Advances in Dynamical Systems and Applications (ADSA).
ISSN 0973-5321, Volume 16, Number 2, (2021) pp. 423-440

https://www.ripublication.com/adsa.htm

Modeling and Analysis of Port PLCs

Rizwan, SM and Taj, SZ

National University of Science and Technology, Sultanate of Oman.

ORCID: 0000-0002-3269-2633

Abstract

Programable Logic Controllers (PLC) operating the port cranes are analyzed. Real down time data of the PLCs have been collected from a particular port. Five types of failures are noted, viz., Power supply failures, failures due to overheating, failures due to electrical noise interference, and Input/Output module failure which needs repair or replacement based on its requirement. Other than the power supply failures, all other failures are detected after inspection once the failure occurs. The operation of the port gets affected due to cranes outages because of the PLCs failure. The system is analyzed by fitting the appropriate probability distribution to failure and repair times and using semi-Markov processes and regenerative point techniques. Easy-fit reveals the closely fitting distribution for failure and repair to be exponential among the other life-time distributions based on its suitability for further mathematical treatment. Important reliability measures for the system effectiveness are obtained.

Keywords: Port Cranes, PLCs, failures, repairs, reliability, Semi – Markov, regenerative processes

1.0 NOMENCLATURE

λ failure rate of the PLC.

α_1 Rate of tripping due to power supply failure.

α_2 Rate of restoration from failed state due to power failure to operative state.

p_1 probability of failure due to overheating

p_2	probability of failure due to electrical noise interference.
p_3	probability of Input/Output module failure need repair.
p_4	probability of Input/Output module failure need replacement.
$h(t), H(t)$	pdf (probability density function) and cdf (cumulative distribution function) of inspection time of failed PLC.
$g_1(t), G_1(t)$	pdf and cdf of repair time due to overheating.
$g_2(t), G_2(t)$	pdf and cdf of replacement time due to electrical noise interference.
$g_3(t), G_3(t)$	pdf and cdf of repair time due to Input/Output module failure.
$g_4(t), G_4(t)$	pdf and cdf of replacement time due to Input/Output module failure.

2.0 INTRODUCTION

Various combinations of one-unit and multiple-units' industrial systems are analyzed in the past under different operating conditions. Most of the earlier papers of 90's considered the reliability analysis based on the model assumptions as far as the transition states of the system are concerned. Later, effort was put in place by authors to collect the real down time data from the industry and the various rates of failure and repair of the repairable system were estimated from the data, and the models were developed by embedding the real operating situations of the systems. Gupta and Goel [1] analyzed a two-unit cold standby system for profit analysis, and Goel et.al. [2] worked on system analysis with correlated failures and repairs. Taneja et. al. [3] evaluated the profit of systems with perfect repair at partial failure and system with four failures categories. Tuteja et.al. [4]-[6] considered systems with assumptions of regular repairmen, tiredness of repairmen, and partial or complete failure units, for analysis. Rizwan & Mohiuddin [7]-[8] presented the analysis with partial failure, alternative repair facility, and critical human error failure. Rizwan et. al. [9]-[13] later extended the previous study and analyzed the system for different operating conditions of comparative analysis, rest period of repairman, systems with accident and inspection, hot standby systems. Rizwan and Ramachandran [14] shown the maintenance management strategies for system analysis. Taneja et.al. [15] carried out economic analysis of a cold standby system. Rizwan et. al. [16]-[17] dealt with secondary coating line manufacturing machine and a two-unit system with partial failure mode. Rizwan [18]-[21] shown the modeling strategies / applications to an industrial system and system analysis with two repairmen. Zuhair and Rizwan [22] shown an analysis of a two-unit system. Rizwan et. al. [23]-[26] presented studies on programmable logic controllers and continuous casting plant. Mathew et. al. [27]-[35] further studied continuous casting plant with different case studies and variations. Rizwan et. al. [36]-[38] analyzed a hot standby system and a desalination plant system and obtained reliability indices of interest. Saud et.al [39]-[40] considered a centrifugal pump of refinery system for analysis. Al-Amri et. al. [41] analyzed recycle gas compressor; Al Maqbali et.al. [42] analyzed AC compressors; Al-Balushi et.al. [43] analyzed a sewage lifting centrifugal pump. Mathew and Rizwan [44] carried out a simple maintenance analysis of port cranes data. Padmavathi et.al. [45]-[50] extensively studied a desalination plant with seven evaporators and obtained various reliability indices along with the cost-benefit analysis of the system. Rizwan et.al. [51]-[53] again considered the desalination plant and variations under different operating conditions of the plant with shutdown during winter season and repair / maintenance on FCFS basis, and inspections were studied. Sharma and Kaur [54]-[55] studied the standby systems with three failure categories and the compressor systems with and without provision of priority to failed compressor unit. Rizwan et.al. [56]-[59] estimated the relevant reliability indices of the different case specific situations of the wastewater treatment plant and anaerobic batch reactor treating fruits and vegetables waste. Rizwan & Mathew [60] carried out the port cranes analysis under minor and major categories of electrical and mechanical components failures of cranes. Later, Al-Rahbi et.al. [61]-[69] focused on the rodding anode plant in aluminum industry where different plant situations are explored for subsystems and main system under multiple repairmen and multiple unit's maintenance management strategies. Much has been discussed by Taj et.al. [70]-[80] about a cable plant sub-systems and the main system as single machine, different failure types, with storage of surplus produce, winter operating strategy, comparative study between the models, and a review mentioning about the future scope of using new distributions and fuzzy optimization models.

Port cranes being extensively used for loading and unloading of heavy vessels in cargo ships and need to be operational continuously, and therefore, drawn interest as a potential case study. The analysis of the cranes under minor and major failure categories is reported [60]. However, it looks more sensible to analyze the Programmable logic controllers (PLCs) rather than the cranes, as mostly the reasons of cranes outages are due to the failures in PLCs, except the mechanical failures in cranes. Programmable logic controllers (PLCs) are normally used to control the automated industrial systems. Despite maintaining the highest operational reliability, their breakdown is inevitable which leads to the costly downtime usually. To avoid substantial losses, there is a need to analyze the operational capabilities of such systems from reliability perspective and improve upon the maintenance practices responsible for such failures.

Four years of real down time data of the PLCs controlling the cranes have been collected from a particular port. Five types of failures are noted and categorized accordingly, viz., Power supply failures, failures due to overheating, failures due to electrical noise interference, and Input/Output module failure which needs repair or replacement based on the type of the problem such as configuration error, tripped circuit breaker, loose terminal block, etc. which are restorable, whereas major issues sometimes need component replacement. Other than the power supply failures where the system is retorted through a redundant power source; all other failures are detected after inspection once the failure occurs. The operation of the port gets affected due to cranes outages because of the PLCs failure.

The following estimations are obtained from the data:

- Estimated value of tripping rate (α_1) = 0.0298 per hour.
- Restoration rate from tripping (α_2) = 0.0118 per hour.
- Probability of failure due to overheating (p_1) = 0.3756
- Probability of failure due to electrical noise interference (p_2) = 0.3162
- Probability of Input/Output module failure need repair (p_3) = 0.2084
- Probability of Input/Output module failure need replacement (p_4) = 0.0998
- Estimated value of failure rate of PLC (λ) = 0.0278 per hour.

The PLCs system is analyzed by fitting the appropriate probability distribution to failure and restoration times and using semi-Markov processes and regenerative point techniques. The following measures of system effectiveness are obtained:

- Steady state availability of PLCs
- Expected busy period of the repairmen for inspection time.
- Expected busy period of the repairmen for repairing the failure due to overheating.
- Expected busy period of the repairmen for repairing the failure due to electrical noise interference.
- Expected busy period of the repairmen for repairing the Input/Output module failure.
- Expected busy period of the repairmen for replacing the Input/Output module failure.

3.0 DESCRIPTION AND ASSUMPTIONS

The Following are the assumption for the proposed analysis:

1. The PLC system consists of several integrated components.
2. The PLC system is operative initially.
3. Failure due to Power supply is restored automatically because of the redundant

power source but takes some activation time.

4. As soon as the PLC system fails, engineer inspects the unit for its root cause and appropriately handles the maintenance based on the type of failure.
5. The type of the failure is revealed through inspection only.
6. After each repair or replacement, the system works as good as new.
7. All the random variables are independent.
8. It is noted that the breakdown times and restoration times are closely fitting to the exponential distribution.

4.0 STATES OF THE SYSTEM

The following are the states of the system:

S_0 (Operative state); S_1 (Power supply failure state); S_2 (Failed State for other reasons); S_3 (Failed state due to overheating); S_4 (Failed state due to electrical noise interference); S_5 (Repairable Input/Output module failure state); S_6 (Replaceable Input/Output module failure state)

Table 1: Transitions states of the plant

	S_0	S_1	S_2	S_3	S_4	S_5	S_6
S_0	0	α_1	λ	0	0	0	0
S_1	α_2	0	0	0	0	0	0
S_2	0	0	0	$p_1h(t)$	$p_2h(t)$	$p_3h(t)$	$p_4h(t)$
S_3	$g_1(t)$	0	0	0	0	0	0
S_4	$g_2(t)$	0	0	0	0	0	0
S_5	$g_3(t)$	0	0	0	0	0	0
S_6	$g_4(t)$	0	0	0	0	0	0

A transition diagram showing the various states of transition of the plant is shown in Table 1. The epochs of entry into states S_i (i=0, 1, 2, 3, 4, 5, 6) are regeneration points and thus are the regenerative states. The states S_i (i=2, 3, 4, 5,6) are failed states. The transition probabilities are given by:

$dQ_{01} = \alpha_1 e^{-(\lambda+\alpha_1)t} dt$

$dQ_{02} = \lambda e^{-(\lambda+\alpha_1)t} dt$

$dQ_{10} = \alpha_2 e^{-\alpha_2 t} dt$

$dQ_{23} = p_1 h(t) dt$

$dQ_{24} = p_2 h(t) dt$

$dQ_{25} = p_3 h(t) dt$

$dQ_{26} = p_4 h(t) dt$

$dQ_{30} = g_1(t) dt$

$dQ_{40} = g_2(t) dt$

$dQ_{50} = g_3(t) dt$

$dQ_{60} = g_4(t) dt$ (1) – (11)

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

$p_{01} = \frac{\alpha_1}{\lambda+\alpha_1}$

$p_{02} = \frac{\lambda}{\lambda+\alpha_1}$

$p_{10} = 1$

$p_{23} = p_1$

$p_{24} = p_2$

$p_{25} = p_3$

$p_{26} = p_4$

$p_{30} = 1$

$p_{40} = 1$

$p_{50} = 1$

$p_{60} = 1$ (12) – (22)

By these transition probabilities it can be verified that:

$p_{01} + p_{02} = 1$

$p_{10} = 1$

$p_{23} + p_{24} + p_{25} + p_{26} = 1$

$p_{30} = p_{40} = p_{50} = p_{60} = 1$ (23) – (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:

$\mu_i = E(T) = Pr[T > t]dt$

$\mu_0 = \int_0^\infty e^{-(\lambda+\alpha_1)t}\, dt = \frac{1}{\lambda+\alpha_1}$

$\mu_1 = \int_0^\infty \overline{H}_1(t)\, dt = \frac{1}{\alpha_2}$

$\mu_2 = \int_0^\infty \overline{H}(t)\, dt = \frac{1}{\beta}$

$\mu_3 = \int_0^\infty \overline{G_1}(t)\, dt = \frac{1}{\beta_1}$

$\mu_4 = \int_0^\infty \overline{G_2}(t)\, dt = \frac{1}{\beta_2}$

$\mu_5 = \int_0^\infty \overline{G_3}(t)\, dt = \frac{1}{\beta_3}$

$\mu_6 = \int_0^\infty \overline{G_4}(t)\, dt = \frac{1}{\beta_4}$ (27) – (33)

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

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

(34)

$m_{01} + m_{02} = \mu_0,$

$m_{10} = \mu_1,$

$m_{23} + m_{24} + m_{25} + m_{26} = \mu_2,$

$m_{30} = \mu_3,$

$m_{40} = \mu_4,$

$m_{50} = \mu_5,$

$m_{60} = \mu_6$ (35) – (41)

4.1 Availability analysis of PLCs

Using the probabilistic arguments and defining availability $A_i(t)$ as the probability that the system will be operational at time t given that it was operative at time 0, we have the following recursive relations for $A_i(t)$

$$A_0(t) = M_0(t) + q_{01}(t)©A_1(t) + q_{02}(t)©A_2(t)$$

$$A_1(t) = M_1(t) + q_{10}(t)©A_0(t)$$

$$A_2(t) = q_{23}(t)©A_3(t) + q_{24}(t)©A_4(t) + q_{25}(t)© A_5(t) + q_{26}(t)© A_6(t)$$

$$A_3(t) = q_{30}(t)©A_0(t)$$

$$A_4(t) = q_{40}(t)©A_0(t)$$

$$A_5(t) = q_{50}(t)©A_0(t)$$

$$A_6(t) = q_{60}(t)©A_0(t) \qquad (42) – (48)$$

Where $M_0(t) = e^{-(\lambda+\alpha_1)t}$ and $M_1(t) = e^{-\alpha_2 t}$

Taking Laplace Transforms (L.T.) of the above equations and solving them for $A_0{}^*(s)$ we get:

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

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

$$A_0 = \lim_{s\to 0} s\, A_0 * (s) = \frac{N_1}{D_1} \qquad (49)$$

Where N_1 and D_1 are obtained by solving equations (42) – (48) and are used to get this measure as shown in section5.0.

4.2 Busy period analysis of the repairmen (inspection time only)

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

$$I_0(t) = q_{01}(t)©I_1(t) + q_{02}(t)©I_2(t)$$

$$I_1(t) = q_{10}(t)©I_0(t)$$

$$I_2(t) = W_2(t) + q_{23}(t)©I_3(t) + q_{24}(t)©I_4(t) + q_{25}(t) ©I_5(t) + q_{26}(t) ©I_6(t)$$

$$I_3(t) = q_{30}(t)©I_0(t)$$

$$I_4(t) = q_{40}(t)©I_0(t)$$

$\mathrm{I}_5(\mathrm{t}) = \mathrm{q}_{50}(\mathrm{t})©\mathrm{I}_0(\mathrm{t})$

$\mathrm{I}_6(\mathrm{t}) = \mathrm{q}_{60}(\mathrm{t})©\mathrm{I}_0(\mathrm{t})$ (50) – (56)

Where $W_2(t) = \overline{I}(t)$

Taking Laplace transforms of the above equations and solving them for $I_0 * (s)$, we get.

$I_0 * (s) = \frac{N_2(s)}{D_1(s)}$

In steady state, the total fraction of time the system is under inspection is given by:

$$I_0 = \lim_{s\to 0} s\, I_0 * (s) = \frac{N_2}{D_1} \quad (57)$$

Where N_2 and D_1 are obtained by solving equations (50) – (56) and are used to get this measure as shown in section5.0.

4.3 Busy period analysis of the repairmen (repair time of failures due to overheating)

Using the probabilistic arguments, we have the following recursive relations for $B_i(t)$:

$\mathrm{B}_0(\mathrm{t}) = \mathrm{q}_{01}(\mathrm{t})©\mathrm{B}_1(\mathrm{t}) + \mathrm{q}_{02}(\mathrm{t})©\mathrm{B}_2(\mathrm{t})$

$\mathrm{B}_1(\mathrm{t}) = \mathrm{q}_{10}(\mathrm{t})©\mathrm{B}_0(\mathrm{t})$

$\mathrm{B}_2(\mathrm{t}) = \mathrm{q}_{23}(\mathrm{t})©\mathrm{B}_3(\mathrm{t}) + \mathrm{q}_{24}(\mathrm{t})©\mathrm{B}_4(\mathrm{t}) + \mathrm{q}_{25}(\mathrm{t})©\mathrm{B}_5(\mathrm{t})$

$\mathrm{B}_3(\mathrm{t}) = \mathrm{W}_3(\mathrm{t}) + \mathrm{q}_{30}(\mathrm{t})©\mathrm{B}_0(\mathrm{t})$

$\mathrm{B}_4(\mathrm{t}) = \mathrm{q}_{40}(\mathrm{t})©\mathrm{B}_0(\mathrm{t})$

$\mathrm{B}_5(\mathrm{t}) = \mathrm{q}_{50}(\mathrm{t})©\ \mathrm{B}_0(\mathrm{t})$

$\mathrm{B}_6(\mathrm{t}) = \mathrm{q}_{60}(\mathrm{t})©\mathrm{B}_0(\mathrm{t})$

(58) – (64)

Where $W_3(t) = \overline{G_1}(t)$

Taking Laplace transforms of the above equations and solving them for$B_0 * (s)$, we get.

$\mathrm{B}_0 * (\mathrm{s}) = \frac{\mathrm{N}_3(\mathrm{s})}{\mathrm{D}_1(\mathrm{s})}$

In steady state the total fraction of time the system is under repair is given by

$$B_0 = \lim_{s\to 0} s\, B_0 * (s) = \frac{N_3}{D_1} \tag{65}$$

Where N_3 and D_1 can be obtained by solving (58) – (64) and are used to get this measure as shown in section 5.0.

Similarly, the expected busy period of the for repairing the failure due to electrical noise interference, Input/Output module repair, and the busy period of the repairmen for replacing the Input/Output module components, can be obtained.

5.0 PARTICULAR CASE

Since easy fit shows the close fitting of the repair data to exponential distribution among the available options and easy handling of numerical calculations, therefore, we have:

$g_1(t) = \beta_1 e^{-\alpha_1 t}$; $g_2(t) = \beta_2 e^{-\beta_2 t}$; $g_3(t) = \beta_3 e^{-\beta_3 t}$; $g_4(t) = \beta_4 e^{-\beta_4 t}$; $h(t) = \beta e^{-\beta t}$

$\mu_0 = \frac{1}{\lambda+\beta_1}$; $\mu_1 = \frac{1}{\beta_2}$; $\mu_2 = \frac{1}{\alpha}$; $\mu_3 = \frac{1}{\alpha_1}$; $\mu_4 = \frac{1}{\alpha_2}$; $\mu_5 = \frac{1}{\alpha_3}$; $p_{01} = \frac{\beta_1}{\lambda+\beta_1}$; $p_{02} = \frac{\lambda}{\lambda+\beta_1}$;
$m_{01} = \frac{\beta_1}{(\lambda+\beta_1)^2}$; $m_{02} = \frac{\lambda}{(\lambda+\beta_1)^2}$

The following values estimated from the data:

$p_1 = 0.3756$, $p_2 = 0.3162$, $p_3 = 0.2084$, $p_4 = 0.0998$

$\alpha_1 = 0.0298$, $\alpha_2 = 0.0118$, $\lambda = 0.0278$, $\beta = 0.02$, $\beta_1 = 0.2335$, $\beta_2 = 0.4234$, $\beta_3 = 0.1604$, $\beta_4 = 0.1904$

Using the above particular case, and the expressions as obtained in section 4.1-4.3, and similarly for other indices, the following measures of the system effectiveness are obtained:

$A_0 = \frac{N_1}{D_1} = \frac{11.0319}{11.2055} = 0.9845$ (Availability)

$I_0 = \frac{N_2}{D_1} = \frac{0.0930}{11.2055} = 0.0083$ (Expected busy period of inspection time)

$B_0 = \frac{N_3}{D_1} = \frac{0.0263}{11.2055} = 0.0023$ (Expected busy period of repair due to overheating failure)

$B_0(ENI) = \frac{N_4}{D_1} = \frac{0.0118}{11.2055} = 0.0011$ (Expected busy period for repair due to electrical noise interference failure)

$B_0\,(IOR1) = \frac{N_5}{D_1} = \frac{0.0207}{11.2055} = 0.0018$ (Expected busy period for repair due to

Input/Output module failure)

$B_0\ (IOR2) = \frac{N_6}{D_1} = \frac{0.0218}{11.2055} = 0.0019$ (Expected busy period for replacement due to Input/Output module failure)

Where $D_1 = \mu_0 + p_{01}\mu_1 + p_{02}(\mu_2 + p_{23}\mu_3 + p_{24}\mu_4 + p_{25}\mu_5 + p_{26}\mu_6)$

$N_1 = \mu_0 + p_{01}\mu_1$; $N_2 = p_{02}\mu_2$; $N_3 = p_{02}p_{23}\mu_3$; $N_4 = p_{02}p_{24}\mu_4$; $N_5 = p_{02}p_{25}\mu_5$; $N_6 = p_{02}p_{26}\mu_6$

The above result indicates that the steady state availability of PLCs is 0.9845 which can be improved by adopting the better and timely maintenance practices. The expected busy period for repair due to electrical noise interference is minimum among all other failure categories. Expected busy period for identifying the failure type by inspection is significantly high compared to others.

REFERENCES

[1] Gupta, R. and Goel, R. (1991). Profit analysis of a two-unit cold standby system with abnormal weather condition. Microelectronics Reliability, 31(1), pp.1-5.

[2] Goel L., Shrivastava, P. and Gupta, R. (1992). A two-unit cold standby system with correlated failures and repairs, International Journal of Systems Science. 23(3), pp. 379-391,

[3] Taneja, G. Rizwan, S. M. and Rajeev, K. (1992). Profit Analysis of a system with perfect repair at partial failure and priority for repair to complete failed unit" Journal of Pure and applied Mathematika Sciences, Vol. 35, No. 1-2, pp. 131-141.

[4] Tuteja, R., Rizwan, S. M. and Taneja, G. (1999). A two-server system with regular repairman, who is not always available. In: 3rd Annual Conference of ISITA and National Symposium on Management Science and Statistics – Applications to Trade & Industry. Amritsar, Punjab, India: pp.231-237.

[5] Tuteja, R., Rizwan, S. M. and Taneja, G. (2000). Profit evaluation of a two-unit cold standby system with tiredness and two types of repairmen. Journal of Indian Society of Statistics and Operation Research, 21(1-4), pp.1-10.

[6] Tuteja, R., Rizwan, S. M. and Taneja, G. (2000). Profit analysis of a system with perfect repair at partial or complete failure, Pure and Applied Mathematika Sciences, 52, (2), pp. 7-14.

[7] Rizwan, S. M., and Mohiuddin, A. (2004). Cost benefits analysis of a two-unit system with partial failure and alternatives repair facility, Caledonian Journal of Engineering, 1(1), pp.5-7.

[8] Rizwan, S. M., and Mohiuddin, A. (2005). Stochastic Analysis of a System with Critical Human Error Failure" Caledonian Journal of Engineering, 1(3), pp.1-5.

[9] Rizwan, S. M., Taneja, G. and Tuteja, R. (2000). Comparative study between

the profits of two models for a two-unit system with rest period of repairman. Journal of Decision and Mathematical Sciences, 5(1-3), pp.27-44.

[10] Rizwan, S. M., Garima., and Mohiuddin, A. (2005). Maintenance Analysis of PLCs, Regional Conference on Maintenance Management, Caledonian College of Engineering, Sultanate of Oman, 2nd October 2005, pp 265-270.

[11] Rizwan, S. M., Ramachandran, K.P. and Mohiuddin, A. (2005). Reliability of a Technological System with Rest Period of Repairman, Caledonian Journal of Engineering, 1(4), pp.1-4.

[12] Rizwan, S. M., Chauhan, H. and Taneja, G. (2005). Stochastic analysis of systems with accident and inspection. Emirates Journal of Engineering Research, 10(2), pp.81-87.

[13] Rizwan, S. M., Khurana, V., and Taneja, G. (2005). Reliability modeling of a hot standby PLC system. International Conference on Communication, Computer and Power. Muscat, Sultanate of Oman: pp.486-489.

[14] Rizwan, S. M., and Ramachandran, K. (2006). Maintenance Management Strategies" International Workshop on Successful Strategies in Supply Chain Management, The Hong Kong Polytechnic University, Hong Kong, 5-6 January 2006, pp 255-260.

[15] Taneja, G., Vipin, K., and Rizwan, S. M. (2006). Economic Analysis of a Reliability model for two-unit Programmable Logic Controller cold standby System with four types of Failure, Journal of Pure and Applied Mathematika Sciences, Vol. LXIII, No. 1-2, pp. 65- 77.

[16] Rizwan, S. M., Mathew, A., Majumdar., and Ramachandran, K. (2006). Maintenance Analysis of a Secondary Coating Line Manufacturing Machine, National Conference on Recent Developments and Future Trends in Mechanical Engineering, National Institute of Tech., HP, India, 3-4 Nov 2006, pp 251-257.

[17] Rizwan, S. M., Ramanathan, S. and Mohiuddin, A. (2006). MTSF Analysis of a Two Unit System with Partial Failure Mode. Caledonian Journal of Engineering, 1(2), pp.1-4.

[18] Rizwan, S. M. (2006). Reliability Modeling Strategy of an Industrial System. ISBN: 0-7699-2569-9, in Proceedings of IEEE Conference Publications of Computer Society, First International Conference on Availability, Reliability and Security (ARES'06), Vienna University of Technology, Austria, 20-22 April 2006. DOI: 10.1109/ARES.2006, pp 625-630.

[19] Rizwan, S. M. (2007). Reliability analysis of a two-unit system with two repairmen. Caledonian Journal of Engineering, 3(2), pp.1-5.

[20] Rizwan, S. M. (2007). An Industrial Application of Reliability Modeling, International Conference QRM Quality Reliability and Maintenance, University of Oxford, UK, 22 – 23 March 2007, pp 247-253.

[21] Rizwan, S. M. (2007). Reliability analysis of a two-unit system with two repairmen. Caledonian Journal of Engineering, 3(2), pp.1-5.

[22] Zuhair, Al Hemyari. and Rizwan, S. M. (2007). Reliability Analysis of a Two

Unit System, in proceedings of IEEE Conference Publications, IEEE International Conference on Industrial Engineering and Engineering Management, Singapore, 2-5 December 2007, ISBN: 978-1-4244-1529-8DOI:10.1109/1EEM.2007. 4419395, pp 1265-1268.

[23] Rizwan, S. M., Khurana, V. and Taneja, G. (2007). Modeling and optimization of a single-unit PLC system. International Journal of Modeling and Simulation, 27(4), pp.361-368.

[24] Rizwan, S. M., Khurana, V., Taneja, G., and Mohiuddin, A. (2008). Reliability Analysis of a single unit PLC with inspection, i - manager's Journal on Future Engineering and Technology, vol.3, No. 4, pp. 19-26.

[25] Rizwan, S. M., Mathew, A., Majumder. M, and Ramachandran. K. (2008) Reliability and Availability of a Continuous Casting Plant" in proceedings of IEEE Conference Publications, IEEE International Conference on Industrial Engineering and Engineering Management, Singapore, 8-11 Dec. 2008, DOI: 10.1109/IEEM.2008.4737927, pp. 541-544.

[26] Rizwan, S. M., Mathew, A., and Taneja, G. (2009). Reliability Analysis of a Continuous Casting Plant" i - manager's Journal on Future Engineering and Technology, vol.5, No. 1, pp 15-21.

[27] Mathew, A., Rizwan, S. M., Majumder, M. and Ramachandran, K. (2009). MTSF and availability of a two-unit CC plant. In: 3rd International Conference on Modeling, Simulation, and Applied Optimization. Sharjah, UAE: pp.1-5.

[28] Mathew, A., Rizwan, S. M., Majumder, M., Ramachandran, K. and Taneja, G. (2009). Optimization of a single unit CC plant with scheduled maintenance policy. In: 2nd International Conference on Recent Advances in Material Processing Technology. Kovilpatti, TN, India: SME, pp.609-613.

[29] Mathew, A., Rizwan, S. M., Majumder, M., Ramachandran, K. and Taneja, G. (2009). Profit evaluation of a single unit CC plant with scheduled maintenance. Caledonian Journal of Engineering, 5(1), pp.25-33.

[30] Mathew, A., Rizwan, S. M., Majumder, M., Ramachandran, K. and Taneja, G. (2010a). Comparative analysis between profits of the two models of a CC plant. In: International Conference on Modeling, Optimization, and Computing. Durgapur, West Bengal, India: AIP, 1298(1), pp.226-231.

[31] Mathew, A., Rizwan, S. M., Majumder, M., Ramachandran, K. and Taneja, G. (2010b). Reliability modeling and analysis of a two-unit parallel CC plant with different installed capacities. Journal of Manufacturing Engineering, 5(3), pp.197-204.

[32] Mathew, A., Rizwan, S. M. & Gulshan, T. (2010). Comparative Analysis between the Two Models of a CC Plant' International Conference on Mathematics and Soft Computing, Panipat, Haryana, India, 4-5 Dec. 2010, pp. 132-135.

[33] Mathew, A., Rizwan, S. M., Majumder, M. and Ramachandran, K. (2011). Reliability modelling and analysis of a two-unit continuous casting plant. Journal of the Franklin Institute, 348(7), pp.1488-1505.

[34] Mathew, A., Rizwan, S. M., Majumder, M., Ramachandran, K. and Taneja, G. (2011). Reliability analysis of an identical two-unit parallel CC plant system operative with full installed capacity. International Journal of Performability Engineering, 7(2), pp.179-185.

[35] Mathew, A., Rizwan, S. M., Majumder, M. & Ramachandran, K. (2011). Reliability modeling and analysis of a two-unit continuous casting plant. Journal of the Franklin Institute, 348, doi: 10.1016/j.jfranklin.2010.04.016, pp. 1488-1505.

[36] Rizwan, S. M., Padmavathi, N., and Taneja, G. (2010). Cost benefit Analysis of a desalination Unit, International Conference on Mathematics and Soft Computing, Panipat, Haryana, India, 4-5 Dec. 2010, pp. 139-142.

[37] Rizwan, S. M., Khurana, V. and Taneja, G. (2010). Reliability analysis of a hot standby industrial system. International Journal of Modeling and Simulation, 30(3), pp.315-322.

[38] Rizwan, S. M., Padmavathi, N., Taneja, G., Mathew, A., and Ali Mohammed Al-Balushi. (2010) Probabilistic Analysis of a Desalination Unit with Nine Failure Categories, World Congress on Engineering 2010, IAENG International Conference of Applied Mathematics, Imperial College London, UK, 30 June - 2 July 2010, pp. 1877-1880.

[39] Saud, Talib., Mathew, A., & Rizwan, S. M. (2011). Reliability and Availability Assessment of a Centrifugal Pump. International Conference on Harnessing Technology, Crown Plaza, Sultanate of Oman, 13-14 Feb. 2011, pp. 34.

[40] Saud, Talib Al Amri., Mathew, A., and Rizwan, S. M. (2011). Reliability Modeling and Analysis of a Refinery Based Centrifugal Pump. Caledonian Journal of Engineering, Vol. 07, No. 01, pp. 38-42.

[41] Al-Amri, M., Mathew, A., and Rizwan, S. M. (2011). A Probabilistic Analysis of Recycle Gas Compressor', National Symposium on Engineering Final Year Projects, College of Engineering and Architecture, University of Nizwa, Sultanate of Oman.

[42] Al-Maqbali, M., Mathew, A., and Rizwan, S. M. (2012). A Probabilistic Risk Analysis of an A.C. Air Compressor (heavy duty)' in Proc. 2nd NSEFYP, 2nd National Symposium on Engineering Final Year Projects, University of Nizwa, Sultanate of Oman.

[43] Al - Balushi, M., Mathew, A., and Rizwan, S. M. (2012). Probabilistic Analysis of a Sewage Lifting Centrifugal Pump (Case Study)' in Proc. 2nd NSEFYP, 2nd National Symposium on Engineering Final Year Projects, 15th May 2012, University of Nizwa, Sultanate of Oman.

[44] Mathew, A. and Rizwan, S. M. (2012). Maintenance Analysis of Port PLCs – Case Study, Caledonian Journal of Engineering, 8(2), pp. 52-57.

[45] Padmavathi, N., Rizwan, S. M., Pal, A. and Taneja, G. (2012). Reliability analysis of an evaporator of a desalination plant with online repair and emergency shutdowns. Aryabhatta Journal of Mathematics & Informatics, 4(1), pp.1-12.

[46] Padmavathi, N., Rizwan, S. M., Pal, A. and Taneja, G. (2013). Comparative analysis of the two models of an evaporator of a desalination plant. International Conference on Information and Mathematical Sciences. Bathinda, Punjab, India: pp.418-422.

[47] Padmavathi, N., Rizwan, S. M., Pal, A. and Taneja, G. (2013). Probabilistic analysis of an evaporator of a desalination plant with priority for repair over maintenance. International Journal of Scientific and Statistical Computing, 4(1), pp.1-8.

[48] Padmavathi, N., Rizwan, S. M., Pal, A. and Taneja, G. (2014). Probabilistic analysis of a desalination plant with major and minor failures and shutdown during winter season. International Journal of Scientific and Statistical Computing, 5(1), pp.15-23.

[49] Padmavathi, N., Rizwan, S. M., Pal, A. and Taneja, G. (2014). Probabilistic analysis of a seven-unit desalination plant with minor/major failures and priority given to repair over maintenance. Aryabhata Journal of Mathematics & Informatics, 6(1), pp.219-230.

[50] Padmavathi, N., Rizwan, S. M. and Senguttuvan, A. (2015). Comparative analysis between the reliability models portraying two operating conditions of a desalination plant. International Journal of Core Engineering and Management, 1(12), pp.1-10.

[51] Rizwan, S. M., Padmavathi, N., Anita, Pal. and Taneja, G. (2013). 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, Sep 2013, pp. 523-528.

[52] Rizwan, S. M., Padmavathi, N., Anita Pal, Taneja, G. (2013). Probabilistic Analysis of an Evaporator of a Desalination Plant with Inspection. i-manager's Journal on Mathematics, Vol. 2, No. 1, pp. 27-34.

[53] Rizwan, S. M., Padmavathi, N. and Taneja, G. (2015). Performance analysis of a desalination plant as a single unit with mandatory shutdown during winter. Arya Bhatta Journal of Mathematics and Informatics, Vol. 7, No.1, pp. 195-202.

[54] Sharma, U. and kaur, J. (2014). Availability Analysis of a Standby System with Three Types of Failure Categories. IOSR Journal of Mathematics, 10(2), pp.23–28.

[55] Sharma, U. and kaur, J. (2014). Comparative Study of Standby Compressor Systems with and without Provision of Priority to Failed Compressor Unit, International Journal of Applied Mathematics & Statistical Sciences,3(6), pp.1-8.

[56] Rizwan. S. M., Thanikal, J. and Torijos, M. (2013). Reliability Analysis of a Domestic Wastewater Treatment Plant' in Proc. of International Conference on Harnessing Technology, 2-3 Dec 2013, Sultanate of Oman.

[57] Rizwan, S. M. and Thanikal, J. (2014). Reliability analysis of a wastewater treatment plant with inspection. i-manager's Journal on Mathematics, 3(2), pp.21-26.

[58] Rizwan, S. M., Thanikal, J. and Torrijos, M. (2014). A general model for reliability analysis of a domestic wastewater treatment plant. International Journal of Condition Monitoring and Diagnostic Engineering Management, 17(3), pp.3-6.

[59] Rizwan, S. M., Thanikal, J., Padmavathi, N. & Yazdi, H. (2015). Reliability & Availability Analysis of an Anaerobic Batch Reactor Treating Fruit and Vegetable Waste. International Journal of Applied Engineering Research, Vol. 10, Issue 24, pp. 44075-44079.

[60] Rizwan, S. M. and Mathew, A. (2015). Performance analysis of port cranes. International Journal of Core Engineering and Management, 2(1), pp.133-140.

[61] Al Rahbi, Y., Rizwan, S. M., Alkali, B., Cowell, A. and Taneja, G. (2017). Reliability analysis of a subsystem in aluminum industry plant. In: 6th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions), Noida, UP, India, pp.199-203.

[62] Al Rahbi, Y., Rizwan, S. M., Alkali, B., Cowell, A. and Taneja, G. (2017). Reliability analysis of rodding anode plant in aluminum industry. *International Journal of Applied Engineering Research*, 12(16), 2017b, pp.5616-5623.

[63] Al Rahbi, Y., Rizwan, S. M., Babakalli, Alkali., Andrew, Cowel. and Gulshan Taneja. (2017). Reliability Analysis of a Subsystem in Aluminum Plant, in Proc. of 6th International Conference on Reliability, Infocom Technologies and Optimization, IEEE Conference, Amity Institute of Information Technology, Amity University, Noida, UP, India. 20-22 Sep. 2017, pp. 203-207,

[64] Al Rahbi, Y., Rizwan, S. M., Alkali, B., Cowell, A. and Taneja, G. (2018). Maintenance analysis of a butt thimble removal station in aluminum plant. *International Journal of Mechanical Engineering and Technology*, 9(4), pp. 695-703.

[65] Al Rahbi, Y., Rizwan, S. M., Alkali, B., Cowell, A. and Taneja, G. (2018). Reliability analysis of rodding anode plant in an aluminum industry with multiple repairmen. *Advances and Applications in Statistics*, 53(5), pp.569-597.

[66] Al Rahbi, Y., Rizwan, S. M., Alkali, B., Cowell, A. and Taneja, G. (2019). Reliability analysis of a rodding anode plant in aluminum industry with multiple units' failure and single repairman. *International Journal of System Assurance Engineering and Management*, **10**(1), pp.97-109.

[67] Al Rahbi, Y., Rizwan, S. M., Alkali, B., Cowell, A. and Taneja, G. (2019). Reliability analysis of multiple units with multiple repairmen of rodding anode plant in aluminum industry. Advances and Applications in Statistics, 54(1), pp.151-178.

[68] Al Rahbi, Y., and Rizwan, S. M. (2020). A Comparative Analysis between the Models of a Single Component with Single Repairman & Multiple Repairmen of an Aluminium Industry, International Conference on Computational Performance Evaluation, North-Eastern Hill University, Shillong, Meghalaya, India. Jul 2-4.

[69] Al Rahbi, Y., Rizwan, S. M. (2020). A Comparative Analysis between the models of a Single Component with single repairman & multiple repairmen of an Aluminum Industry, International Conference on Computational Performance Evaluation, IEEE Conference, 2-4 July 2020, Department of Biomedical Engineering, North-Eastern Hill University, Shillong, Meghalaya, India, IEEE Proceedings, pp. 132-135.

[70] Taj, S., Rizwan, S. M., Alkali, B., Harrison, D. and Taneja, G. (2017a). Probabilistic modelling and analysis of a cable plant subsystem with priority to repair over preventive maintenance, i-manager's Journal on Mathematics, 6(3), pp.12-21.

[71] Taj, S., Rizwan, S. M., Alkali, B., Harrison, D. and Taneja, G. (2017). Reliability analysis of a single machine subsystem of a cable plant with six maintenance categories. International Journal of Applied Engineering Research, 1(8), pp. 1752-1757.

[72] Taj, S., Rizwan, S. M., Alkali, B., Harrison, D. and Taneja, G. (2017). Reliability modeling and analysis of a single machine subsystem of a cable plant. In proceedings of 7th International Conference on Modeling, Simulation, and Applied Optimization. Sharjah, UAE: IEEE, pp.1-4.

[73] Taj, S., Rizwan, S. M., Alkali, B., Harrison, D. and Taneja, G. (2018). Comparative analysis of reliability models of a cable plant portraying summer and winter operating strategy. In: 9thInternational Conference on Quality, Reliability, Infocom Technology and Business Operations. Delhi, India: Springer.

[74] Taj, S., Rizwan, S. M., Alkali, B., Harrison, D. and Taneja, G. (2018). Performance analysis of a rod breakdown system. International Journal of Engineering and Technology, 7(3.4), pp.243-248.

[75] Taj, S., Rizwan, S. M., Alkali, B., Harrison, D. and Taneja, G. (2018). Performance and cost benefit analysis of a cable plant with storage of surplus produce. International Journal of Mechanical Engineering and Technology, 9(8), pp.814-826.

[76] Taj, S., Rizwan, S. M., Alkali, B., Harrison, D. and Taneja, G. (2018). Profit analysis of a cable manufacturing plant portraying the winter operating strategy. International Journal of Mechanical Engineering and Technology, 9(11), pp.370-381.

[77] Taj, S., Rizwan, S. M., Alkali, B., Harrison, D. and Taneja, G. (2018). Reliability analysis of a 3-unit subsystem of a cable plant. Advances and Applications in Statistics, 52(6), pp.413-429.

[78] Taj, S., Rizwan, S. M. and Taneja, G. (2018). Reliability analysis of a wire drawing system with mandatory rest period. International Journal of Mechanical Engineering and Technology, 9(4), pp.1–10.

[79] Taj, S., Rizwan, S. M. (2019). Reliability modeling and analysis of complex industrial systems–a review. i-manager's Journal on Mathematics, 8(2), pp. 43-60.

[80] Taj, S., Rizwan, S. M., Alkali, B., Harrison, D. and Taneja, G. (2020). Three Reliability Models of a Building Cable Manufacturing Plant: A comparative Analysis. International Journal of System Assurance Engineering and Management, 11, pp. 239–246.