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Reliability analysis of the wirerod mill system of an intergated steel plant

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Abstract

This paper deals with the reliability analysis of wirerod mill system of an integrated steel plant. The system consists of two sets of crane and a charging grid. At some particular time one set of crane and charging grid comes into the operation whereas the other set remains in standby mode. The main function of this mill is to provide the support to the Blooming and Billet mill area. Using regenerative point technique, various characteristics of interest to the system designers as well as for operation managers have been evaluated which is helpful to improve the reliability of overall systems. Finally with the help of some graphs we have tried to show the effective result.

Key words : Regenerative point technique, Transition Probability, Mean Sojourn Time, MTSF, Availability and Busy Period Analysis.

Introduction

Now-a-days, improvement in the design and development of large scale complex systems have been taken as a challenge by the engineers and operation managers. Engineers are interested in the development of those systems whose reliability and profit earned by them are maximum on one hand and purchasing cost of the units and their running cost are minimum on the other. Modern techniques are introduced to increase profit and to overcome the maintenance problems on the basis of real configuration of the model with real assumptions. Reliability technology encompasses with such models to reach at optimality. It is well known that the performance of any system can be considerably improved by carrying out preventive maintenance on it. Further where shut-down or off-line maintenance is uneconomical, the system performance can be increased by resorting to on-line preventive maintenance. Although, lot of work have been done in the field of reliability but most of it are concerned with hypothetical models. Very few works has been reported by taking practical models and real data. Gupta *et al.*[1] have analyzed the availibility of two-unit parallel redudant complex system. Dhillion *et al.*[2] and Neteson *et al.*[6] have analyzed pulverize systems with common cause failures. Kochar *et al.*[4] developed a systematic method for investment decision on additional equipment to form a standby or redundant system in a production system. Kumar *et al.*[5] have analyzed a feeding system in sugar industry. Recently Singh *et al.*[7] have studied a stone crushing system having one apron feeder, one grizzly, one primary gyratory crusher. This group of equipments is used to get iron ores from stones in mining crushing plants. Singh *et al.*[8] have also studied the stochastic modeling and analysis of door-extractor system. They have obtained various parameters of the systems which are useful to the system managers and engineers. For the purpose of analyzing industrial models Bhilai Steel Plant one of the leading steel plant of India is selected as our working area. Through this paper we have tried to study the Wire Rod Mill of an integrated steel plant.

Brief discription of the wire-rod mill :

The Wire-rod Mill is designed to roll 6,7,8,10 & 12 mm diameter wire rods into coils from square billets obtained from Blooming and Billet Mill.

Inspected billets are fed on the charging gate of the furnace by magnetic finger cranes. The billets are fed one by one to the furnace through roll table and draw-in-roller mechanism. Billets are moved into the furnace by means of pushers at the charging end and soaked billets are ejected out by means of ejector ram from the discharging end.

There are Reheating furnaces of size 18m x 12m. Mixed coke-oven and Blast furnace gas is used in the furnace as fuel. Capacity of the furnace is 120 T/hour.

Flying shears are provided for each individual stand between the roughing group and horizontal stands to cut the front end of the bars and also to cut the bar when trouble occurs in other groups.

Model :

The purpose of the present paper is to study a Wirerod mill system consisting of a crane and a charging grid in standby configuration. This system is helpful in placing blooms towards the furnace. Blooms are obtained from Blooming and Billet mill area. In the stock yard where blooms are stored, crane is used to carry those blooms from the stock yard and throw it near the charging grid and from this place charging grids automatically push the blooms onto the roll table which charges the blooms inside the furnace for further processing and thereby converting it into wires of required sizes. Using regenerative point technique following measures of system effectiveness are obtained to carry out the profit analysis:

(i) Steady state transition probabilities and Mean sojourn times in different states;
(ii) Mean time to system failure;

(iii) Mean up time during (0,t];
(iv) Expected busy period of the repairman in repair (electrical, mechanical, on - line) in (0,t] and in steady state;
(v) Expected busy period of the repairman in shut-down repair in (0,t] and in steady state;
(vi) Expected profit earned by the system in (0,t] and in steady state;

At last some particular cases are also discussed and graphs are plotted to highlight the important results.

Description of the system :

1. System consists of two cranes and two charging grids in standby configuration. At a time a combination of a crane and charging grid works simultaneously whereas other combination remains in standby mode.
2. Shut-down occurs due to failure either in crane or in charging grid provided the other combination is already under repair.
3. As soon as crane / charging grid of a single combination fails, the other charging grid / crane comes into good and ideal state and with the repair of that particular the other unit comes into operation.
4. Failure time distributions of all the units are negative exponentially distributed whereas repair time distributions are arbitrarily distributed.
5. After repair units work as good as new.

State transition diagram and graphs are shown in figures 1, 2, 3 and 4 respectively.

Notation :

ψ : Constant failure rate of the Crane.

$g_1(t)$: p.d.f. of repair time of the Crane.

λ : p.d.f. of failure time of Grid.

$g_2(t)$: p.d.f. of repair time of Grid.

$g_3(t)$: p.d.f. of shut down repair time.

E_0 : State of the system at epoch t=0

E : Set of regenerative state.

$B_i^j(t)$: p[repairman is busy in repair / shut down repair (j = 1,2) respectively ($E_0 = S_i \in E$).

[S] : Symbol for Laplace stieltjes convolution.

[C] : Symbol for Laplace convolution

$*$: Sybmol for Laplace transform/Laplace-stieltjes transform.

Symbols used for states of the system :

C_o / G_o : Crane / Grid is in under operation.

C_s / G_s : Crane / Grid is in standby position.

C_r / G_r : Crane / Grid is under repair.

C_g / G_g : Crane / Grid is good and non operative.

SD : Whole system under shut-down repair.

UP and regenerative states :

$S_0 = (C_o, G_c, C_s, G_s)$;

$S_1 = (C_g, G_r, C_o, G_o)$;

$S_2 = (C_r, G_g, C_o, G_o)$

Down state :

$S_3 = (S.D.)$

Possible transitions among states are shown in Fig. 1.

Transition probabilities and sojourn times:

Simple probabilistic considerations yield the following expressions for non zero transition:

$$p_{01} = \psi \int_0^{\infty} e^{-X_1 t} dt;\quad p_{02} = \lambda \int_0^{\infty} e^{-X_1 t} dt;$$

$$p_{10} = \int_0^{\infty} g_2(t) e^{-X_1 t} dt$$

$$p_{13} = X_1 \int_0^{\infty} e^{-X_1 t} \overline{G}_2(t) dt;$$

$$p_{20} = \int_0^{\infty} g_1(t) e^{-X_1 t} dt;$$

$$p_{23} = X_1 \int_0^{\infty} e^{-X_1 t} \overline{G}_1(t) dt$$

$$p_{30} = \int_0^{\infty} g_3(t) dt \qquad (1\text{-}7)$$

Mean sojourn time μ_i, in state S_i, which is based on the similar arguments are :

$$\mu_0 = \int_0^{\infty} e^{-X_1 t} dt;\ \mu_1 = \int_0^{\infty} \overline{G}_2(t) e^{-X_1 t} dt;\ \mu_2$$

$$= \int_0^{\infty} \overline{G}_1(t) e^{-X_1 t} dt;\ \mu_3 = \int_0^{\infty} \overline{G}_3(t) dt \qquad (8\text{-}11)$$

Mean time to system failure :

Time to system failure can be regarded as first passage time to the failed state. To obtain it, we regard the down states as absorbing states. Using arguments as for the regenerative process we obtain the following recursive relations for $\pi_i(t)$:

$$\pi_0(t) = \sum_{i=1,2} Q_{0i}(t) \text{ S } \pi_i(t);$$

$$\pi_1 = Q_{10}(t) \text{ S } \pi_0(t) + Q_{13}(t)$$

$$\pi_2(t) = Q_{20}(t) \text{ S } \pi_0(t) + Q_{23}(t) \quad (12\text{-}14)$$

Taking Laplace-Stieltjes transforms of equations [12-14], and after solving for $\tilde{\pi}_0(s)$, we have

$$\text{MTSF} = E(T) = -\frac{d}{ds}\tilde{\pi}(s)\Big|_{s=0}$$

$$= \frac{D_1'(0) - N_1'(0)}{D_1(0)} = \frac{\mu_0 + \mu_1 p_{01} + \mu_2 p_{02}}{1 - p_{01}p_{10} - p_{02}p_{20}} \qquad (15)$$

System availability :

Let $M_i(t)$ be the probability that the system is up initially in regenerative state S_i has no transition till time t, then by probabilistic arguments we have

$$M_0 = e^{-X_7 t};\ M_1 = \overline{G}_2(t) e^{-X_2 t};$$

$$M_2 = \overline{G}_1(t) e^{-X_3 t};\ M_3 = \overline{G}_3(t) \qquad (16\text{-}19)$$

Recursive relations giving the point wise availability $A_i(t)$:

$$A_0(t) = M_0(t) + \sum_{i=1,2} q_{0i}(t) \text{ C } A_i(t);$$

$$A_1(t) = M_1(t) + \sum_{i=0,3} q_{1i}(t) \copyright A_i(t)$$

$$A_2(t) = M_2(t) + \sum_{i=0,3} q_{2i}(t) \copyright A_i(t);$$

$$A_3(t) = q_{30}(t) \copyright A_0(t) \qquad (20\text{-}23)$$

Taking laplace transforms of [20-23] and after solving for $A_0^*(s)$ the steady state availability A_0 is given by

$$A_0(\infty) = \lim_{t\to 0} A_0(t) = \lim_{s\to 0} sA_0^*(s) = \frac{N_2(0)}{D_2'(0)}$$

$$for \left.\frac{d}{ds}\right|_{s=0}$$

$$= \frac{\mu_0 + \mu_1 p_{01} + \mu_2 p_{02}}{\mu_0 + \mu_1 p_{01} + \mu_2 p_{02} + \mu_3(p_{01}p_{13} + p_{02}p_{23})} \qquad (24)$$

Where

$$N_2(0) = \mu_0 + \mu_1 p_{01} + \mu_2 p_{02} \quad \text{and}$$

$$D_2'(0) = \mu_0 + \mu_1 p_{01} + \mu_2 p_{02} + \mu_3(p_{01}p_{13} + p_{02}p_{23}) \qquad (25\text{-}26)$$

Busy period analysis :

Expected busy period analysis of the repairman in repair in (0,t] :

Let $W_i(t)$ denote the probability that the repairman busy initially in regenerative state S_i and remains busy at epoch t without transiting to any other regenerative state. It might return to itself through one or more non-regenerative states, so that it either continues to be busy in regenerative state S_i without visiting to any other regenerative state including itself. By probabilistic arguments we have:

$$W_1(t) = \overline{G}_2(t)e^{-X_2 t};$$

$$W_2(t) = \overline{G}_1(t)e^{-X_3 t} \qquad (27\text{-}28)$$

We define $B_i^1(t)$ the probability that repairman is busy at epoch t starting from state $S_i \in E$. By probabilistic arguments we have

$$B_0^1(t) = \sum_{i=1,2} q_{0i}(t) \copyright B_i^1(t);$$

$$B_1^1(t) = W_1(t) + \sum_{i=0,3} q_{1i}(t) \copyright B_i^1(t)$$

$$B_2^1(t) = W_2(t) + \sum_{i=0,3} q_{2i}(t) \copyright B_i^1(t);$$

$$B_3^1(t) = q_{30}(t) \copyright B_0^1(t) \qquad (29\text{-}32)$$

Taking laplace transforms of [27-30], and by calculating $W_i^*(0)$, we get the expression for $B_0^{*1}(0)$ *i. e.*

$$W_1^*(0) = \int_0^\infty \overline{G}_2(t)e^{-X_2 t}dt = \mu_1$$

$$W_1^*(0) = \int_0^\infty \overline{G}_1(t)e^{-X_3 t}dt = \mu_2 \qquad (33\text{-}34)$$

Using equation [33-34] and equation [1-7], we get

$$N_3(0) = \mu_1 p_{01} + \mu_2 p_{02} \qquad (35)$$

Therefore, in the long run, the fraction of time for which the system is under repair is given by:

$$B_0^1(\infty) = \lim_{t\to\infty} B_0^1(t) = \lim_{s\to\infty} sB_0^1(s) = \frac{N_3(0)}{D_2^{\prime}(0)} \quad (36)$$

Where $N_3(0)$ and $D_2^{\prime}(0)$ is given by [26] and [35] respectively.
Similarly

Expected busy period analysis of the repairman in shut down repair in (0,t] is given by

$$B_0^2(\infty) = \lim_{t\to\infty} B_0^2(t) = \lim_{s\to\infty} sB_0^2(s) = \frac{N_4(0)}{D_2^{\prime}(0)}$$

Where

$$N_4(0) = \mu_3(p_{01}p_{13} + p_{02}p_{23}) \quad (37)$$

and is given by [26].

Particular cases :

When all repair time distributions are n-phase Erlang distributed *i.e.*

density function $g_i(t) = nr_i(nr_it)^{n-1}e^{-nr_it} / (n-1)!$

survival function $\bar{G}_i(t) = \sum_{i=0}^{n-1} \frac{(nr_jt)^i e^{-nr_jt}}{i!}$

and other time distributions are negative exponential *i.e.* $a(t) = ae^{-at}, b(t) = be^{-bt}$, Then the steady state equations are given by

(1) Mean Time To System Failure (MTSF)

$$= \frac{K_0}{K} \quad (38)$$

(2) Availability: $A_0(0) = \frac{K_{01}}{K_2}$ (39)

(3) Busy Period analysis.

(a) Expected Busy period analysis of the repairman in repair in (0,t]

$$B_0^1(\infty) = \lim_{t\to\infty} B_0^1(t) = \lim_{s\to\infty} sB_0^1(s) = \frac{K_{02}^1}{K_2}$$

(b) Expected Busy period analysis of the repairman shut down repair in (0,t]

$$B_0^2(\infty) = \lim_{t\to\infty} B_0^2(t) = \lim_{s\to\infty} sB_0^2(s) = \frac{K_{02}^2}{K_2}$$

Where

$$K_0 = \mu_0 + \mu_1 p_{01} + \mu_2 p_{02} = \frac{1}{X_1} + b_2\frac{\lambda}{X_1} + b_4\frac{\psi}{X_1} = K_{01};$$

$$K_1 = (1 - p_{01}p_{10} - p_{02}p_{20}) = (1 - \frac{\lambda}{X_1}b_1 - \frac{\psi}{X_1}b_3)$$

$$K_2 = \mu_0 + \mu_1 p_{01} + \mu_2 p_{02} + \mu_3(p_{01}p_{13} + p_{02}p_{23})$$

$$= \frac{1}{X_1} + b_2\frac{\lambda}{X_1} + b_4\frac{\psi}{X_1} + b_5(\frac{\lambda}{X_1}X_1b_2 + \frac{\psi}{X_1}X_1b_4)$$

$$K_{02}^1 = \mu_1 p_{01} + \mu_2 p_{02} = b_2\frac{\lambda}{X_1} + b_4\frac{\psi}{X_1}$$

$$K_{02}^2 = \mu_3(p_{01}p_{13} + p_{02}p_{23})$$

$$= b_5(\frac{\lambda}{X_1}X_1b_2 + \frac{\psi}{X_1}X_1b_4) \quad (42\text{-}46)$$

Where :

$p_{01} = \lambda / X_1$; $p_{02} = \psi / X_1$;

$p_{10} = b_1$; $p_{13} = X_1b_2$

$p_{20} = b_3$; $p_{23} = X_1b_4$;

$p_{30} = 1$; $\mu_0 = 1 / X_1$

$\mu_1 = b_2$; $\mu_2 = b_4$; $\mu_3 = b_7$ (47-57)

Where :

$$b_1 = \frac{(nr_2)^n}{(nr_2 + X_1)^n} \; ; \; b_2 = \sum_{i=0}^{n-1} \frac{(nr_2)^i}{(nr_2 + X_1)^{i+1}} \; ;$$

$$b_3 = \frac{(nr_1)^n}{(nr_1 + X_1)^n}$$

$$b_4 = \sum_{i=0}^{n-1} \frac{(nr_1)^i}{(nr_1 + X_1)^{i+1}} \, , \qquad b_5 = \sum_{i=0}^{n-1} \frac{1}{nr_2} \; ;$$

$$X_1 = (\lambda + \psi) \tag{58-63}$$

When we put n =1 in above equations [58-62] then repair time follows negative exponential distribution.

$$p_{01} = \lambda / X_1 \; ; \quad p_{02} = \psi / X_1$$

$$p_{10} = r_2 /(r_2 + X_1)$$

$$p_{13} = X_1 /(r_2 + X_1) \; ; \; p_{20} = r_1 /(r_1 + X_1);$$

$$p_{23} = X_1 /(r_1 + X_1)$$

$$p_{30} = 1 \; ; \quad \mu_0 = 1/X_1 \; ; \quad \mu_0 = 1/X_1$$

$$\mu_2 = 1/(r_1 + X_1) \; ; \; \mu_3 = 1/r_3 = 1 \tag{64-74}$$

Using equation [64-74] in equation [42-46] we get,

$$K_0 = \frac{1}{X_1} + \frac{1}{(r_2 + X_1)} \frac{\lambda}{X_1} + \frac{1}{(r_1 + X_1)} \frac{\psi}{X_1} = K_{01};$$

$$K_1 = (1 - \frac{\lambda}{X_1} \frac{r_2}{(r_2 + X_1)} - \frac{\psi}{X_1} \frac{r_1}{(r_1 + X_1)})$$

$$K_2 = \frac{1}{X_1} + \frac{1}{(r_2 + X_1)} \frac{\lambda}{X_1} + \frac{1}{(r_1 + X_1)} \frac{\psi}{X_1}$$

$$+ \frac{1}{r_3} (\frac{\lambda}{X_1} \frac{X_1}{(r_2 + X_1)} + \frac{\psi}{X_1} \frac{X_1}{(r_1 + X_1)})$$

$$K_{02}^1 = \frac{1}{(r_2 + X_1)} \frac{\lambda}{X_1} + \frac{1}{(r_1 + X_1)} \frac{\psi}{X_1} \; ;$$

$$K_{02}^2 = \frac{1}{r_3} (\frac{\lambda}{X_1} \frac{X_1}{(r_2 + X_1)} + \frac{\psi}{X_1} \frac{X_1}{(r_1 + X_1)}) \tag{75-79}$$

Using equation [75-79] in equation [38-41] we get the required results.

When we put n =2 in above equations [58-62] then repair time follows 2-phase Erlang distribution and equation [47-57] will reduce to

$$p_{01} = \lambda / X_1 ; \quad p_{02} = \psi / X_1 ;$$

$$p_{10} = 4r_2^2 /(2r_2 + X_1)^2$$

$$p_{13} = X_1 (\frac{1}{(2r_2 + X_1)} + \frac{2r_2}{(2r_2 + X_1)^2});$$

$$p_{20} = \frac{2r_1^2}{(2r_1 + X_1)^2}$$

$$p_{23} = X_1 (\frac{1}{(2r_1 + X_1)} + \frac{2r_1}{(2r_1 + X_1)^2});$$

$$p_{30} = 1 \quad ; \quad \mu_0 = 1/X_1$$

$$\mu_1 = (\frac{1}{(2r_2 + X_1)} + \frac{2r_2}{(2r_2 + X_1)^2}) \; ;$$

$$\mu_2 = (\frac{1}{(2r_1 + X_1)} + \frac{2r_1}{(2r_1 + X_1)^2})$$

$$\mu_3 = \frac{1}{2r_2} \tag{80-90}$$

Using equation [80-90] in equation [42-46] and then using equation [38-41], we get the required results

Cost analysis :

The cost benefit analysis of the system can be carried out by considering the expected busy period of the repairman in repair in (0,t]. Therefore,

G(t) = expected revenue earned by the system in (0,t]-expected repair cost of the machine in (0,t] - expected busy period in shut down of the system in (0,t].

$$= C_1\mu_{up}(t) - C_2\mu_b^1(t) - C_3\mu_b^2(t) \quad (91)$$

Where :

$$\mu_{up}(t) = \int_0^t A_0(t)dt \;;\; \mu_b^1(t) = \int_0^t B_0^1(t)dt;$$

$$\mu_b^2(t) = \int_0^t B_0^2(t)dt$$

The expected profit per unit of time in steady state is

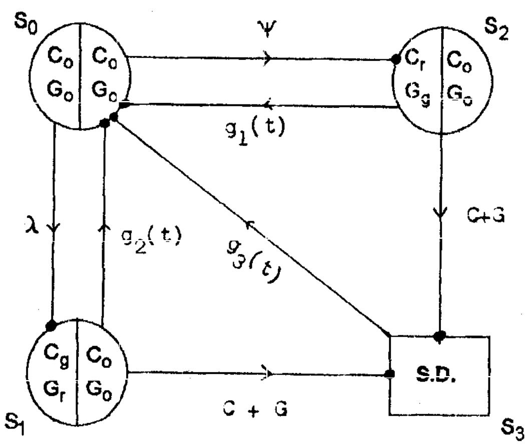

Figure 1.
STATE TRANSITION DIAGRAM
○ UP STATE □ DOWN STATE
• REGENERATIVE POINT

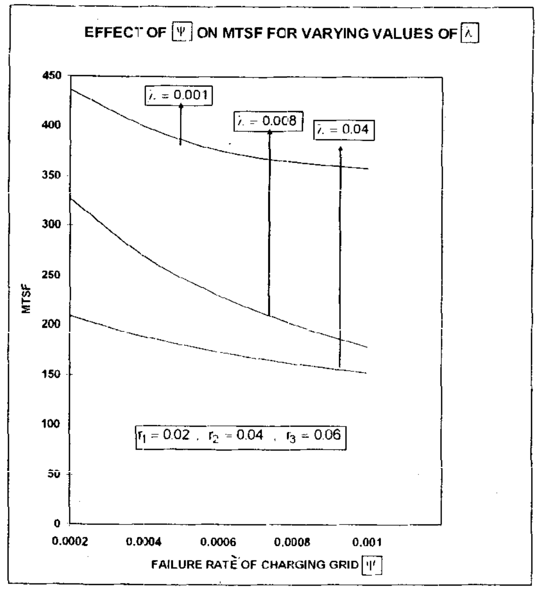

Figure 2

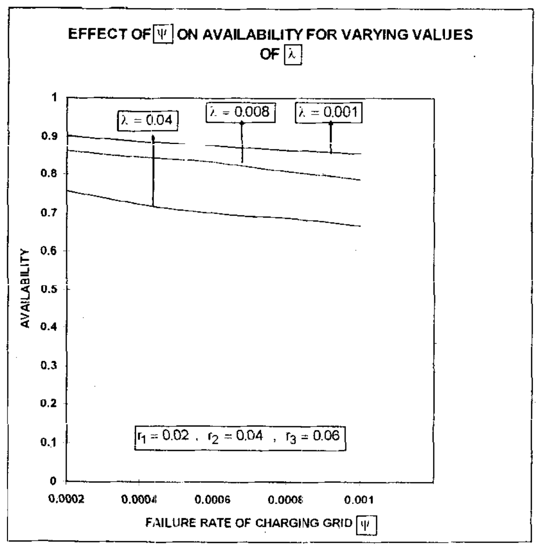

Figure 3

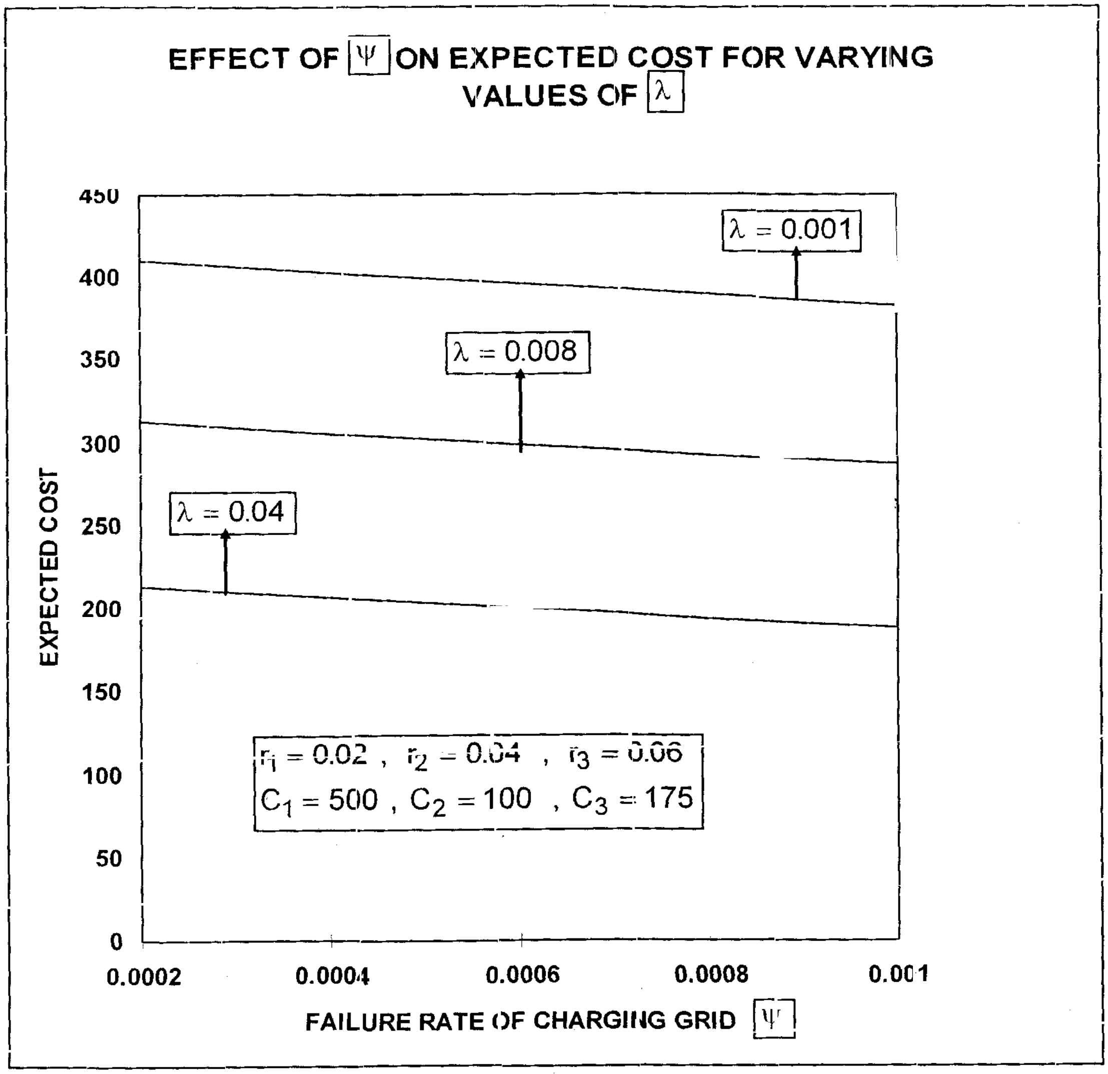

Figure 4

$$G = \lim_{t \to \infty} \frac{G(t)}{t} = \lim_{s \to 0} s^2 G^*(s) = C_1 \mu_{up}(t) - C_2 \mu_b^1(t) - C_3 \mu_b^2(t) \qquad (92)$$

where C_1 is the revenue per unit up time and C_2 and C_3 are the repair cost and shut down repair cost respectively.

Graphical representation :

Fig. 2 shows the behaviour of the

mean- time-to-system-failure of the hot metal crane system with respect to ψ (failure rate of charging grid) for varying values of λ (failure rate of crane). From the graph it can be observed that MTSF of the machine increases as failure rate λ decreases. Same case arises in case of availability and expected cost or profit as shown in figure 3 and figure 4.

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