - q_{36}^*q_{62}^* - q_{37}^*q_{72}^*)] + q_{01}^*(q_{13}^* + q_{12}^*q_{23}^*)(q_{34}^*Z_4^* + q_{35}^*Z_5^* + q_{36}^*Z_6^*) + q_{01}^*q_{37}^*Z_7^*(q_{01}^* + q_{23}^*q_{12}^*)]$$

In the long run the probability that the repairman is busy in the repair of system, is given by

$$B_0 = \lim_{t \rightarrow \infty} B_0(t) = \lim_{s \rightarrow 0} B_0^*(s) = \frac{N_3(0)}{D_2'(0)} \quad (17)$$

where

$$N_3(0) = \mu_2 p_{01}[p_{12}(1 - p_{34}p_{43} - p_{35}p_{53} - p_{36}p_{63} - p_{37}p_{73}) + p_{13}(p_{34}p_{42} + p_{35}p_{52} + p_{36}p_{62} - p_{37}p_{72})] + p_{34}\mu_4 + p_{35}\mu_5 + p_{36}\mu_6 + p_{37}\mu_7$$

PROFIT ANALYSIS

The profit function $P(t)$ can easily be obtained for the system model under study with the help of characteristics obtained earlier. The expected total profits incurred during $(0, t)$ are

$$P(t) = \text{expected total revenue in } (0, t) - \text{expected total expenditure in } (0, t) \\ = K_0 \mu_{up}(t) - K_1 \mu_b(t)$$

where K_0 is revenue per unit up time is, K_1 is the cost per unit time for which repair man is busy in repair of the failed unit.

The expected total profit per unit time, in steady state, is

$$P = \lim_{t \rightarrow \infty} [P(t)/t] = \lim_{s \rightarrow 0} s^2 P^*(s)$$

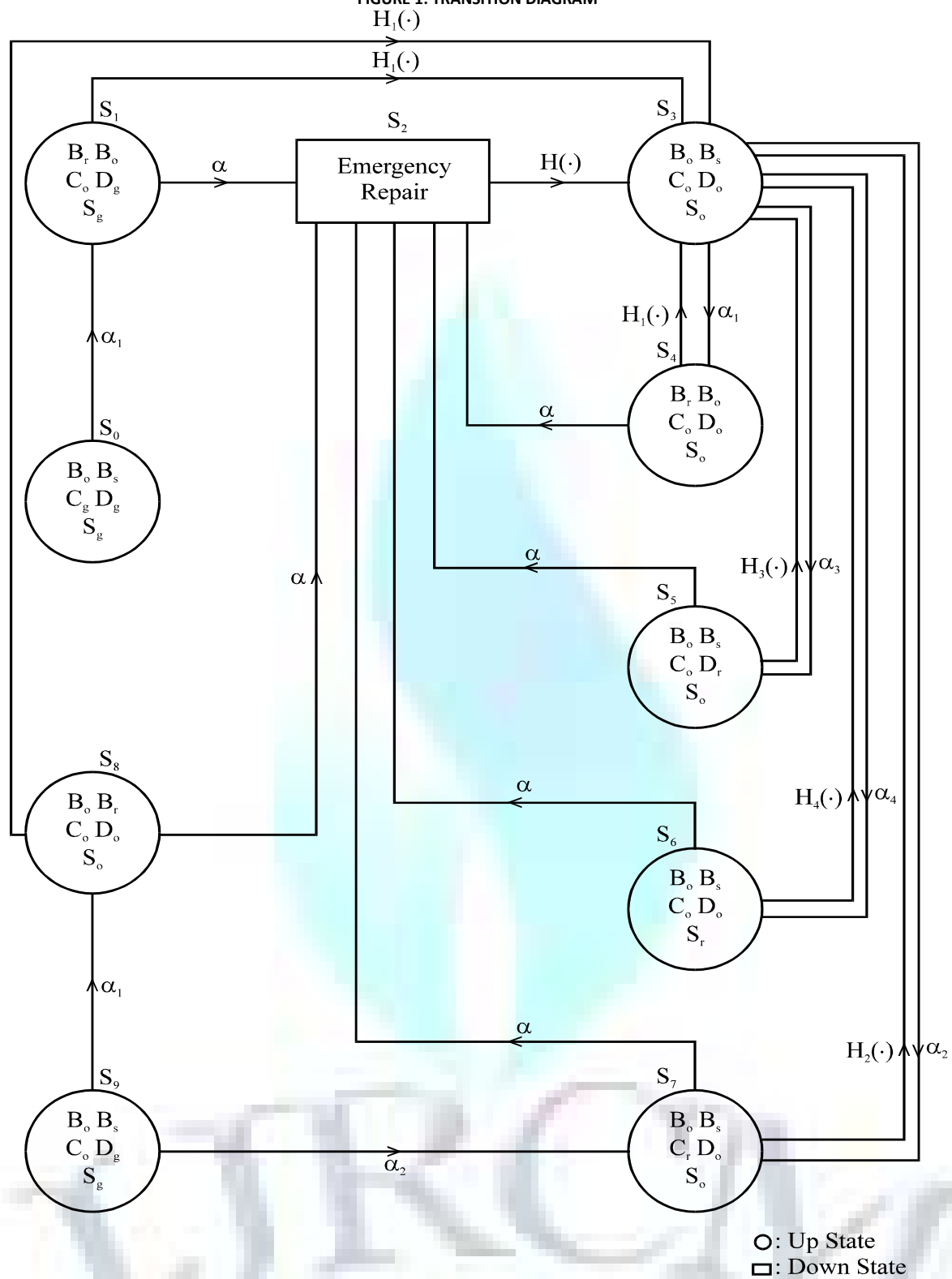
So that

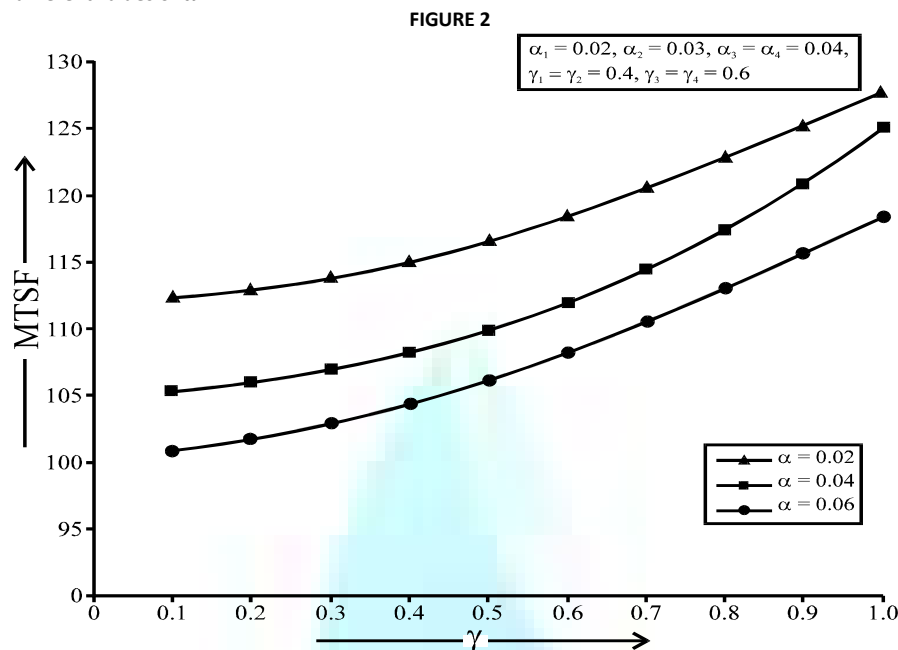
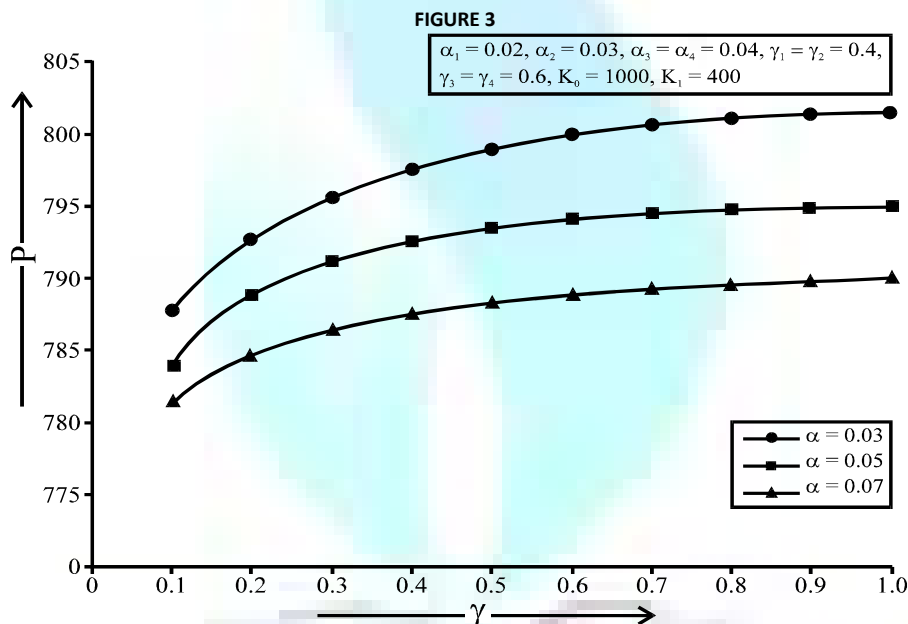
$$P = K_0 A_0 - K_1 B_0$$

GRAPHICAL STUDY OF THE SYSTEM MODEL

For a more concrete study of system behavior, we plot the graphs of MTSF and profit function for the system model. In figure 2, curves represent the graph of MTSF w.r.t. γ (emergency repair rate) for different values of α (failure rate of any other unit when one unit is already under repair) as 0.02, 0.04, 0.06, while the other parameters are fixed as $\alpha_1 = 0.02$, $\alpha_2 = 0.03$, $\alpha_3 = \alpha_4 = 0.04$, $\gamma_1 = \gamma_2 = 0.04$, and $\gamma_3 = \gamma_4 = 0.06$. We observe that the MTSF increases with increase in emergency repair rate. Initially the rate of increase in MTSF is slow but as the emergency repair rate is more than 0.7 the rate of increase in the MTSF is higher. Moreover as the value of α increases MTSF decreases. In figure 3, curves represent the graph of Profit function P w.r.t. γ (emergency repair rate) for different values of α (failure rate of any other unit when one unit is already under repair) as 0.03, 0.05, 0.07, while the other parameters are fixed as $\alpha_1 = 0.02$, $\alpha_2 = 0.03$, $\alpha_3 = \alpha_4 = 0.04$, $\gamma_1 = \gamma_2 = 0.04$, $\gamma_3 = \gamma_4 = 0.06$, $K_0 = 1000$ and $K_1 = 400$. Initially the graph for the profit function increases rapidly but as the emergency repair rate increases, the increase in the profit goes on slow and becomes almost constant for repair rate greater than 0.9. Moreover as the value of α increases profit decreases

FIGURE 1: TRANSITION DIAGRAM



Behavior of Profit Function P w.r.t γ for different values of α **ACKNOWLEDGEMENT**

The second author is thankful to **Ministry of Science & Technology, Government of India**, for providing financial support in the form of INSPIRE fellowship.

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