GCU

Glasgow Caledonian
University

University for the Common Good

Probabilistic modeling and analysis of a cable plant subsystem with priority to repair over preventive maintenance

Taj, S.Z.; Rizwan, S.M.; Alkali, B.M.; Harrison, D.K.; Taneja , G.

PROBABILISTIC MODELING AND ANALYSIS OF A CABLE PLANT SUBSYSTEM WITH PRIORITY TO REPAIR OVER PREVENTIVE MAINTENANCE

Taj SZ[1], Rizwan SM[2] , Alkali BM[3], Harrison DK[4] and Taneja G[5]

[1&2]Department of Mathematics & Statistics, Caledonian College of Engineering, Sultanate of Oman
[3&4]Department of Mechanical Engineering, Glasgow Caledonian University, Scotland, UK
[5]Department of Mathematics, Maharshi Dayanand University, Haryana, India

Abstract – The paper presents probabilistic modeling and analysis of a cable plant subsystem with two identical machines operating in parallel. Seven years failure data of the cable plant depicts three types of maintenances for the subsystem: repair, minor preventive maintenance and major preventive maintenance. The subsystem undergoes repair upon failure while minor and major preventive maintenance is performed as per schedule. Priority is given to repair over preventive maintenance. Mean time to failure, availability, expected busy period and expected number of repairs have been estimated by analyzing the subsystem using semi Markov process and regenerative point technique. Graphs have been established to demonstrate simulated results.

NOTATIONS

MIPM	Minor preventive maintenance
MAPM	Major preventive maintenance
PM	Preventive maintenance
S_i	State i
β_1	Estimated value of rate of requirement of MIPM
β_2	Estimated value of rate of requirement of MAPM
λ	Estimated value of failure rate
$f_1(t)$	Probability density functionof MIPM times
$f_2(t)$	Probability density function of MAPM times
$g(t)$	Probability density functionof repair times
α_1	Estimated value of rate of performing MIPM
α_2	Estimated value of rate of performing MAPM
γ	Estimated value of repair rate
Q_{ij}	Cumulative distribution functionfrom S_i to S_j
q_{ij}	Probability density functionfrom S_i toS_j
©	Laplace convolution
Ⓢ	Laplace Stieltje's convolution
*	Laplace transform
**	Laplace Stieltje's transform

I. INTRODUCTION

Literature shows ample work reported by researchers in the area ofreliability specifically using stochastic or probabilstic analysis forindustrial systems under different operating conditions and assumptions. Probabilistic analysis using modeling approach plays an important role in understanding the system behaviour in terms of reliability indices and cost benefit evaluation. Gulshan et al. [1] analyzed system with perfect repair under partial failure mode and priority for repair to completely failed unit, Gopalan & Bhanu [2] considered two unit repairable system subject to online preventive maintenance and/or repair, Tuteja et al. [3]-[5] worked for two units system with regular repairman who is not always available, system with perfect repair at partial failure or complete failure mode, and the profit evaluation of a two units cold standby system with tiredness and two types of repairmen. Rizwan et al. [6]-[12] analyzed cold and hot standby systems with single unit and two units under different failure and repair situations where the reliability indices of interest are obtained and the cost benefit analysis of the systems are carried out. Mathew et al. [13]-[19] extensively analyzed the continuous casting plant and studied the variations under different operating conditions of the plant. Detailed analysis was reported for desalination plant by Padmavathi et al. [20] with online repair under emergency shutdowns, Rizwan et al. [21] with repair/maintenance strategy on first come first served basis, Padmavathi et al. [22]-[26] continued on desalination plant with priority for repair over maintenance, comparative analysis between the plant models, analysis under major and minor

failures consideration, analysis by prioritizing repair over maintenance under major/minor failures, and comparative analysis between the plant models portraying two operating conditions of the plant as to which model is better than the other. The methodology was further extended for various industrial systems analysis by Gupta & Gupta [27] with post inspection concept, Ram et al. [28] waiting repair strategy, Malhotra & Taneja [29] both units operative on demand, Niwas et al. [30] obtained mean time to system failure and profit of a single unit system with inspection for feasibility of repair beyond warranty. Later, Rizwan et al. [31]-[33] focused on waste water treatment plant and anaerobic batch reactor and reliability indices of interest were obtained in order to assess the plant/reactor performance. Sharma & Kaur [34] presented cost benefit analysis of a compressor standby system with preference of service, repair and replacement is given to recently failed unit. Recently, Naithani et al. [35] discussed probabilistic analysis of a 3-unit induced draft fan system with one warm standby with priority to repair of the unit in working state. Taj et al. [36]-[37] further explored the methodology to analyze two different subsystems of a cable plant and obtained reliability indices of interest. Hence, the methodology for system analysis has been widely studied. However, the novelty lies in its application to a different industrial situation. Electric cables being widely used in the construction industry, therefore, the analysis of cable manufacturing plant is of great importance from reliability perspective. Subsystems being instrumental in the entire plant effectiveness, need to be analysed seperately before addesssing the entire plant.

Thus, the paper is an attempt to present analysis of a cable plant subsystem using seven years maintenence data of a plant currently operational in Oman. Based on various operating states of the subsystem, a detailed analysis is carried out using semi-Markov process and regenerative point technique. Outcome of the entire analysis is measured in terms of mean time to subsystem failure, availability of the subsystem, expected busy period of the repairman and expected number of subsystem repairs. Simulated results are demonstrated graphically.

II. DESCRIPTION OF THE SUBSYSTEM

The subsystem under consideration consists of two identical machines operating in parallel. Seven years maintenance data of the cable plant depicts three types of maintenance practices for the subsystem: repair, minor preventive maintenance (MIPM) and major preventive maintenance (MAPM). The subsystem is repaired upon normal failures whereas MIPM and MAPM are carried out at scheduled basis. Priority is given to repair over preventive maintenance (PM).

Possible transition states of the subsystem are described below:

State 0 (S_0): both machines are operative

State 1 (S_1): one machine is down for MIPM, other machine is operative

State 2 (S_2): one machine is down for MAPM, other machine is operative

State 3 (S_3): one machine is under repair, other machine is operative

State 4 (S_4): one machine is under repair, other machine is waiting for MAPM

State 5 (S_5): one machine is under repair, other machine is waiting for repair

S_0, S_1, S_2, S_3 and S_4 are regenerative states whereas S_5 is a non-regenerative state. Table1 gives the rates of transition from S_i to S_j. 0 stands for no transition to the mentioned state. Failure rates are taken as exponential whereas repair/PM rates as arbitrary.

S_i \ S_j	S_0	S_1	S_2	S_3	S_4	S_5
S_0	0	β_1	β_2	2λ	0	0
S_1	$f_1(t)$	0	0	0	0	0
S_2	$f_2(t)$	0	0	0	λ	0
S_3	$g(t)$	0	0	0	0	λ
S_4	0	0	$g(t)$	0	0	0
S_5	0	0	0	$g(t)$	0	0
For non-regenerative state 5						
S_3 to S_3 via S_5	$dQ_{33}^5(t) = \left(\lambda e^{-\lambda t} \copyright 1\right) g(t) dt$					

Table1: Rates for the subsystem

Table 2 shows estimated values of rates of repair/failure and rates of performing/requirement of PM.

S.No.	Rate/ hour	Estimated value
1	β_1, rate of requirement of MIPM	0.0018
2	β_2, rate of requirement of MAPM	0.0005
3	λ, failure rate	0.0054
4	α_1, rate of performing MIPM	0.8668
5	α_2, rate of performing MAPM	0.0510
6	γ, repair rate	0.1936

Table2: Estimated values of rates for the subsystem

III. TRANSITON PROBABILITIES AND MEAN SOJOURN TIMES

Transition probabilities from S_i to S_j are given by the equations (1) – (10):

$$dQ_{01}(t) = \beta_1 e^{-(\beta_1+\beta_2+2\lambda)t}dt \tag{1}$$
$$dQ_{02}(t) = \beta_2 e^{-(\beta_1+\beta_2+2\lambda)t}dt \tag{2}$$
$$dQ_{03}(t) = 2\lambda e^{-(\beta_1+\beta_2+2\lambda)t}dt \tag{3}$$
$$dQ_{10}(t) = f_1(t)dt \tag{4}$$
$$dQ_{20}(t) = e^{-\lambda t}f_2(t)dt \tag{5}$$
$$dQ_{24}(t) = \lambda e^{-\lambda t}\overline{F_2(t)}dt \tag{6}$$
$$dQ_{30}(t) = e^{-\lambda t}g(t)dt \tag{7}$$
$$dQ_{35}(t) = \lambda e^{-\lambda t}\overline{G(t)}dt \tag{8}$$
$$dQ_{33}^5(t) = \left(\lambda e^{-\lambda t}©1\right)g(t)dt \tag{9}$$
$$dQ_{42}(t) = g(t)dt \tag{10}$$

The non zero elements p_{ij} can be obtained as follows:

$$p_{ij} = \lim_{s\to 0} q_{ij}{}^*(s)$$
$$p_{01} = \frac{\beta_1}{\beta_1+\beta_2+2\lambda} \tag{11}$$
$$p_{02} = \frac{\beta_2}{\beta_1+\beta_2+2\lambda} \tag{12}$$
$$p_{03} = \frac{2\lambda}{\beta_1+\beta_2+2\lambda} \tag{13}$$
$$p_{10} = 1 \tag{14}$$
$$p_{20} = f_2{}^*(\lambda) \tag{15}$$
$$p_{24} = 1 - f_2{}^*(\lambda) \tag{16}$$
$$p_{30} = g^*(\lambda) \tag{17}$$
$$p_{35} = 1 - g^*(\lambda) \tag{18}$$
$$p_{33}^5 = 1 - g^*(\lambda) \tag{19}$$
$$p_{42} = 1 \tag{20}$$

Following relations can easily be verified
$$p_{01} + p_{02} + p_{03} = 1 \tag{21}$$
$$p_{10} = 1 \tag{22}$$
$$p_{20} + p_{24} = 1 \tag{23}$$
$$p_{30} + p_{35} = 1 \tag{24}$$
$$p_{30} + p_{33}^5 = 1 \tag{25}$$
$$p_{42} = 1 \tag{26}$$

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

$$\mu_i = E(T) = \int_0^\infty \Pr[T > t]\, dt$$

$$\mu_0 = \frac{1}{\beta_1 + \beta_2 + 2\lambda} \tag{27}$$

$$\mu_1 = \int_0^\infty \overline{F_1(t)}\, dt \tag{28}$$

$$\mu_2 = \int_0^\infty e^{-\lambda t} \overline{F_2(t)}\, dt \tag{29}$$

$$\mu_3 = \int_0^\infty e^{-\lambda t} \overline{G(t)}\, dt \tag{30}$$

$$\mu_4 = \int_0^\infty \overline{G(t)}\, dt \tag{31}$$

IV. MATHEMATICAL ANALYSIS

A. Mean time to subsystem failure

Let $\phi_i(t)$ be the cumulative distribution function of the first passage time from regenerative state i to a failed state j. Using probabilistic arguments, the following recursive relations for $\phi_i(t)$ are obtained:

$$\phi_0(t) = Q_{01}(t)\circledS\phi_1(t) + Q_{02}(t)\circledS\phi_2(t) + Q_{03}(t)\circledS\phi_3(t) \tag{32}$$

$$\phi_1(t) = Q_{10}(t)\circledS\phi_0(t) \tag{33}$$

$$\phi_2(t) = Q_{20}(t)\circledS\phi_0(t) + Q_{24}(t)\circledS\phi_4(t) \tag{34}$$

$$\phi_3(t) = Q_{30}(t)\circledS\phi_0(t) + Q_{35}(t) \tag{35}$$

$$\phi_4(t) = Q_{42}(t)\circledS\phi_2(t) \tag{36}$$

Taking Laplace Stieltjes transform of equations (32-36) and solving for $\phi_0^{**}(s)$, we get equation (37)

$$\phi_0^{**}(s) = \frac{N(s)}{D(s)} \tag{37}$$

Mean time to subsystem failure when the subsystem started at the beginning of state 0 is given by equation (38)

$$\text{Mean time to subsystem failure} = \lim_{s\to 0} \frac{1 - \phi_0^{**}(s)}{s} = \frac{N}{D} \tag{38}$$

where

$$N = p_{02}\mu_2 + p_{02}p_{24}\mu_4 + p_{20}\mu_0 + p_{20}p_{01}\mu_1 + p_{20}p_{03}\mu_3$$

$$D = p_{20}p_{03}p_{35}$$

B. Availability of the subsystem

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

$$A_0(t) = M_0(t) + q_{01}(t)\copyright A_1(t) + q_{02}(t)\copyright A_2(t) + q_{03}(t)\copyright A_3(t) \tag{39}$$

$$A_1(t) = q_{10}(t)\copyright A_0(t) \tag{40}$$

$$A_2(t) = q_{20}(t)\copyright A_0(t) + q_{24}(t)\copyright A_4(t) \tag{41}$$

$$A_3(t) = q_{30}(t)\copyright A_0(t) + q_{33}^5(t)\copyright A_3(t) \tag{42}$$

$$A_4(t) = q_{42}(t)\copyright A_2(t) \tag{43}$$

here, $M_0(t) = e^{-(\beta_1 + \beta_2 + 2\lambda)t}$

Taking Laplace transform of equations (39-43) and solving for $A_0^*(s)$, we get equation (44)

$$A_0^*(s) = \frac{N_1(s)}{D_1(s)} \tag{44}$$

In steady state, availability of the subsystem is given by equation (45)

$$A_0 = \lim_{s\to 0} s\, A_0^*(s) = \frac{N_1}{D_1} \tag{45}$$

where

$$N_1 = p_{20}p_{30}\mu_0$$

$$D_1 = p_{20}p_{30}\mu_0 + p_{30}p_{02}\mu_2 + p_{03}p_{20}\mu_4 + p_{20}p_{30}p_{01}\mu_1 + p_{30}p_{02}p_{24}\mu_4$$

C. Expected busy period of the repairman

Using probabilistic arguments and defining $B_i(t)$ as the probability that the repairman is busy at instant t, given that the system entered regenerative state i at $t = 0$, we get the following recursive relations:

$$B_0(t) = q_{01}(t)©B_1(t)+q_{02}(t)©B_2(t)+q_{03}(t)©B_3(t) \tag{46}$$
$$B_1(t) = q_{10}(t)©B_0(t) \tag{47}$$
$$B_2(t) = q_{20}(t)©B_0(t)+q_{24}(t)©B_4(t) \tag{48}$$
$$B_3(t) = W_3(t) + q_{30}(t)©B_0(t)+q_{33}^5(t)©B_3(t) \tag{49}$$
$$B_4(t) = W_4(t) + q_{42}(t)©B_2(t) \tag{50}$$

here, $W_3(t) = e^{-\lambda t}\overline{G(t)}$ and $W_4(t) = \overline{G(t)}$

Taking Laplace transform of equations (46-50) and solving for $B_0^*(s)$, we obtain equation (51)

$$B_0^*(s) = \frac{N_2(s)}{D_1(s)} \tag{51}$$

In steady state, expected busy period of the repairman is given by equation (52)

$$B_0 = \lim_{s \to 0} s B_0^*(s) = \frac{N_2}{D_1} \tag{52}$$

where

$N_2 = p_{24}p_{03}\mu_3 + p_{30}p_{02}p_{20}\mu_4$

D_1 is already specified

D. Expected number of subsystem repairs

Using probabilistic arguments and defining $R_i(t)$ as the expected number of repairs in $(0, t]$, given that the subsystem entered regenerative state i at $t = 0$, we get the following recursive relations:

$$R_0(t) = Q_{01}(t)ⓈR_1(t)+Q_{02}(t)ⓈR_2(t)+Q_{03}(t)Ⓢ\{R_3(t) + 1\} \tag{53}$$
$$R_1(t) = Q_{10}(t)ⓈR_0(t) \tag{54}$$
$$R_2(t) = Q_{20}(t)ⓈR_0(t)+Q_{24}(t)Ⓢ\{R_4(t) + 1\} \tag{55}$$
$$R_3(t) = Q_{30}(t)ⓈR_0(t)+Q_{33}^5(t)Ⓢ\{R_3(t) + 1\} \tag{56}$$
$$R_4(t) = Q_{42}(t)ⓈR_2(t) \tag{57}$$

Taking Laplace Stieltjes transform of equations (53-57) and solving for $R_0^{**}(s)$, we get equation (58)

$$R_0^{**}(s) = \frac{N_3(s)}{D_1(s)} \tag{58}$$

In steady state, expected number of repairs per unit time is given by equation (59)

$$R_0 = \lim_{s \to 0} s R_0^{**}(s) = \frac{N_3}{D_1} \tag{59}$$

where

$N_3 = p_{20}p_{03} + p_{30}p_{02}p_{24}$

D_1 is already specified

V. PARTICULAR CASE

For this particular case, the failure times are exponential, wheras other times follow arbitrary distribution.

$$f_1(t) = \alpha_1 e^{-\alpha_1 t} \tag{60}$$
$$f_2(t) = \alpha_2 e^{-\alpha_2 t} \tag{61}$$
$$g(t) = \gamma e^{-\gamma t} \tag{62}$$

Using the estimated values from table 2 and expressions (38), (45), (52), (59); the following reliability indices are obtained:

Mean time to subsystem failure = 3644.3713 hours

Availability of the subsystem = 0.9350

Expected busy period of the repairman = 0.0079

Expected number of subsystem repairs = 0.0104

VI. GRAPHICAL INTERPRETATION

Figures 1 and 2 showsthe trend of mean time to subsystem failure and availability of the subsystem respectively when plotted against failure rate λ. It can be seen that mean time to subsystem failure and availability of the subsystem decreases with the increase in failure rate λ.
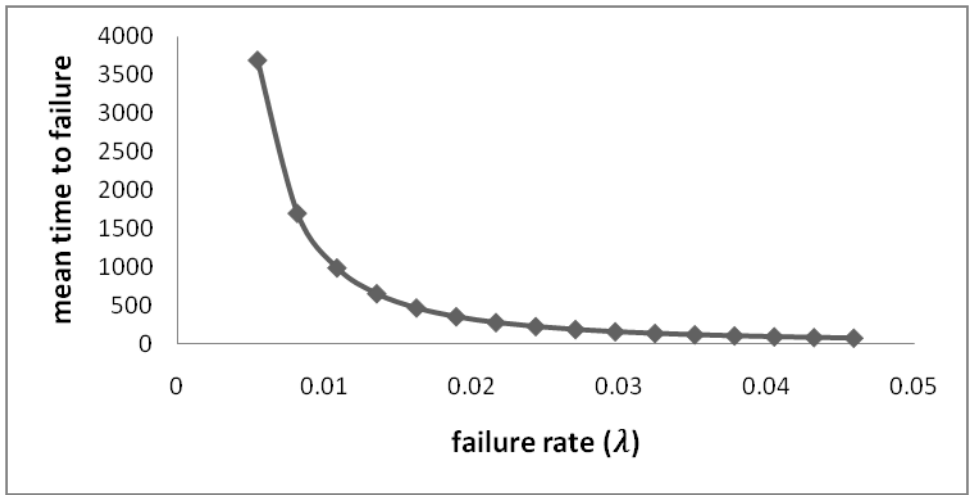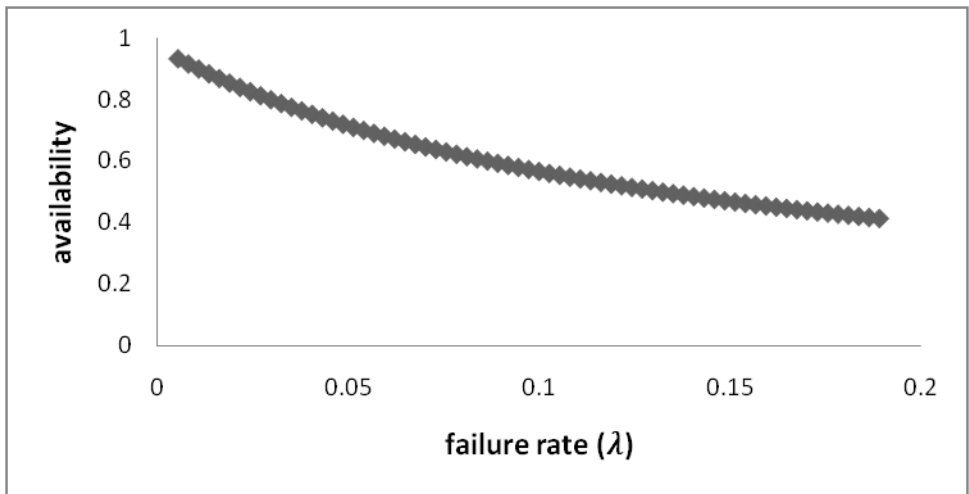

Figure1

Figure2

VII. CONCLUSION

Indices for a cable plant subsystem are obtained to measure the subsystem effectiveness in terms of mean time to subsystem failure, availability of the subsystem, expected busy period of the repairman and expected number of subsystem repairs. Simulated results are shown graphically. There is potential scope of extending system analysis for multiple machines operating in parallel/series with various online/offline maintenance arrangements.

References

[1] Taneja, G., Rizwan, S.M. and Rajeev Kumar, "Profit analysis of a system with perfect repair at partial failure and priority for repair to complete failed unit", Pure and Applied Mathematika Sciences, vol. 35, no. 1-2, pp. 131-141, 1992.

[2] M.N. Gopalan and K.S. Bhanu, "Cost analysis of a two unit repairable system subject to on line preventive maintenance and/or repair", Microelectron Reliability, vol 35, pp. 251-258, 1995.

[3] R.K.Tuteja, S.M. Rizwan and Gulshan Taneja, "A two server system with regular repairman, who is not always available", National Symposium on Management Science and Statistics – Applications to Trade and Industry, Guru Nanak Dev University, Amritsar, India, pp. 231-237, 12-14 Feb, 1999.

[4] R.K.Tuteja, S.M. Rizwan and Gulshan Taneja, "Profit analysis of a system with perfect repair at partial or complete failure", Pure and Applied Mathematika Sciences, vol. 52, no. 1/2, pp. 7-14, 2000.

[5] R.K.Tuteja, S.M. Rizwan and Gulshan Taneja, "Profit evaluation of a two unit cold stand by system with tiredness and two types of repairman", Journal of Indian Society of Statistics and Operation Research, vol. 21, no. 1-4, pp. 1-10, 2000.

[6] S.M. Rizwan, Gulshan Taneja and R.K.Tuteja, "Comparative study between the profits of two models for a two unit system with rest period of repairman", Journal of Decision and Mathematical Sciences, vol. 5, no. 1-3, pp. 27-44, 2000.

[7] S.M. Rizwan, Vipin Khurana and Gulshan Taneja, "Reliability modeling of a hot standby PLC system", Proceedings of the International Conference on Communication, Computer and Power (ICCCP'05), Sultan Qaboos University, Sultanate of Oman, pp. 486-489, 14-16 Feb, 2005.

[8] S.M. Rizwan, "Reliability analysis of a two unit system with two repairmen", Caledonian Journal of Engineering, vol. 3, no. 2, pp. 1-5, 2007.

[9] S.M. Rizwan, Harjeet Chauhan and Gulshan Taneja, "Stochastic analysis of systems with accident and inspection", Emirates Journal of Engineering Research, UAE, vol. 10, no. 2, pp. 81-87, 2005.

[10] S.M. Rizwan, Vipin Khurana and Gulshan Taneja, "Modeling and optimization of a single unit PLC system", International Journal of Modeling and Simulation, Canada, vol. 27, no. 4, pp. 361-368, 2007.

[11] S.M. Rizwan, Vipin Khurana and Gulshan Taneja, "Reliability analysis of a hot standby industrial system", International Journal of Modeling and Simulation, vol. 30, no. 3, pp. 315-322, 2010.

[12] S.M. Rizwan and A.G. Mathew "Performance analysis of port cranes", International Journal of Core Engineering and Management, vol. 2, no. 1, pp. 133-140, 2015.

[13] A.G. Mathew, S.M.Rizwan, M.C. Majumder, K.P. Ramachandran, &Gulshan Taneja, "Profit evaluation of a single unit CC plant with scheduled maintenance", Caledonian Journal of Engineering, vol. 5, no.1, pp. 25-33, 2009.

[14] A.G. Mathew, S.M. Rizwan, M.C. Majumder and K.P. Ramachandran, "MTSF and availability of a two unit CC Plant", Proceedings of the International Conference on Modeling, Simulation and Applied Optimization, ISBN 978-9948-427-12-4, American University, Sharjah, UAE, pp.1-5, 20-22 Jan, 2009.

[15] A.G. Mathew, S.M. Rizwan, M.C. Majumder, K.P. Ramachandran and Gulshan Taneja, "Optimization of a single unit CC plant with scheduled maintenance policy", Proceedings of the International Conference on Recent Advances in Material Processing Technology, ISBN 978-81-904334-1-9, India, pp. 609-613, 25-27 Feb, 2009.

[16] A.G. Mathew, S.M. Rizwan, M.C. Majumder, K.P. Ramachandran and Gulshan Taneja, "Comparative analysis between the profits of the two models of a CC plant", AIP Conference Proceedings, International Conference on Modeling, Optimization and Computing, National Institute of Technology, Durgapur, India, vol. 1298, no. 1, pp. 226-231, October 26, 2010.

[17] A.G. Mathew, S.M. Rizwan, M.C. Majumder, K.P. Ramachandran and Gulshan Taneja, "Reliability modeling and analysis of a two-unit parallel CC plant with different installed capacities", Journal of Manufacturing Engineering, vol. 5, no. 3, pp. 197-204, 2010.

[18] A.G. Mathew, S.M. Rizwan, M.C. Majumder and K.P. Ramachandran, "Reliability modeling and analysis of a two unit continuous casting plant", Journal of the Franklin Institute,vol. 348, no. 7, pp.1488-1505, 2011.

[19] A.G. Mathew, S.M. Rizwan, M.C. Majumder, K.P. Ramachandran and Gulshan Taneja, "Reliability modeling and analysis of an identical two-unit parallel CC plant system operative with full installed capacity", International Journal of Performability Engineering, vol.7, no. 2, pp. 179-185, 2011.

[20] N. Padmavathi, S.M. Rizwan, Anita Pal and Gulshan Taneja, "Reliability analysis of an evaporator of a desalination plant with online repair and emergency shutdowns", Aryabhatta Journal of Mathematics and Informatics, vol.4, no. 1, pp. 1-11, 2012.

[21] S.M. Rizwan, N. Padmavathi, Anita Pal and Gulshan Taneja, "Reliability analysis of a seven unit desalination plant with shutdown during winter season and repair / maintenance on FCFS basis", International Journal of Performability Engineering, vol. 9, no. 5, pp. 523-528, 2013.

[22] N. Padmavathi, S.M. Rizwan, Anita Pal and Gulshan Taneja, "Probabilistic analysis of an evaporator of a desalination plant with priority for repair over maintenance", International Journal of Scientific and Statistical Computing, vol. 4, no. 1, pp. 1-8, 2013.

[23] N. Padmavathi, S.M. Rizwan, Anita Pal and Gulshan Taneja, "Comparative analysis of the two models of an evaporator of a desalination plant", Proceedings of International Conference on Information and Mathematical Science, Punjab, India, pp. 418-422, 24-26 Oct, 2013.

[24] N. Padmavathi, S.M. Rizwan, Anita Pal and Gulshan Taneja, "Probabilistic analysis of a desalination plant with major and minor failures and shutdown during winter season", International Journal of Scientific and Statistical Computing.vol. 5, no. 1, pp. 15-23, 2014.

[25] N. Padmavathi, S.M. Rizwan, Anita Pal and Gulshan Taneja, "Probabilistic analysis of a seven unit desalination plant with minor/major failures and priority given to repair over maintenance", Aryabhatta Journal of Mathematics and Informatics, vol. 6, no. 1, pp. 219-230, 2014.

[26] N. Padmavathi, S.M. Rizwan and A. Senguttuvan, "Comparative analysis between the reliability models portraying two operating conditions of a desalination plant", International Journal of Core Engineering and Management, vol.1, no. 12, pp. 1-10, 2015.

[27] S. Gupta and S.K. Gupta, "Stochastic analysis of a reliability model of one unit system with post inspection, post repair, preventive maintenance and replacement", International Journal of Mechanical Engineering and Robotics Research, vol. 2, no. 2, pp. 178-188, 2013.

[28] M. Ram, S.B. Singh and V.V. Singh, "Stochastic analysis of a standby system with waiting repair strategy", IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 43, no. 3, 2013.

[29] R. Malhotra and Gulshan Taneja, "Stochastic analysis of a two unit cold standby system wherein both units may become operative depending upon the demand", Journal of Quality and Reliability Engineering, vol. 2014, Article ID 896379, 13 pages, 2014. DOI:10.1155/2014/896379

[30] R. Niwas, M.S. Kadyan and J. Kumar, "MTSF and profit analysis of a single unit system with inspection for feasibility of repair beyond warranty", International Journal of System Assurance Engineering and Management, vol. 7, no. 1, 198-204, 2014.

[31] S.M. Rizwan, Joseph V. Thanikal and Michel Torrijos, "A general model for reliability analysis of a domestic waste water treatment plant", International Journal of Condition Monitoring and Diagnostic Engineering Management, vol. 17, no. 3, pp. 3-6, 2014.

[32] S.M. Rizwan and Joseph V. Thanikal, "Reliability analysis of a waste water treatment plant with inspection", i-manager's Journal on Mathematics, vol. 3, no. 2, pp. 21-26, 2014.

[33] S.M. Rizwan, Joseph V. Thanikal, N. Padmavathi and Hathem Yazidi, "Reliability and availability analysis of an anaerobic batch reactor treating fruit and vegetable waste", International Journal of Applied Engineering Research, vol. 10, no. 24, pp. 44075-44079, 2015.

[34] U. Sharma and J. Kaur, "Cost benefit analysis of a compressor standby system with preference of service, repair and replacement is given to recently failed unit", International Journal of Mathematics Trends and Technology, vol. 30, no. 2, pp. 104-108, 2016.

[35] A. Naithani, B. Parashar, P.K. Bhatia and G. Taneja, "Probabilistic analysis of a 3-unit induced draft fan system with one warm standby with priority to repair of the unit in working state", Int J Syst Assur Eng Manag, 2017. DOI:10.1007/s13198-017-0608-6

[36] S.Z. Taj, S.M. Rizwan, B.M. Alkali, D.K. Harrison and G.L. Taneja, "Reliability modeling and analysis of a single machine subsystem of a cable plant", International Conference on Modeling, Simulation and Applied Optimization, American University of Sharjah, Sharjah, UAE, pp. 1–4, 4-6 April, 2017. DOI: 10.1109/ICMSAO.2017.7934917

[37] S.Z. Taj, S.M. Rizwan, B.M. Alkali, D.K. Harrison and G.L. Taneja, "Reliability analysis of a single machine subsystem of a cable plant with six maintenance categories", International Journal of Applied Engineering Research, vol. 1, no. 8, pp. 1752-1757, 2017.