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RELIABILITY MODELING AND ANALYSIS OF A TWO-UNIT PARALLEL CC PLANT WITH DIFFERENT INSTALLED CAPACITIES

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ABSTRACT

The CC technique accounts for more than 60% of total liquid steel in the world. Thus, the applied reliability modeling and analysis of a CC plant is of great importance; and hence, the paper explores a real, case specific modeling and analysis of a CC plant, where two 200 ton (unit I) and two 100 ton (unit II) EOT cranes are operating in parallel. Both units operate at full installed capacity and priority for maintenance and operation is given to the unit with higher installed capacity. When a unit fails, it is inspected to decide the type of maintenance job to be performed. The components are then repaired, replaced or reconditioned/reinstalled as required. Optimized reliability indices of the plant are obtained using semi-Markov processes and regenerative point techniques. Profit incurred to the CC plant is also evaluated and graphs pertaining to these indices are plotted.

Keywords: *Continuous Casting plant (CC plant), Reliability, Semi-Markov process, Regenerative Process, Repair, Failure.*

1. Introduction

In the CC route the BF – BOF heats are transported by ladle cars into the bay of unit I and unit II. The ladle handling crane loads these ladles onto the supports of the LTS. At the end of the treatment the ladle handling crane puts a cover on the ladle and brings the heat to the CC machine. Once casting of the strand is over, it is straightened and then cut into predetermined lengths by a mechanical shear. These cut billets are cooled suitably and once it is ready, it is transported by a billet handling crane with magnetic hoist system to the storage yard and later onto railroad cars. The tandem arrangement in which the four EOT cranes operate in pairs within the CC plant is referred to as unit I and unit II and categorized as critical equipment. Snag free operation of the critical equipment is imperative for the profitable running of the CC plant.

Reliability models to evaluate system effectiveness and profit have been studied by a number of researchers [3]-[11] where in diverse concepts for system analysis such as, reliability and profit of a PLC hot standby system on master-slave concept and two types of repair facilities, optimization of a single unit PLC system, comparative study of two reliability models with patience time, repairable system with three units and repair facilities, two unit deteriorating standby system with repair and so forth were studied. Later, Taneja et.al [2] wrote about a 2-out-of-3 unit system for an ash handling plant wherein a failure free situation was considered. Goyal et. al [1] evaluated the reliability and profit of a 2-unit cold standby system working in a sugar mill with operating and rest periods. A new concept to the existing literature can be added in terms of a real case example, where the units of the system operate in parallel with different installed capacities and the priority for operation and maintenance is given to the unit with higher installed capacity. The system under consideration is a CC plant with two units operating in parallel and possessing different installed capacities.

To this effect, the downtime maintenance data on EOT cranes from a CC plant for a period of four years have been collected. Three distinct causes of plant failure are seen in the data viz., repairable, replaceable, and reconditioning/reinstallation. The repair, replacement and reconditioning/reinstallation rates along with the probabilities of various failures of the critical equipments of the CC plant have been estimated from the data. The failure situations considered in the model is the same as depicted in the data and the analysis is carried out by using the real estimated values of various rates and probabilities. Thus, this paper offers a new contribution to the reliability literature in terms of a real case analysis of two-unit parallel CC plant equipment with different installed capacities. The various possible transition

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states of the system are as shown in Fig. 1.

The following measures of plant effectiveness in terms of reliability indices are obtained using the semi-Markov processes and regenerative point techniques:

1. Mean time to system failure.
2. Plant availability.
3. Expected busy period of the repairman for inspection.
4. Expected busy period of the repairman for repair.
5. Expected busy period of the repairman for replacement.
6. Expected busy period of the repairman for reconditioning/reinstallation.
7. Expected number of visits by the repairman.
8. Expected number of repairs.
9. Expected number of replacements.
10. Expected number of reconditioning/reinstallation.
11. Profit incurred to the system.

These reliability results proved to be meaningful to the plant engineers in analyzing the system behavior and thereby improving the performance of the plant.

The data are summarized as under:

1. Probability that the failed unit I needs repair $p_1 = 0.378$.
2. Probability that the failed unit I needs replacement $p_2 = 0.4$.
3. Probability that the failed unit I needs reconditioning/ reinstallation $p_3 = 0.222$.
4. Probability that the failed unit II needs repair $p_4 = 0.309$.
5. Probability that the failed unit II needs replacement $p_5 = 0.329$.
6. Probability that the failed unit II needs reconditioning/ reinstallation $p_6 = 0.36$.
7. Estimated value of failure rate for unit I $\lambda_1 = 0.0013$ per hour.
8. Estimated value of failure rate for unit II $\lambda_2 = 0.0026$ per hour.
9. Estimated value of repair rate of unit I $\alpha_1 = 0.298$ per hour.
10. Estimated value of replacement rate of unit I $\alpha_2 = 0.043$ per hour.
11. Estimated value of reconditioning / reinstallation rate of unit I $\alpha_3 = 0.286$ per hour.
12. Estimated value of repair rate of unit II $\beta_1 = 0.6$ per hour.
13. Estimated value of replacement rate of unit II $\beta_2 = 0.086$ per hour.
14. Estimated value of reconditioning/reinstallation rate of unit II $\beta_3 = 0.564$ per hour.

2. Model Description and Assumptions

1. The CC plant has two units: unit I & unit II.
2. Unit I and unit II constitutes a parallel system.
3. Repairman is called to carry out the inspection, repair, replacement and reconditioning / reinstallation.
4. As soon as a unit fails, inspection is carried out to reveal the type of failure and subsequent maintenance job is to be performed.
5. Priority for maintenance and operation is given to unit I, which is the higher capacity unit.
6. Unit I and Unit II always work at full installed capacity.
7. During the inspection, the other unit doesn't fail.
8. Failure times are exponentially distributed.
9. After each repair, the system works as good as new.

3. Transition Probabilities and Mean Sojourn Times

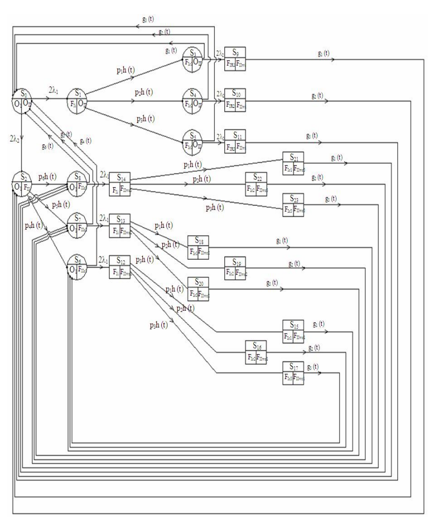

Fig. 1 Transition States of the System

A transition diagram showing the various states of the system in the CC plant is shown in Fig. 1. The epochs of entry into states 0, 1, 2, 3, 4, 5, 6, 7 and 8 are regenerative points and thus these states are classified as regenerative states. The states 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22 and 23 are failed states. The transition probabilities are given by:

$dQ_{01} = 2\lambda_1 e^{-2(\lambda_1+\lambda_2)t}dt$
$dQ_{02} = 2\lambda_2 e^{-2(\lambda_1+\lambda_2)t}dt$
$dQ_{13} = p_1 h(t)dt$
$dQ_{14} = p_2 h(t)dt$
$dQ_{15} = p_3 h(t)dt$
$dQ_{26} = p_4 h(t)dt$
$dQ_{27} = p_5 h(t)dt$
$dQ_{28} = p_6 h(t)dt$
$dQ_{30} = e^{-2\lambda_2 t} g_1(t)dt$
$dQ_{39} = 2\lambda_2 e^{-2\lambda_2 t}\overline{G}_1(t)dt$
$dQ_{32}^{(9)} = [2\lambda_2 e^{-2\lambda_2 t}©1]g_1(t)dt$
$dQ_{40} = e^{-2\lambda_2 t} g_2(t)dt$
$dQ_{4,10} = 2\lambda_2 e^{-2\lambda_2 t}\overline{G}_2(t)dt$
$dQ_{42}^{(10)} = [2\lambda_2 e^{-2\lambda_2 t}©1]g_2(t)dt$
$dQ_{50} = e^{-2\lambda_2 t} g_3(t)dt$
$dQ_{5,11} = 2\lambda_2 e^{-2\lambda_2 t}\overline{G}_3(t)dt$
$dQ_{52}^{(11)} = [2\lambda_2 e^{-2\lambda_2 t}©1]g_3(t)dt$
$dQ_{60} = e^{-2\lambda_1 t} g_4(t)dt$
$dQ_{6,12} = 2\lambda_1 e^{-2\lambda_1 t}\overline{G}_4(t)dt$
$dQ_{70} = e^{-2\lambda_1 t} g_5(t)dt$
$dQ_{7,13} = 2\lambda_1 e^{-2\lambda_1 t}\overline{G}_5(t)dt$
$dQ_{80} = e^{-2\lambda_1 t} g_6(t)dt$
$dQ_{8,14} = 2\lambda_1 e^{-2\lambda_1 t}\overline{G}_6(t)dt$
$dQ_{12,15} = p_1 h(t)dt$
$dQ_{12,16} = p_2 h(t)dt$
$dQ_{12,17} = p_3 h(t)dt$
$dQ_{13,18} = p_1 h(t)dt$
$dQ_{13,19} = p_2 h(t)dt$
$dQ_{13,20} = p_3 h(t)dt$
$dQ_{14,21} = p_1 h(t)dt$
$dQ_{14,22} = p_2 h(t)dt$
$dQ_{14,23} = p_3 h(t)dt$
$dQ_{15,6} = g_1(t)dt$
$dQ_{16,6} = g_2(t)dt$
$dQ_{17,6} = g_3(t)dt$
$dQ_{18,7} = g_1(t)dt$
$dQ_{19,7} = g_2(t)dt$
$dQ_{20,7} = g_3(t)dt$
$dQ_{21,8} = g_1(t)dt$
$dQ_{22,8} = g_2(t)dt$
$dQ_{23,8} = g_3(t)dt$ *(1) - (41)*

The non-zero elements p_{ij} are given below:

$p_{01} = \dfrac{\lambda_1}{\lambda_1+\lambda_2}$, $p_{02} = \dfrac{\lambda_2}{\lambda_1+\lambda_2}$, $p_{13} = p_1$, $p_{14} = p_2$,
$p_{15} = p_3$, $p_{26} = p_4$, $p_{27} = p_5$, $p_{28} = p_6$,
$p_{30} = \dfrac{\alpha_1}{2\lambda_2+\alpha_1}$, $p_{39} = p_{32}^{(9)} = \dfrac{2\lambda_2}{2\lambda_2+\alpha_1}$, $p_{40} = \dfrac{\alpha_2}{2\lambda_2+\alpha_2}$,
$p_{4,10} = p_{42}^{(10)} = \dfrac{2\lambda_2}{2\lambda_2+\alpha_2}$, $p_{50} = \dfrac{\alpha_3}{2\lambda_2+\alpha_3}$,
$p_{5,11} = p_{52}^{(11)} = \dfrac{2\lambda_2}{2\lambda_2+\alpha_3}$, $p_{60} = \dfrac{\beta_1}{2\lambda_1+\beta_1}$,
$p_{6,12} = \dfrac{2\lambda_1}{2\lambda_1+\beta_1}$, $p_{70} = \dfrac{\beta_2}{2\lambda_1+\beta_2}$, $p_{7,13} = \dfrac{2\lambda_1}{2\lambda_1+\beta_2}$,
$p_{80} = \dfrac{\beta_3}{2\lambda_1+\beta_3}$, $p_{8,14} = \dfrac{2\lambda_1}{2\lambda_1+\beta_3}$, $p_{12,15} = p_1$,
$p_{12,16} = p_2$, $p_{12,17} = p_3$, $p_{13,18} = p_1$, $p_{13,19} = p_2$,
$p_{13,20} = p_3$, $p_{14,21} = p_1$, $p_{14,22} = p_2$,
$p_{15,6} = p_{16,6} = p_{17,6} = p_{18,7} = p_{19,7} = p_{20,7} = p_{21,8} = p_{22,8}$
$= p_{23,8} = 1$ *(42) - (70)*

By these transition probabilities it can be verified that:

$p_{01} + p_{02} = 1$
$p_{13} + p_{14} + p_{15} = 1$
$p_{26} + p_{27} + p_{28} = 1$
$p_{30} + p_{39} = p_{30} + p_{32}^{(9)} = 1$
$p_{40} + p_{4,10} = p_{40} + p_{42}^{(10)} = 1$
$p_{50} + p_{5,11} = p_{50} + p_{52}^{(11)} = 1$
$p_{60} + p_{6,12} = p_{70} + p_{7,13} = p_{80} + p_{8,14} = 1$
$p_{12,15} + p_{12,16} + p_{12,17} = 1$
$p_{13,18} + p_{13,19} + p_{13,20} = 1$
$p_{14,21} + p_{14,22} + p_{14,23} = 1$

$$p_{15,6}+p_{16,6}+p_{17,6}=1$$
$$p_{18,7}+p_{19,7}+p_{20,7}=1$$
$$p_{21,8}+p_{22,8}+p_{23,8}=1 \qquad \textit{(71) - (83)}$$

The mean sojourn time (μ_i) in the regenerative state '*i*' is defined as the time of stay in that state before transition to any other state. If '*T*' denotes the sojourn time in the regenerative state '*i*', then:

$$\mu_i = E(T) = \Pr[T > t]dt$$
$$\mu_0 = \int_0^\infty [e^{-2\lambda_1 t}e^{-2\lambda_2 t}]dt = \frac{1}{2(\lambda_1+\lambda_2)};$$
$$\mu_1 = \int_0^\infty \overline{H}(t)dt\,;\ \mu_2 = \int_0^\infty \overline{H}(t)dt\,;$$
$$\mu_3 = \int_0^\infty e^{-2\lambda_2 t}\overline{G}_1 dt\,;\ \mu_4 = \int_0^\infty e^{-2\lambda_2 t}\overline{G}_2 dt\,;$$
$$\mu_5 = \int_0^\infty e^{-2\lambda_2 t}\overline{G}_3 dt\,;\ \mu_6 = \int_0^\infty e^{-2\lambda_1 t}\overline{G}_4 dt\,;$$
$$\mu_7 = \int_0^\infty e^{-2\lambda_1 t}\overline{G}_5 dt\,;\ \mu_8 = \int_0^\infty e^{-2\lambda_1 t}\overline{G}_6 dt \qquad \textit{(84) - (92)}$$

The unconditional mean time taken by the system to transit to any of the regenerative state '*j*' when time is counted from the epoch of entry into state '*i*', is mathematically stated as:

$$m_{ij} = \int_0^\infty t dQ_{ij}(t) = -q_{ij}{*}'(0) \qquad \textit{(93)}$$

Thus,

$$m_{01}+m_{02}=\mu_0\,;\ m_{13}+m_{14}+m_{15}=\mu_1\,;$$
$$m_{26}+m_{27}+m_{28}=\mu_2\,;\ m_{30}+m_{39}=\mu_3\,;$$
$$m_{40}+m_{4,10}=\mu_4\,;\ m_{50}+m_{5,11}=\mu_5\,;$$
$$m_{60}+m_{6,12}=\mu_6\,;\ m_{70}+m_{7,13}=\mu_7\,;$$
$$m_{80}+m_{8,14}=\mu_8\ ;\ m_{30}+m_{32}^{(9)}=k_3(\text{say})\,;$$
$$m_{40}+m_{42}^{(10)}=k_4(\text{say})\,;\ m_{50}+m_{52}^{(11)}=k_5(\text{say})$$

4. Maintenance Effectiveness and Performance Analysis

Considering the failed states as absorbing states and making use of the arguments for regenerative processes, the recursive relations for mean time to system failure, availability, expected busy periods of the repairman for various maintenance jobs, expected number of visits by the repairman, expected number of repairs, replacements, and reconditioning/reinstallation are obtained. Solving the recursive relations with Laplace/Laplace Stieltje's Transforms, the steady-state solutions for the various measures of system effectiveness in terms of reliability indices of the CC plant equipment are estimated.

4.1 Mean time to system failure

Let $\phi_i(t)$ be the c.d.f. of the first passage time from regenerative state 'i' to a failed state 'j'. Using the simple probabilistic arguments, the following recursive relations for $\phi_i(t)$ are obtained:

$$\phi_0(t) = Q_{01}(t) \circledS \phi_1(t) + Q_{02}(t) \circledS \phi_2(t)$$
$$\phi_1(t) = Q_{13}(t) \circledS \phi_3(t) + Q_{14}(t) \circledS \phi_4(t) + Q_{15}(t) \circledS \phi_5(t)$$
$$\phi_2(t) = Q_{26}(t) \circledS \phi_6(t) + Q_{27}(t) \circledS \phi_7(t) + Q_{28}(t) \circledS \phi_8(t)$$
$$\phi_3(t) = Q_{30}(t) \circledS \phi_0(t) + Q_{39}(t)$$
$$\phi_4(t) = Q_{40}(t) \circledS \phi_0(t) + Q_{4,10}(t)$$
$$\phi_5(t) = Q_{50}(t) \circledS \phi_0(t) + Q_{5,11}(t)$$
$$\phi_6(t) = Q_{60}(t) \circledS \phi_0(t) + Q_{6,12}(t)$$
$$\phi_7(t) = Q_{70}(t) \circledS \phi_0(t) + Q_{7,13}(t)$$
$$\phi_8(t) = Q_{80}(t) \circledS \phi_0(t) + Q_{8,14}(t) \qquad \textit{(94) - (102)}$$

Taking the Laplace Stieltjes Transforms (L.S.T.) of the above equations and solving them for $\phi_0{**}(s)$;

$$\phi{**}(s) = \frac{N(s)}{D(s)}$$

Where,

$$N(s) = Q_{01}{**}(s)Q_{13}{**}(s)Q_{39}{**}(s) + Q_{01}{**}(s)Q_{14}{**}(s)Q_{410}{**}(s) + Q_{01}{**}(s)Q_{15}{**}(s)Q_{5,11}{**}(s) + Q_{02}{**}(s)Q_{26}{**}(s)Q_{6,12}{**}(s) + Q_{02}{**}(s)Q_{27}{**}(s)Q_{7,13}{**}(s) + Q_{02}{**}(s)Q_{28}{**}(s)Q_{8,14}{**}(s)$$

$$D(s) = 1 - Q_{01}{**}(s)Q_{13}{**}(s)Q_{30}{**}(s) - Q_{01}{**}(s)Q_{14}{**}(s)Q_{40}{**}(s) - Q_{01}{**}(s)Q_{15}{**}(s)Q_{50}{**}(s) - Q_{02}{**}(s)Q_{26}{**}(s)Q_{60}{**}(s) - Q_{02}{**}(s)Q_{27}{**}(s)Q_{70}{**}(s) - Q_{02}{**}(s)Q_{28}{**}(s)Q_{80}{**}(s)$$

Now the mean time to system failure (MTSF) when the system started at the beginning of state 0 is given by:

$$\mathrm{MTSF} = \lim_{s\to 0}\frac{1-\phi_0{}^{**}(s)}{s} = \frac{N}{D} \qquad (103)$$

Where $N = m_{01} + m_{02} + p_{01} + p_{02} + \mu_2$

and

$D = 1 - p_{01}p_{13}p_{30} + p_{01}p_{14}p_{40} + p_{01}p_{15}p_{50} + p_{02}p_{13}p_{60} + p_{02}p_{14}p_{70} + p_{02}p_{15}p_{80}$

4.2 Plant availability

Using the probabilistic arguments of point wise availability of the plant and defining $A_i(t)$ as the probability that the plant is in upstate at instant t, given that it enters in the regenerative state i at t=0, the following recursive relations can be obtained:

$$A_0(t) = M_0(t) + q_{01}(t)©A_1(t) + q_{02}(t)©A_2(t)$$
$$A_1(t) = q_{13}(t)©A_3(t) + q_{14}(t)©A_4(t) + q_{15}(t)©A_5(t)$$
$$A_2(t) = q_{26}(t)©A_6(t) + q_{27}(t)©A_7(t) + q_{28}(t)©A_8(t)$$
$$A_3(t) = q_{30}(t)©A_0(t) + q_{32}^{(9)}(t)©A_2(t)$$
$$A_4(t) = q_{40}(t)©A_0(t) + q_{42}^{(10)}(t)©A_2(t)$$
$$A_5(t) = q_{50}(t)©A_0(t) + q_{52}^{(11)}(t)©A_2(t)$$
$$A_6(t) = q_{60}(t)©A_0(t) + q_{6,12}(t)©A_{12}(t)$$
$$A_7(t) = q_{70}(t)©A_0(t) + q_{7,13}(t)©A_{13}(t)$$
$$A_8(t) = q_{80}(t)©A_0(t) + q_{8,14}(t)©A_{14}(t)$$
$$A_{12}(t) = q_{12,15}(t)©A_{15}(t) + q_{12,16}(t)©A_{16}(t) + q_{12,17}(t)©A_{17}(t)$$
$$A_{13}(t) = q_{13,18}(t)©A_{18}(t) + q_{13,19}(t)©A_{19}(t) + q_{13,20}(t)©A_{20}(t)$$
$$A_{14}(t) = q_{14,21}(t)©A_{21}(t) + q_{14,22}(t)©A_{22}(t) + q_{14,23}(t)©A_{23}(t)$$
$$A_{15}(t) = q_{15,6}(t)©A_6(t)$$
$$A_{16}(t) = q_{16,6}(t)©A_6(t)$$
$$A_{17}(t) = q_{17,6}(t)©A_6(t)$$
$$A_{18}(t) = q_{18,7}(t)©A_7(t)$$
$$A_{19}(t) = q_{19,7}(t)©A_7(t)$$
$$A_{20}(t) = q_{20,7}(t)©A_7(t)$$
$$A_{21}(t) = q_{21,8}(t)©A_8(t)$$
$$A_{22}(t) = q_{22,8}(t)©A_8(t)$$
$$A_{23}(t) = q_{23,8}(t)©A_8(t) \qquad (104)-(124)$$

Where $M_0(t) = e^{-2(\lambda_1+\lambda_2)t}$

Taking Laplace Transforms (L.T.) of the above equations and solving them for $A_0^*(s)$;

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

Therefore the steady state availability of the plant is given by:

$$A_0 = \lim_{s\to 0} sA_0{}^*(s) \qquad (125)$$

Proceeding in similar method as above we get the following measures of system effectiveness in steady state:

Expected busy period for inspection (I_0): N_2/D_1

Expected busy period for repairable failure (B_0): N_3/D_1.

Expected busy period for replaceable failure (BR_0): N_4/D_1.

Expected busy period for reconditioning/reinstallation failure (BRR_0): N_5/D_1.

Expected number of visits by the repairman (V_0): N_6/D_1.

Expected number of repairable failure (R_0): N_7/D_1.

Expected number of replaceable failure (RP_0): N_8/D_1.

Expected number of reconditioning/reinstallation failure (RR_0): N_9/D_1.

5. Profit Analysis

Combining the elements discussed above, the profit is defined as:

$$P = C_0A_0 - C_1I_0 - C_2B_0 - C_3BR_0 - C_4BRR_0 - C_5V_0 - C_6R_0 - C_7RP_0 - C_8RR_0 \qquad (126)$$

6. Particular Case

For the particular case, the rate of repairable failure, replaceable failure and reconditioning/reinstallation failure and inspection is assumed to be exponentially distributed i.e.

$g_1(t) = \alpha_1 e^{-\alpha_1 t}$; $g_2(t) = \alpha_2 e^{-\alpha_2 t}$; $g_3(t) = \alpha_3 e^{-\alpha_3 t}$;

$g_4(t) = \beta_1 e^{-\beta_1 t}$ $g_5(t) = \beta_2 e^{-\beta_2 t}$ $g_6(t) = \beta_3 e^{-\beta_3 t}$;

$h(t) = \alpha e^{-\alpha t}$;

Using the values of various probabilities and rates as estimated in section 3, the following measures of the system effectiveness are estimated:

Mean Time to System Failure: 4767.303 hours.

Plant availability: 0.954125.

Expected busy period for inspection I_0 : 0.01873.

Expected busy period for repairable failure B_0 : 0.005835.

Expected busy period for replaceable failure BR_0 : 0.019462.

Expected busy period for reconditioning/reinstallation failure BRR_0 : 0.00527.

Expected number of visits by the repairman V_0 : 0.007522.

Expected number of repairable failure R_0 : 0.002566.

Expected number of replaceable failure RP_0 : 0.002696.

Expected number of reconditioning/reinstallation failure RR_0 : 0.002394.

7. Graphical Interpretations

The particular case discussed above is considered for the graphical interpretation.

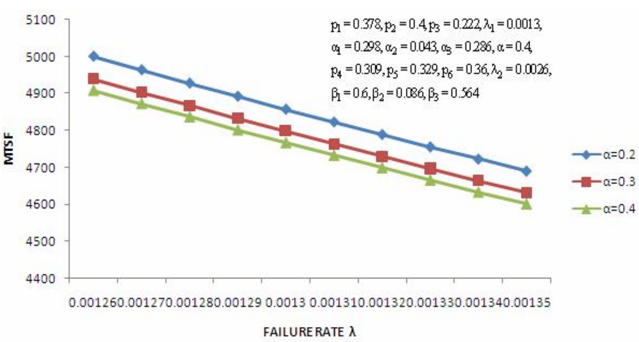

Fig. 2 MTSF vs Failure Rate (λ) for Different Values of Inspection Rate (α)

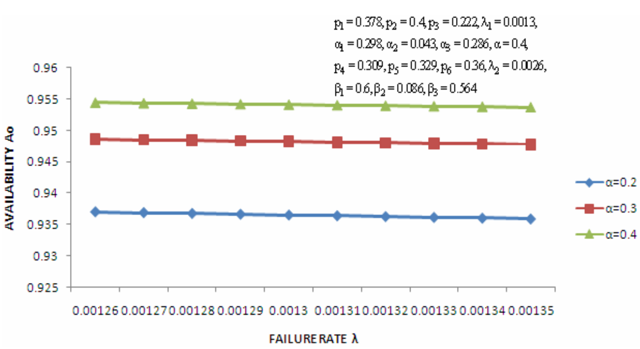

Fig. 3 Availability (A_0) vs Failure Rate (λ) for Different Values of Inspection Rate (α)

Fig. 2 shows the behavior of MTSF with respect to the failure rate (λ) for different values of inspection rate (α). It can be concluded from the graph that MTSF decreases with the increase in values of inspection rate (α) and has lower values for higher values of inspection rate (α).

Fig. 3 shows the behavior of plant availability (A_0) with respect to the failure rate (λ) for different values of inspection rate (α). It can be concluded from the graph that availability (A_0) decreases with the increase in values of inspection rate (α) and has lower values for higher values of inspection rate (α).

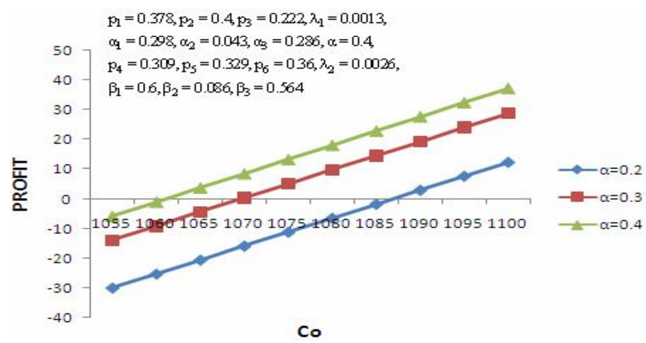

Fig. 4 Profit (P) vs Revenue Per Unit Uptime (C_0) for Different Values of Inspection Rate (A)

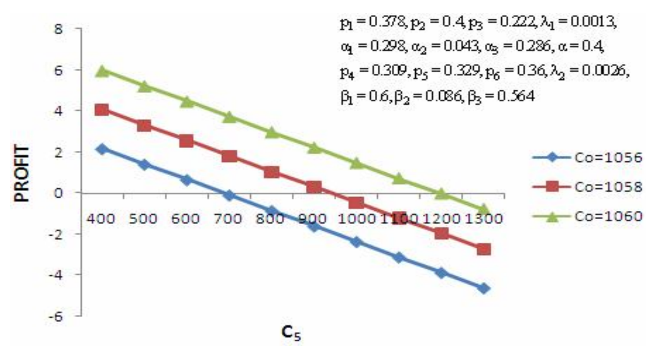

Fig. 5 Profit (P) vs Cost Per Visit (C_5) for Different Values of Revenue Per Unit Uptime (C_0)

Fig. 4 demonstrates the pattern of profit (P) with respect to revenue per unit up time (C_0) for different values of inspection rate (α). The following interpretation could be achieved from this graph:

(i) The profit increases with increase in the values of revenue per unit up time and has higher values for higher values of inspection rate (α).

(ii) For α = 0.2, the profit is positive or zero or negative according as C_O > or = or < 1085.00.

(iii) For α = 0.3, the profit is positive or zero or negative according as C_O > or = or < 1067.50.

(iv) For α = 0.4, the profit is positive or zero or negative according as C_O > or = or < 1057.50.

Fig 5 demonstrates the pattern of profit (P) with respect to cost per visit of repairman (C_5) for different values of revenue per unit up time (C_O). The following interpretation could be achieved from this graph:

(i) The profit decreases with increase in values of cost per visit of repairman (C_5).

(ii) For C_O = 1056, the profit is positive or zero or negative according as C_5 > or = or < 650.00.

(iii) For C_O = 1058, the profit is positive or zero or negative according as C_5 > or = or < 1000.00.

(iv) For C_O = 1060, the profit is positive or zero or negative according as C_5 > or = or < 1150.00.

8. Conclusions

Various measures of plant effectiveness in terms of reliability indices have been estimated numerically, which facilitates the plant engineers in analyzing the system behavior and thereby improving the performance of the plant. Using the estimated values, some useful graphs are plotted for the particular case.

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Acronym

CC	Continuous Casting
EOT	Electrically Operated Overhead Travelling Crane
INR	Indian National Rupee
MTSF	Mean Time to System Failure
BF	Blast Furnace
BOF	Basic Oxygen Furnace
LTS	Ladle Treatment Station
PLC	Programmable Logic Controller

Nomenclature

	Operative state of the CC plant
	Failed state of the CC plant
O	Cranes working under full installed capacity
α	Inspection rate
λ_1	Failure rate of either crane of unit I
p_1	Probability of repairable failure of unit I
p_2	Probability of replaceable failure of unit I
p_3	Probability of reconditioning/reinstallation failure of unit I
F_{Ii}	Failed unit I is under inspection
F_{Ir1}	Failed unit I is under repair
F_{Ir2}	Failed unit I is under replacement
F_{Ir3}	Failed unit I is under reconditioning/reinstallation
F_{IR1}	Failed unit I under repairable failure continues from previous state
F_{IR2}	Failed unit I under replaceable failure continues from previous state
F_{IR3}	Failed unit I under reconditioning/reinstallation failure continues from previous state
F_{Iwi}	Failed unit I is waiting for inspection
$g_1(t), G_1(t)$	p.d.f. (probability density function) and c.d.f. (cumulative distribution function) of repair time of unit I
$g_2(t), G_2(t)$	p.d.f. and c.d.f. of replacement time of unit I
$g_3(t), G_3(t)$	p.d.f. and c.d.f. of reconditioning/reinstallation time of unit I
λ_2	Failure rate of either crane of unit II

p_4	Probability of repairable failure of unit II
p_5	Probability of replaceable failure of unit II
p_6	Probability of reconditioning/reinstallation failure of unit II
F_{IIi}	Failed unit II is under inspection
F_{IIr1}	Failed unit II is under repairable failure
F_{IIr2}	Failed unit II is under replaceable failure
F_{IIr3}	Failed unit II is under reconditioning/reinstallation failure
F_{IIR1}	Failed unit II under repairable failure continues from previous state
F_{IIR2}	Failed unit II under replaceable failure continues from previous state
F_{IIR3}	Failed unit II under reconditioning/reinstallation failure continues from previous state
F_{IIwi}	Failed unit II is waiting for inspection
*	Symbol for Laplace transforms
**	Symbol for Laplace Stieltje's transforms
©	Symbol for Laplace convolution
Ⓢ	Symbol for Stieltje's convolution
$h(t), H(t)$	p.d.f. and c.d.f. of inspection time of a failed unit
$g_4(t), G_4(t)$	p.d.f. and c.d.f. of repair time of unit II
$g_5(t), G_5(t)$	p.d.f. and c.d.f. of replacement time of unit II
$g_6(t), G_6(t)$	p.d.f. and c.d.f. of reconditioning/reinstallation time of unit II
A_0	Steady state availability of the system
I_0	Busy period of the repairman for inspection
B_0	Busy period of the repairman for repairable failure
BR_0	Busy period of the repairman for replaceable failure
BRR_0	Busy period of the repairman for reconditioning/reinstallation failure
V_0	Expected number of visits by the repairman
R_0	Expected number of repairs
RP_0	Expected number of replacements
RR_0	Expected number of reconditioning/reinstallation
C_0	Revenue per unit up time
C_1	Cost per unit up time for which the repairman is busy for inspection
C_2	Cost per unit up time for which the repairman is busy for repairable failure
C_3	Cost per unit up time for which the repairman is busy for replaceable failure
C_4	Cost per unit up time for which the repairman is busy for reconditioning/reinstallation failure
C_5	Cost per visit of repairman.
C_6	Cost per unit repair
C_7	Cost per unit replacement
C_8	Cost per unit reconditioning/reinstallation

(All costs are in Indian Rupee)