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Comparative Analysis between Three Reliability Models of a Two-Unit Complex Industrial System

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ABSTRACT

This paper presents the reliability modelling and analysis of a complex industrial system with two units operating in parallel. To facilitate the study, real failure-maintenance data of the system are collected. Data depicts that a unit is repaired upon failure by a single repairman. Reliability indices of the system such as mean time between failures, availability, expected number of repairs, and expected busy period of the repairman are estimated using semi-Markov processes and regenerative processes. Finally, a comparative analysis between the reliability indices of three reliability models for the system is presented.

1. Introduction

Numerous researchers have contributed to the field of reliability modelling and analysis while analyzing complex industrial systems under different operating conditions and assumptions.

Rizwan and Taneja [1] estimated the profit of a system with perfect repair, partial failure and complete failure. In a study, Rizwan *et al.,* [2] carried out a comparative study between the profits of two models for a two-unit system that incorporates a rest period for the repairman. In another study, Rizwan *et al.,* [3] introduced the concept of an accident during the inspection and the possibility of multiple post-repair inspections while examining one-unit and two-unit systems. Later, Rizwan *et al.,* [4-6] extensively analyzed PLC systems with a single unit and hot standby, various reliability indices and profit incurred were estimated. Rizwan [7] also performed a reliability analysis of a two-unit system with two repairmen. A detailed analysis of a CC plant was reported by Mathew *et al.,* [8,9] to estimate key performance indicators such as mean time to system failure, availability, etc. Mathew *et al.,* [10-14] continued to work on the CC plant with scheduled maintenance policy, different installed capacities, full installed capacity, and profit evaluation; and presented a comparative analysis between profits of two models of the CC plant. In several studies, Padmavathi *et al.,* [15-19] analyzed a desalination plant with online repair and emergency shutdowns, with minor/major failures and priority given to repairing over maintenance, with major and minor failures and

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shutdown during the winter season, and finally presented a comparative analysis of two models of the desalination plant. To examine to a greater extent the desalination plant with mandatory shutdown during winter season and repair/maintenance on FCFS basis and compare the various reliability models of the desalination plant, the methodology was [20-22]. Subsequently, analysis of a wastewater treatment plant and an anaerobic batch reactor was presented; reliability indices of interest were estimated to assess the plant/reactor performance [23-25]. Rizwan and Mathew [26] extended their work for the performance analysis of port cranes. A detailed study of the aluminium industry was presented by Al Rahbi *et al.,* [27-32], wherein, the butt thimble removal station and rodding anode plant were analyzed for important reliability indices. Later, Al Rahbi and Rizwan [33] presented a comparative analysis between the models of a single component with a single repairman and multiple repairmen in the aluminium industry. Taj *et al.,* [34-39] carried out a detailed reliability analysis of a cable plant and its subsystems with different maintenance categories, storage of surplus produce, season based operating strategy, and presented a comparative analysis between three profit models of the cable plant. Taj and Rizwan [40] critically reviewed the reliability modelling and analysis of complex industrial systems, whereas Rizwan and Taj [41] presented reliability modeling and analysis of port PLCs. Kunalan *et al.,* [42] investigated the performance of a multi-staging hydrokinetic turbine for river flow. Taj and Rizwan [43,44] further discussed the reliability analysis of a system using best-fit distributions for repair/restoration times, and a 3-unit parallel system with a single maintenance facility, respectively.

Hence, the methodology for reliability modelling and analysis of complex industrial systems under various failure/maintenance situations has been widely presented in the literature.

In this paper, reliability modelling and analysis of a complex industrial system with two units operating in parallel is presented. Real failure-maintenance data of the system shows that a failed unit undergoes repair by a single repairman. Using semi-Markov processes and regenerative processes, important reliability indices of the system namely mean time between failures, availability, expected number of repairs, and expected busy period of the repairman are estimated. Recently, Taj *et al.,* [45,46] analyzed two reliability models of the system under different operating conditions and assumptions. Thus, a comparative analysis between the reliability indices of the three reliability models for the system is also presented in this paper. The analysis is useful in deducing the suitability of one model over the other.

2. Model Description (Model I)

The following operating conditions and assumptions are considered

i. The system consists of two units.
ii. The units operate in parallel.
iii. A unit is repaired upon failure.
iv. After each repair, the failed unit regenerates.
v. There is only one repairman.
vi. Repair times are assumed to be arbitrarily distributed.
vii. Failure times are assumed to be exponentially distributed.

State-transition table of the system is shown in Table 1. Zero (0) stands for no transition to the mentioned state.

Table 1
State-transition table

S_i \ S_j	S_0	S_1	S_2
S_0	0	$2\lambda_1$	0
S_1	$g_1(t)$	0	λ_1
S_2	0	$g_1(t)$	0
For non-regenerative state S_2			
S_1 to S_1 via S_2	$q_{11}^2(t) = \left(\lambda_1 e^{-\lambda_1 t} © 1\right) g_1(t)$		

States of the system are described below

S_0: both units are operative.
S_1: one unit has failed and is under repair; one unit is operative.
S_2: one unit has failed and is under repair from the previous state; one unit has failed and is waiting for repair.

here,

S_0 and S_1 are regenerative states.
S_2 is the non-regenerative state as well as the failed state.

Note: System is considered to be in the failed state when both units have failed.

3. Transition Probabilities and Mean Sojourn Times

Using the definition of transition probabilities $q_{ij}(t)$, we get [47]

$$q_{01}(t) = 2\lambda_1 e^{-2\lambda_1 t} \tag{1}$$

$$q_{10}(t) = g_1(t) e^{-\lambda_1 t} \tag{2}$$

$$q_{12}(t) = \lambda_1 e^{-\lambda_1 t} \overline{G_1}(t) \tag{3}$$

$$q_{11}^2(t) = \left(\lambda_1 e^{-\lambda_1 t} © 1\right) g_1(t) \tag{4}$$

$$q_{21}(t) = g_1(t) \tag{5}$$

where,

$G_1(t)$ denotes the cdf of repair times.

Using the definition of non-zero elements p_{ij}, we get [47]

$$p_{01} = \frac{2\lambda_1}{2\lambda_1} \tag{6}$$

$$p_{10} = {g_1}^*(\lambda_1) \tag{7}$$

$$p_{12} = 1 - {g_1}^*(\lambda_1) \tag{8}$$

$$p_{11}^2 = 1 - {g_1}^*(\lambda_1) \tag{9}$$

$$p_{21} = {g_1}^*(0) \tag{10}$$

The following can be easily verified

$$p_{01} = 1 \tag{11}$$

$$p_{10} + p_{12} = 1 \tag{12}$$

$$p_{10} + p_{11}^2 = 1 \tag{13}$$

$$p_{21} = 1 \tag{14}$$

Using the definition of mean sojourn time μ_i, we get [47]

$$\mu_0 = \frac{1}{2\lambda_1} \tag{15}$$

$$\mu_1 = \int_0^\infty \overline{G_1}(t)e^{-\lambda_1 t}dt \tag{16}$$

$$\mu_2 = \int_0^\infty \overline{G_1}(t)dt \tag{17}$$

Using the definition of unconditional mean time m_{ij}, following can be easily verified [47]

$$m_{01} = \mu_0 \tag{18}$$

$$m_{10} + m_{12} = \mu_1 \tag{19}$$

$$m_{10} + m_{11}^2 = \mu_2 \tag{20}$$

$$m_{21} = \mu_2 \tag{21}$$

4. Mean Time Between Failures

Using simple probabilistic arguments and the definition of $\phi_i(t)$, we get [47]

$$\phi_0(t) = Q_{01}(t) \circledS \phi_1(t) \tag{22}$$

$$\phi_1(t) = Q_{10}(t) \circledS \phi_0(t) + Q_{12}(t) \tag{23}$$

Taking LST of the above equation and solving for ${\phi_0}^{**}(s)$, we obtain

$${\phi_0}^{**}(s) = \frac{N(s)}{D(s)} \tag{24}$$

The MTBF, given that the system started at the beginning of state 0 is given by

$$\mathrm{MTBF} = \lim_{s \to 0} \frac{1-\phi_0{}^{**}(s)}{s} = \frac{N}{D} \tag{25}$$

where,

$$N = \mu_0 + \mu_1 \tag{26}$$

$$D = p_{12} \tag{27}$$

5. Availability of the System

Using simple probabilistic arguments and the definition of $A_i(t)$, we get [47]

$$A_0(t) = M_0(t) + q_{01}(t) © A_1(t) \tag{28}$$

$$A_1(t) = q_{10}(t) © A_0(t) + q_{11}^2 © A_1(t) \tag{29}$$

where,

$$M_0(t) = e^{-2\lambda_1 t} \tag{30}$$

Taking LT of the above equations and solving for $A_0{}^*(s)$, we get

$$A_0{}^*(s) = \frac{N_1(s)}{D_1(s)} \tag{31}$$

In steady state, the availability of the system is given by

$$A_0 = \lim_{s \to 0} s\, A_0{}^*(s) = \frac{N_1}{D_1} \tag{32}$$

where,

$$N_1 = p_{10}\mu_0 \tag{33}$$

$$D_1 = p_{10}\mu_0 + \mu_2 \tag{34}$$

6. Expected Busy Period of the Repairman

Using simple probabilistic arguments and the definition of $B_i(t)$, we get [47]

$$B_0(t) = q_{01}(t) © B_1(t) \tag{35}$$

$$B_1(t) = W_1(t) + q_{10}(t) © B_0(t) + q_{11}^2(t) © B_1(t) \tag{36}$$

where,

$$W_1(t) = e^{-\lambda_1 t}\overline{G_1}(t) \tag{37}$$

Taking LT of above equations and solving for $B_0{}^*(s)$, we obtain

$$B_0{}^*(s) = \frac{N_2(s)}{D_1(s)} \tag{38}$$

In steady state, the expected busy period of the repairman is given by

$$B_0 = \lim_{s\to 0} s\, B_0{}^*(s) = \frac{N_2}{D_1} \tag{39}$$

where,

$$N_2 = W_1{}^*(0) \tag{40}$$

D_1 is specified in Eq. (34).

7. Expected Number of System Repairs

Using simple probabilistic arguments and the definition of $R_i(t)$, we get [47]

$$R_0(t) = Q_{01}(t)\circledS\{R_1(t) + 1\} \tag{41}$$

$$R_1(t) = Q_{10}(t)\circledS R_0(t) + Q_{11}^2(t)\circledS\{R_1(t) + 1\} \tag{42}$$

Taking LST of the above equations and solving for $R_0{}^{**}(s)$, we get

$$R_0{}^{**}(s) = \frac{N_3(s)}{D_1(s)} \tag{43}$$

In steady state, the expected number of system repairs is given by

$$R_0 = \lim_{s\to 0} s\, R_0{}^{**}(s) = \frac{N_3}{D_1} \tag{44}$$

where,

$$N_3 = 1 \tag{45}$$

D_1 is specified in Eq. (34).

8. Particular Case

As a particular case, we assume that the repair times also follow exponential distribution, let us say

$$g_1(t) = \gamma_1 e^{-\gamma_1 t} \tag{46}$$

Table 2 shows the values of various rates estimated from the real-maintenance failure data of the system.

Table 2
Estimated values of rates for the system

S. No.	Rate	Value (per hour)
1	constant failure rate, λ_1	0.00368
2	constant repair rate, γ_1	0.24729

Substituting the above table values in the expressions obtained in sections 4 to 7, following reliability indices of the system are obtained

Mean time between failures: 2063 hours (47)

Availability of the system: 0.901 (48)

Expected number of system repairs: 0.016 (49)

Expected busy period of the repairman: 0.062 (50)

9. Previous Work

Earlier, two reliability models of the system under consideration were analysed by Taj *et al.,* [45,46] wherein different operating conditions and assumptions were taken into account.

For Model II, the following were considered (in addition to the operating conditions and assumptions of Model I) [45]

i. Three types of maintenances are performed: repair, minor PM, and major PM.
ii. Minor/major PM are performed at a scheduled basis.
iii. Priority is given to repair over minor/major PM.

However for Model III, the authors considered the following (in addition to the operating conditions and assumptions of Models I and II) [46]

i. Machines are queued for major PM.
ii. An operative machine requires a cooling period of half hour before undergoing major PM.

For Model II, the following values of reliability indices of the system were obtained (refer Taj *et al.,* [45] for details)

Mean time between failures = 3644.3713 hours (51)

Availability of the system = 0.9350 (52)

Expected number of system repairs = 0.0104 (53)

Expected busy period of the repairman = 0.0079 (54)

Whereas for Model III, the estimated reliability indices of the system were as follows (refer Taj *et al.,* [46] for details)

Mean time between failures = 3475.6 hours (55)

Availability of the system = 0.92523 (56)

Expected number of system repairs = 0.01077 (57)

Expected busy period of the repairman = 0.05362 (58)

10. Comparative Analysis

This section presents a comparison between the values of reliability indices of the system obtained for Model I (section 8) with those given for Models II and III (section 9).

Comparison between the values of mean time between failures for the three models is shown in Figure 1.

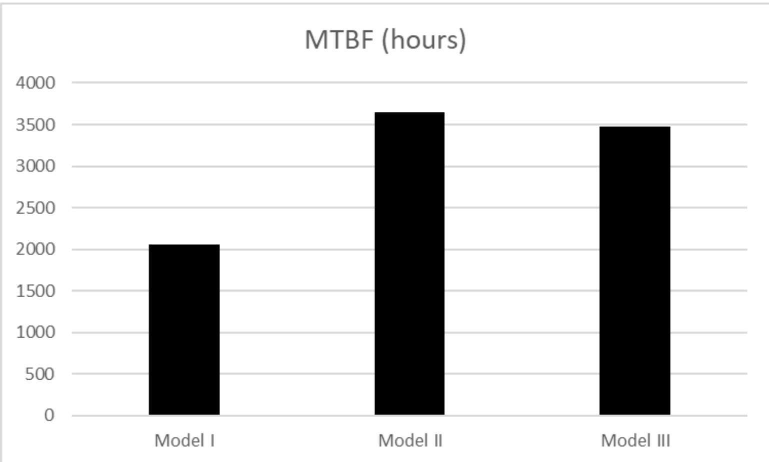

Fig. 1. Comparison between MTBF (hours)

Comparison between the values of availability of the system for the three models is shown in Figure 2.

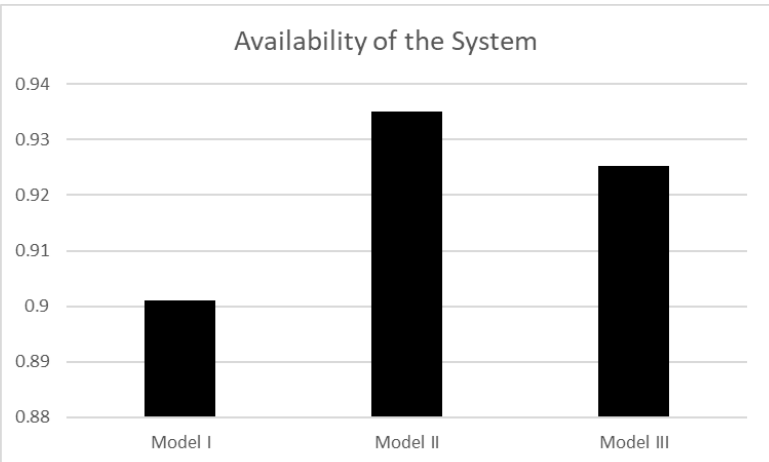

Fig. 2. Comparison between availability of the system

Comparison between the values of expected number of system repairs for the three models is shown in Figure 3.

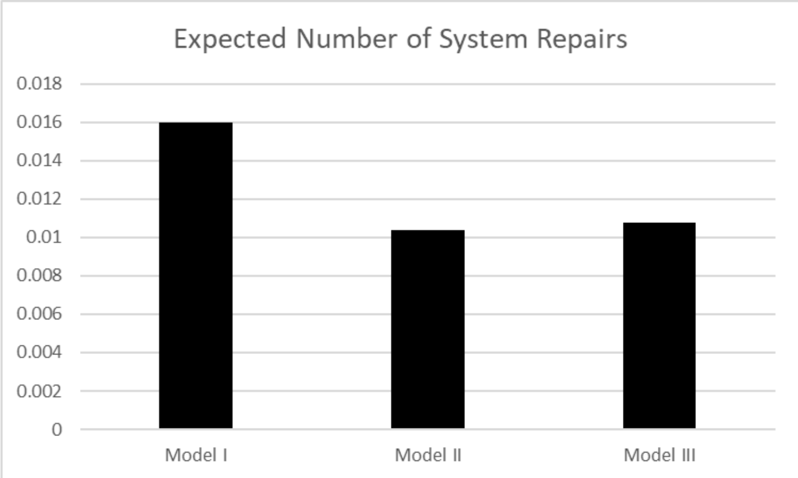

Fig. 3. Comparison between expected number of system repairs

Comparison between the values of expected busy period of the repairman for the three models is shown in Figure 4.

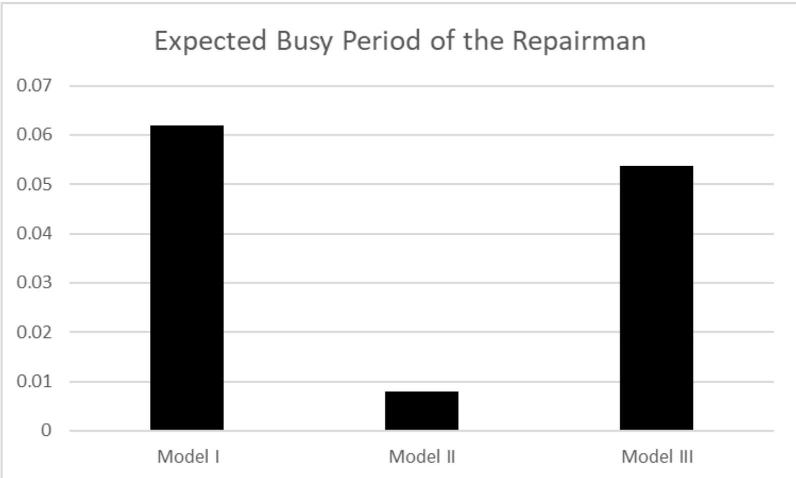

Fig. 4. Comparison between expected busy period of the repairman

From Figure 1 to Figure 4, following observations can be drawn

i. The MTBF for Model II is more as compared to Models I and III.
ii. The availability of the system for Model II is more as compared to Models I and III.
iii. The expected number of system repairs for Model II is less as compared to Models I and III.
iv. The expected busy period of the repairman for Model II is less as compared to Models I and III.

11. Conclusion

Reliability modelling and analysis of a complex industrial system with two units operating in parallel is presented. Reliability indices of the system viz. mean time between failures, availability, expected number of repairs, and expected busy period of the repairman are estimated. Comparative analysis between the reliability indices of three reliability models of the system is presented. The comparison clearly indicates the suitability of Model II over Models I and III.

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