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Stochastic Analysis of a Bread Making System

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Abstract: This paper is concerned with the analysis of a stochastic model of bread making system. The system consists of five different subsystems namely- Mixer, DRR (Divider, Rounder and Roller), Proofer, Oven and Tunnels connected in series configuration. To make the system more reliable an additional mixer unit of similar nature is also taken in parallel configuration with the concerned sub-system. Taking constant failure and general repair rates for each sub-system several measures of system effectiveness such as reliability, MTSF, steady-state availability, busy period and expected profit etc. useful to industrial managers are obtained by using regenerative point technique. The MTSF and profit function have also been studied through graphs with respect to various parameters in a particular case.

Keywords: Reliability, availability, MTSF, busy- period of repairman, profit function

1 Introduction

The reliability of complex systems has emerged as a thrust area due to the occurrence of disastrous event in the industries. The process industries comprise of high complex engineering system and sub-systems arranged in different configurations. For efficient and economical operations of process plant, each system and sub-system should run for long duration of time with less repair cost under the required operative conditions. So, the improvement in effectiveness of a complex industrial system in respect of various reliability and cost affected indices has become important in recent years. An industrial system may consist of a number of sub-systems working in varying nature and each subsystem may further be composed of various units connected in different configurations.

A lot of work has been done in the field of reliability analyzing models based on producing different kind of products. Kumar D. et al.[9] obtained the availability of crystallization system in sugar industry under common cause failure. Later on, Kaushik and Singh[6] performed the reliability analysis of the naphtha fuel oil and water system under priority repair used in thermal power plant. Singh and Goel [13] studied the availability of heating system with warm standby and imperfect switch in sugar industry. Prabhuswami [12] studied the reliability based optimization of manufacturing systems. Gupta and Shivakar [5] performed the stochastic analysis of a cloth weaving system model. Gupta et al. [3] discussed the reliability and availability analysis of serial processes of butter oil plant and behavior analysis of the cement industry. Gupta and Kumar [4] carried out the cost-benefit analysis of a distillery plant. Kumar and Tewari [10] presented the analysis for evaluating the performance measures for co-shift conversion system model in a fertilizer plant. They further in [11] carried out the steady-state availability and performance optimization using genetic algorithm technique for CO2 cooling system of a fertilizer plant. Recently, Khanduja et al. [7] analyzed a bleaching system model of a paper plant regarding the steady-state behavior and maintenance planning. More recently, some of the other industrial system models producing different products have been already analyzed by Damghani, K.K.et al. [1]; Kumar, A. et al. [8]; Dev, N. et al. [2] and Vayenas and Peng [14].

Keeping in view the importance of analyzing a real existing industrial system model, the present paper deals with the stochastic analysis of a bread making system. Arsh food Pvt. Ltd., Meerut (U.P.) at present is working on such type of industrial system manufacturing the Bonn Bread. A bread making system is a complex type reparable engineering system model involving high risk of economic loss in case of any interruption in its operation. The system consists of a number of different sub-systems which are connected in series. The failure rates of the sub-systems are assumed to be exponential while the repair rates are taken to be general. The working of these sub-systems is explained as follows:-

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1. **Mixer:** This is used for mixing the ingredients to form dough. An active redundancy of Mixer is also considered in the system to make it more reliable.
2. **DRR (Divider, Rounder and Roller):** This is used to divide dough pieces and then they pass through the rounder for the rounding of dough pieces. After this, the dough is flattened by the adjustable stainless steel moulders of the dough Roller.
3. **Proofer:** This is used for twisting dough to take a jump to attain the level of the mould size.
4. **Oven:** This unit is used for baking the bread coming from proofer at the desired temperature.
5. **Tunnels:** After baking, the mould is put into the hot tunnel where the hot loaves attain the required temperature and then it is transferred into the cold tunnel for cooling.

By using regenerative point technique, the following measures of the system effectiveness are obtained.

– Transition probabilities and mean sojourn time in different states.
– Reliability of the system and mean time to system failure.
– Pointwise and steady-state availabilities of the system during $(0,t)$.
– Expected busy period of the repairman in different sub-systems during $(0,t)$ and in steady- state.
– Net expected profit incurred by the system in $(0,t)$ and in steady-state.

2 System Description and Assumptions

A bread making system is composed of five sub-systems connected in series network. The working of each sub-system is necessary for successful operation of the system. To make this system more reliable an additional mixer unit is also taken in parallel with its similar subsystem. The system may fail if any one of the sub-system except mixture unit fails or both the standby and main mixer units are failed. The working of different subsystems are shown in **Fig. 1** and explained as follows:-

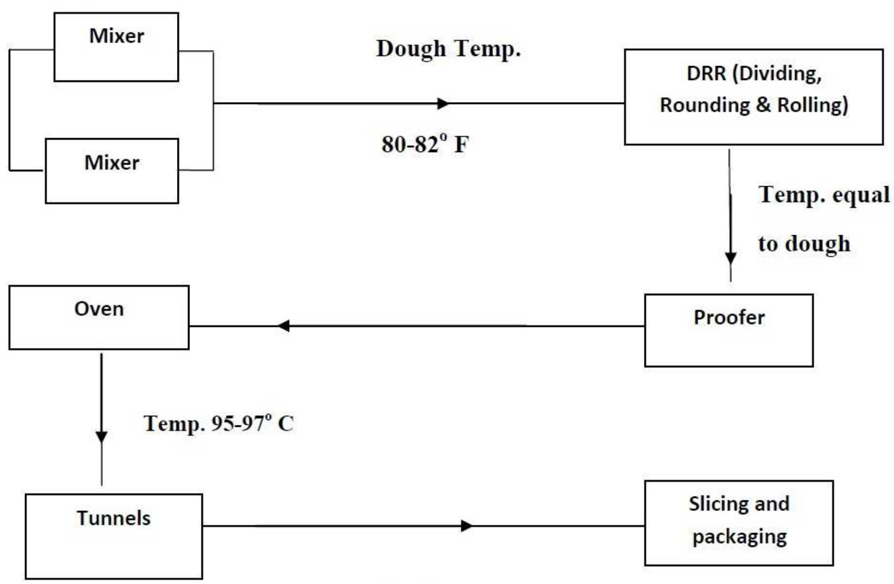

Fig. 1: The Working of different subsystems

Mixer (M):- In the production of bread we use sieved flour. The spiral mixer ensures a fast yet gentle development of dough and also helps in maintaining dough temperatures. This mixer has the capacity of mixing ingredients into 44 kg. flour at a time. All the ingredients should be measured carefully and added according to the variety of bread to be made.

Divider, Rounder and Roller (DRR):- The dough is to be divided after the mixing is done. There is a specially designed machine for dividing dough into pieces which is called divider. After dividing of the dough pieces it passes through the rounder for the processing of rounding of dough pieces into uniform dough balls. After the rounding, the dough is flattened by the adjustable stainless steel moulders of the dough roller. After the rolling, the twisting of the rolled dough is done with the hand.

Proofer (P):- A proofer is a chamber in which the temperature is set so that the twisted dough will take a jump to attain the level of the mould size and take 55 minutes to one hour to reach the next level.

Oven (O):- In the oven there are plates which move automatically. The workers put the twisted dough on the oven's plate. After sometime that plate with the moulds comes back to the opening and the workers take out the baked bread from it.

Tunnels (T):- After baking; the mould with hot loaves is put it into the rack and then this rack is put into the hot tunnel where the hot loaves attains the required temperature. It is then cooled in the cold tunnel. After this process the loaf are ready to be slicing which is placed in the poly bags for different variety.

The system model is analyzed by taking all the failure time distributions to be exponentials while the repair time distributions are assumed to be general. Since all the sub-systems are connected in series network, so it is necessary that they all should be in good condition for successful operation of the system. The repair is carried out by single repairman only when the sub-system breaks-down and after each repair the sub-system acts as good as new.

3 Notations and States of the System

(a) We define the following notations:-

$\alpha_M, \alpha_D, \alpha_P, \alpha_O, \alpha_T$	: constant failure rates of mixer, DRR, proofer, oven and tunnels.
$G_M(.), G_D(.), G_P(.), G_O(.), G_T(.)$	: c.d.f. of repair time of mixer, DRR, proofer, oven and tunnels.
$q_{ij}(.), Q_{ij}(.)$	: p.d.f. and c.d.f. of transition time from state S_i to S_j.
p_{ij}	: † steady- state probability of transition from state S_i to S_j. $= \int q_{ij}(u)du$
$Z_i(t)$	: probability that the system sojourns in state S_i up to time t.
ψ_i	: mean sojourn time in state S_i.
$\theta_M, \theta_D, \theta_P, \theta_O, \theta_T$	: mean repair time of mixer, DRR, proofer, oven and tunnels units.
$*, \sim$	: symbols for Laplace and Laplace-Stieltjes transforms.
†	: The limits of integration are not mentioned whenever they are 0 to ∞.

(b) To write the various states of the system, we define the following symbols:-

$M_o, M_s, M_g, M_r, M_{wr}, M_f$	: Mixer is operative, standby, good under repair, waiting for repair and failed.
D_o, D_g, D_r, D_{wr}	: DRR unit is operative, good under repair and waiting for repair.
P_o, P_g, P_r, P_{wr}	: Proofer is operative, good under repair and waiting for repair.
O_o, O_g, O_r, O_{wr}	: Oven is operative, good under repair and waiting for repair.

Using the above symbols and considering the networking of the sub systems in view, the transition diagram of the system model is shown in **Fig. 2**.

4 Transition Probabilities and Mean Sojourn

(a) By simple probabilistic arguments, we have the following steady-state transition probabilities:-

$$\begin{aligned} p_{01} &= \int \alpha_M e^{-(\alpha_M+\alpha_D+\alpha_P+\alpha_O+\alpha_T)u} du \\ &= \alpha_M / A; \quad \text{where,} \quad A = \alpha_M + \alpha_D + \alpha_P + \alpha_O + \alpha_T \end{aligned}$$

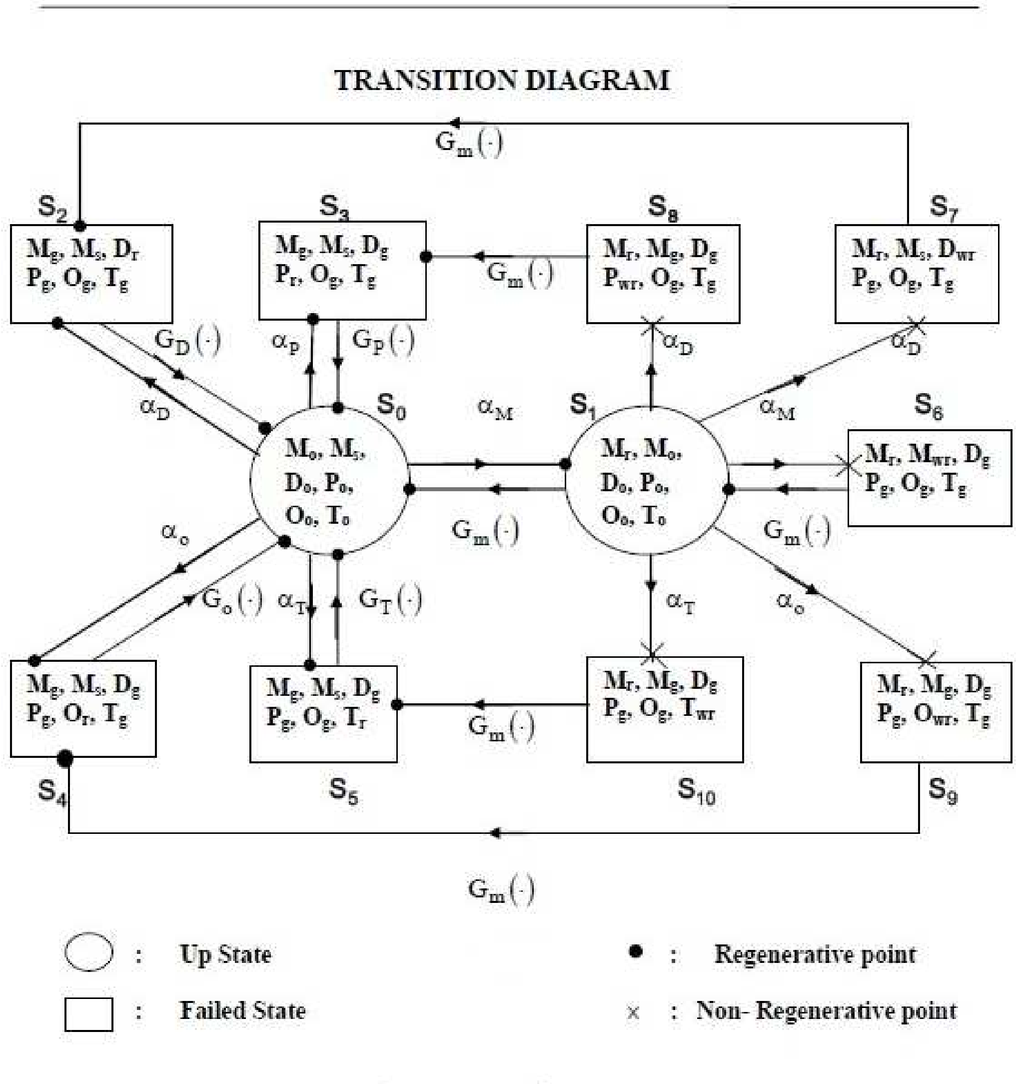

Fig. 2: Transition Diagram

Similarly,

$$p_{02} = \alpha_D/A, p_{03} = \alpha_P/A, p_{04} = \alpha_O/A, p_{05} = \alpha_T/A$$

$$p_{10} = \int e^{-(\alpha_M+\alpha_D+\alpha_P+\alpha_O+\alpha_T)u} dG_M(u)$$
$$= \tilde{G}_M(A)$$

$$p_{16} = p_{11}^{(6)} = \alpha_M \left[1 - \tilde{G}_M(A)\right]/A$$

$$p_{17} = p_{12}^{(7)} = \alpha_D \left[1 - \tilde{G}_M(A)\right]/A$$

$$p_{18} = p_{13}^{(8)} = \alpha_P \left[1 - \tilde{G}_M(A)\right]/A$$

$$p_{19} = p_{14}^{(9)} = \alpha_O \left[1 - \tilde{G}_M(A)\right]/A$$

$$p_{1,10} = p_{15}^{(10)} = \alpha_T \left[1 - \tilde{G}_M(A)\right]/A$$

$$p_{20} = p_{30} = p_{40} = p_{5,10} = 1 \tag{1-12}$$

We observe the following relations:-

$$p_{01} + p_{02} + p_{03} + p_{04} + p_{05} = 1$$

$$p_{10} + p_{11}^{(6)} + p_{12}^{(7)} + p_{13}^{(8)} + p_{14}^{(9)} + p_{15}^{(10)} = 1$$

$$p_{10} + p_{16} + p_{17} + p_{18} + p_{19} + p_{1,10} = 1 \tag{13-15}$$

(b) The mean sojourn time ψ_i in state S_i is defined as the expected time for which the system stays in state S_i before transiting to any other state. If T_i is the sojourn time in state S_i, then mean sojourn time in state S_i is

$$\psi_i = \int P(T_i > t)dt$$

Its values for various states are as follows:-

$$\psi_0 = 1/A$$

$$\psi_1 = \int e^{-At}\overline{G}_M(t)dt$$

$$\psi_2 = \int \overline{G}_D(t)dt = \theta_D$$

$$\psi_3 = \int \overline{G}_P(t)dt = \theta_P$$

$$\psi_4 = \int \overline{G}_O(t)dt = \theta_O$$

$$\psi_5 = \int \overline{G}_T(t)dt = \theta_T \tag{16-21}$$

5 Reliability of the System and MTSF

Let the random variable T_i be the time to system failure when it initially starts from state $S_i \in E$, then the reliability of the system is given by

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

To determine it we regard the failed state of the system as absorbing states. By using simple probabilistic arguments, one has the following recurrence relations among $R_i(t); i = 0, 1$.

$$R_0(t) = Z_0(t) + q_{01}(t) \copyright R_1(t)$$

$$R_1(t) = Z_1(t) + q_{10}(t) \copyright R_0(t) \tag{22-23}$$

Taking Laplace-transforms of these relations and simplifying the resulting equations for $R_0^*(s)$, we get

$$R_0^*(s) = \frac{Z_0^*(s) + q_{01}^*(s)Z_1^*(s)}{1 - q_{01}^*(s)q_{10}^*(s)} \tag{24}$$

where $Z_0^*(s)$ and $Z_1^*(s)$ are the Laplace-transforms of $Z_0(t) = e^{-At}; \quad Z_1(t) = e^{-At}\overline{G}_M(t)$

The expression of reliability $R_0(t)$ can be obtained by taking inverse-Laplace transform of $R_0^*(s)$ for known forms of the repair time distribution of Mixer. Now, the mean time to system failure(MTSF) is given by

$$E(T) = \lim_{s \to 0} R_0^*(s)$$

$$= \frac{\psi_0 + p_{01}\psi_1}{1 - p_{01}p_{10}} \tag{25}$$

6 Cost-benefit Analysis

In order to find the net expected profit earned by the system during interval $(0,t)$ and in steady-state, we compute the following:

(a) Availability Analysis

Let us define $A_i(t)$ as the probability that the system is up at epoch t when it initially starts from state $S_i \in E$. Using the definition of $A_i(t)$ and the basic probabilistic concepts as in case of reliability, the recurrence relations among $A_i(t); t = 0,1,2,3,4,5$ can easily be developed.
Then taking the Laplace Transforms and solving the resulting set of algebraic equations for $A_0^*(s)$ one gets

$$A_0^*(s) = \frac{N_1(s)}{D_1(s)} \tag{26}$$

Where,

$$N_1(s) = \left(1 - q_{11}^{(6)*}\right) Z_0^* + q_{01}^* Z_1^*$$

and

$$D_1(s) = \left(1 - q_{11}^{(6)*}\right)(1 - q_{02}^* q_{20}^* - q_{03}^* q_{30}^* - q_{04}^* q_{40}^* - q_{05}^* q_{50}^*) - q_{01}^* \left(q_{10}^* + q_{12}^{(7)*} q_{20}^* + q_{13}^{(8)*} q_{30}^* + q_{14}^{(9)*} q_{40}^* + q_{15}^{(10)*} q_{50}^*\right)$$

The argument 's' has been omitted throughout the paper from $q_{ij}^*(s)$ and $Z_i^*(s)$ for brevity.

The steady-state availability of the system is given by

$$A_0 = \lim_{t\to\infty} A_0(t) = \lim_{s\to 0} s\, A_0^*(s) = \frac{N_1}{D_1} \tag{27}$$

Where,

$$N_1 = \left(1 - p_{11}^{(6)}\right) \psi_0 + p_{01} \psi_1$$

and

$$D_1 = \left(1 - p_{11}^{(6)}\right) \psi_0 + p_{01} \theta_M + \left(1 - p_{11}^{(6)}\right) (p_{02} \theta_D + p_{03} \theta_P + p_{04} \theta_O + p_{05} \theta_T)$$

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

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

so that

$$\mu_{up}^*(s) = A_0^*(s)/s \tag{28}$$

(b)Busy-Period Analysis

Let $B_i^M(t), B_i^D(t), B_i^P(t), B_i^O(t)$ and $B_i^T(t)$ be the respective probabilities that the system is under repair at epoch t due to the failure of Mixer, DRR, Proofer, Oven and Tunnels when system initially starts from state S_0.

Using simple probabilistic arguments, the values of the above five probabilities in terms of their Laplace Transforms can easily be obtained as follows:-

$$B_0^{M*}(s) = \frac{q_{11}^{(6)*} W_1^*}{D_2(s)}$$

$$B_0^{D*}(s) = \frac{q_{12}^{(7)*} W_2^*}{D_2(s)}$$

$$B_0^{P*}(s) = \frac{q_{13}^{(8)*}W_3^*}{D_2(s)}$$

$$B_0^{O*}(s) = \frac{q_{14}^{(9)*}W_4^*}{D_2(s)}$$

and

$$B_0^{T*}(s) = \frac{q_{15}^{(10)*}W_5^*}{D_2(s)} \quad (29\text{-}33)$$

Where, $W_1^*, W_2^*, W_3^*, W_4^*$ and W_5^* are the Laplace-transforms of

$$W_1(t) = \overline{G}_M(t)$$

$$W_2(t) = \overline{G}_D(t)$$

$$W_3(t) = \overline{G}_P(t)$$

$$W_4(t) = \overline{G}_O(t)$$

$$W_5(t) = \overline{G}_T(t)$$

and $D_1(s)$ is same as given in sub-section **6(a)**.

In the long-run, the probabilities that the repairman will be busy in the repair of Mixer, DRR, Proofer, Oven and Tunnels respectively are given by

$$B_0^M = p_{11}^{(6)}\theta_M/D_1$$

$$B_0^D = p_{12}^{(7)}\theta_D/D_1$$

$$B_0^P = p_{13}^{(8)}\theta_P/D_1$$

$$B_0^O = p_{14}^{(9)}\theta_O/D_1$$

$$B_0^T = p_{15}^{(10)}\theta_T/D_1 \quad (34\text{-}38)$$

The expected busy period of repairman in the repair of Mixer, DRR, Proofer, Oven and Tunnels during interval $(0,t)$ respectively are given by

$$\mu_b^M(t) = \int_0^t B_0^M(u)du$$

$$\mu_b^D(t) = \int_0^t B_0^D(u)du$$

$$\mu_b^P(t) = \int_0^t B_0^P(u)du$$

$$\mu_b^O(t) = \int_0^t B_0^O(u)du$$

$$\mu_b^T(t) = \int_0^t B_0^T(u)du \quad (39\text{-}43)$$

So that,

$$\mu_b^{M*}(s) = B_0^{M*}(s)/s$$

$$\mu_b^{D*}(s) = B_0^{D*}(s)/s$$

$$\mu_b^{P*}(s) = B_0^{P*}(s)/s$$

$$\mu_b^{O*}(s) = B_0^{O*}(s)/s$$

$$\mu_b^{T*}(s) = B_0^{T*}(s)/s \quad (44\text{-}48)$$

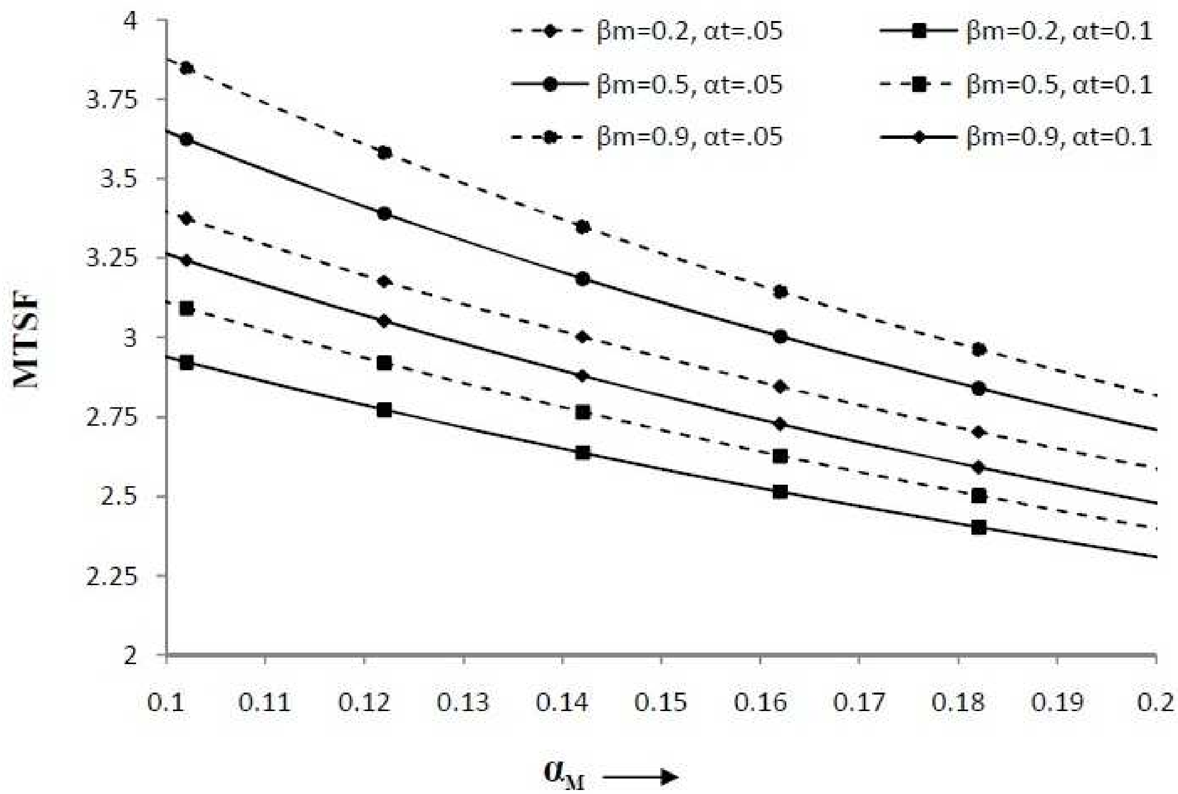

Fig. 3: Behaviour of MTSF with respect to α_M, β_M and α_T

(c) Profit Function Analysis

We are now in the position to obtain the net expected profit earned by the system during time interval $(0,t)$ as given below:-

$$P(t) = K_0\mu_{up}(t) - K_1\mu_b^M(t) - K_2\mu_b^D(t) - K_3\mu_b^P(t) - K_4\mu_b^O(t) - K_5\mu_b^T(t) \tag{49}$$

Where K_0 is the per-unit time revenue earned by the system and K_1, K_2, K_3, K_4, K_5 are the repair costs per-unit of time when repairman is busy in the repair of Mixer, DRR, Proofer, Oven, Tunnels respectively.

The net- expected profit per-unit time in steady-state is given by

$$P = \lim_{t\to\infty} \frac{P(t)}{t} = K_0A_0 - K_1B_0^M - K_2B_0^D - K_3B_0^P - K_4B_0^O - K_5B_0^T \tag{50}$$

7 Particular Case

When all repair time distributions are exponentials i.e

$$G_M(t) = 1 - e^{\beta_M t}$$

$$G_D(t) = 1 - e^{\beta_D t}$$

$$G_P(t) = 1 - e^{\beta_P t}$$

$$G_O(t) = 1 - e^{\beta_O t}$$

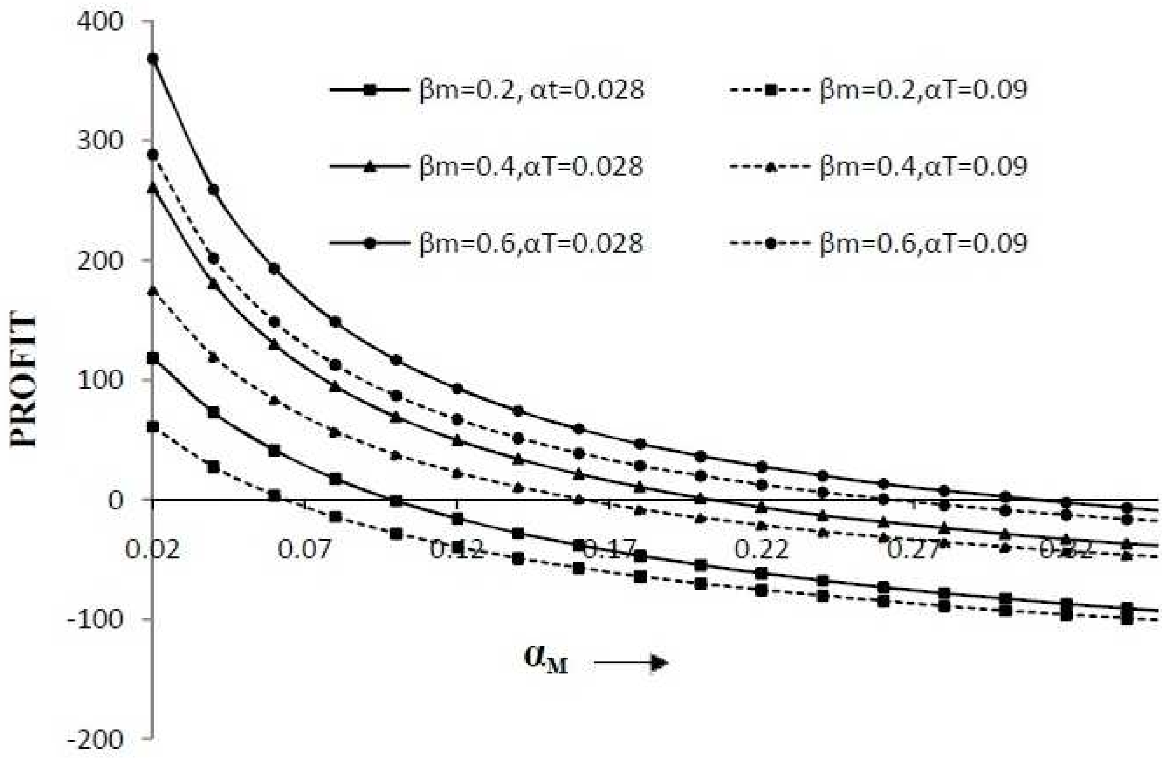

Fig. 4: Behaviour of Profit function with respect to α_M, β_M and α_T

$$G_T(t) = 1 - e^{\beta_T t}$$

In view of above, we have the following changes in results (1-12) and (16-21)

$$p_{10} = \beta_M/(A+\beta_M)$$

$$p_{16} = p_{11}^{(6)} = \alpha_M/(A+\beta_M)$$

$$p_{17} = p_{12}^{(7)} = \alpha_D/(A+\beta_M)$$

$$p_{18} = p_{13}^{(8)} = \alpha_P/(A+\beta_M)$$

$$p_{19} = p_{14}^{(9)} = \alpha_O/(A+\beta_M)$$

$$p_{1,10} = p_{15}^{(10)} = \alpha_T/(A+\beta_M)$$

$$\psi_1 = 1/(A+\beta_M)$$

$$\psi_2 = 1/\beta_D$$

$$\psi_3 = 1/\beta_P$$

$$\psi_4 = 1/\beta_O$$

$$\psi_5 = 1/\beta_T \quad (51\text{-}61)$$

8 Graphical Representation

The curves for MTSF and profit function are drawn in respect of different values of parameters of the α_M, β_M and α_T. **Figure 3** depict the variations in MTSF with respect to α_M for three different values of β_M (0.2, 0.5 and 0.9) and two values of α_T (0.05 and 0.1) when the values of other parameters are kept fixed as $\alpha_D = 0.3, \alpha_P = 0.05, \alpha_O = 0.005, \beta_D = 0.02, \beta_P = 0.4, \beta_O = 0.01$ and $\beta_T = 0.55$. From the curves we observe that MTSF decrease uniformly as α_M increases. It also reveals that the MTSF decrease with the increase in the values of β_M and α_T.

Similarly, **Figure 4** reveals the variations in steady state profit function (P) with respect to α_M for three different values of β_M (0.2, 0.4 and 0.6) and two values of α_T (0.028 and 0.09) when the values of $\alpha_D, \alpha_P, \alpha_O, \beta_D, \beta_P, \beta_O$ and β_T are taken same as in case of MTSF and the values of $K_0 = 2200, K_1 = 500, K_2 = 150, K_3 = 500, K_4 = 500$ and $K_5 = 900$ are taken respectively. From the **Figure 3** the same trends in profit variation in respect to α_M, β_M and α_T have been observed as reported in case of MTSF. Further, it is important to note from dotted curves that system goes in loss if α_M exceeds from 0.06, 0.163 and 0.262 respectively for $\alpha_T = 0.09$. Similarly, from smooth curves it is obvious that the system goes in loss if α_M exceeds from 0.10, 0.202 and 0.31 respectively from $\alpha_T = 0.028$. Thus, it is observed that the profit decreases as α_M increases.

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