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SENSITIVITY AND AVAILABILITY ANALYSIS OF A GAS COMPRESSOR

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Abstract

In this paper, an availability analysis of a gas compressor extensively used in the oil and gas industry is presented. It aims to investigate possible causes of compressor unavailability and to obtain various reliability indices that reflect the overall system's operational capabilities. Results demonstrate the impact of operating conditions and various faults on compressor reliability, with sensitivity analysis revealing how variations in failure and repair rates affect the overall system's reliability. The analysis utilizes real data from an oil and gas exploration and production company. The findings offer insights for enhancing compressor robustness and suggest future research directions to address the system's reliability challenges, contributing to more resilient oil and gas infrastructure.

Keywords: availability, Markov processes, sensitivity analysis, regenerative processes, reliability analysis.

I. Introduction

Reliability modeling and analysis of industrial systems have become pivotal in ensuring the optimal performance and longevity of complex machinery and processes. As industries become increasingly dependent on sophisticated technology, the need to understand and predict system reliability has never been more critical. This field involves developing mathematical and statistical models that simulate various failure and repair scenarios, allowing engineers to predict system behavior under different conditions. These models are essential for designing maintenance strategies that minimize downtime and costs while maximizing operational efficiency. By analyzing real failure and maintenance data, these models can provide valuable insights into the reliability indices of systems, such as mean time between failures (MTBF), system availability, etc. This comprehensive approach helps industries to not only improve their maintenance policies but also enhance the overall reliability and performance of their systems, thereby ensuring sustained productivity and economic benefits.

Over the years, significant contributions have been made in the field of reliability studies. Notably, [II] contributed a case study analyzing reliability models for a PLC system with an economic perspective. This research was based on critical methodologies for assessing complex systems. Reference [I] applied reliability modeling to the industrial manufacturing sector, specifically to a two-unit continuous casting plant, offering vital insights into maintenance strategies that enhance operational continuity. Reference [V] delved into the probabilistic analysis of a desalination plant, incorporating both major and minor failures, and highlighted the seasonal impact on system performance. In the realm of environmental sustainability, [VII] proposed a general model for the reliability analysis of a waste treatment reactor, thereby demonstrating how reliability models can significantly contribute to environmental engineering. Following this, [X] investigated the reliability challenges in the aluminum industry, particularly in a rodding anode plant with multiple units and a single repairman, emphasizing the complexities of maintaining operational continuity amidst multiple failures. While analyzing a cable manufacturing plant, [VIII] introduced novel analytical methods for assessing the reliability impacts of individual subsystems within complex manufacturing environments. Reference [VI] conducted a probabilistic analysis of power transformers with six types of failures and inspection. The study offered critical insights into the factors affecting the reliability and robustness of power distribution systems. Most recently, [IX] provided insights into the efficacy of a reliability model for a wastewater treatment plant, illustrating the ongoing evolution and refinement of reliability assessment techniques.

Collectively, these studies emphasize the critical importance of advanced reliability modeling and analysis across various industrial and environmental applications, offering profound insights into system design and maintenance optimization to enhance overall operational efficacy and sustainability. In the context of oil and gas exploration and production, the reliability of gas compressors is crucial for maintaining a consistent outflow of oil from the wells. This paper presents a reliability analysis of a gas compressor, aiming to obtain reliability indices that reflect the compressor's behavior and to conduct a sensitivity analysis. The study explores the causes of compressor unavailability, which may arise from overhauling, including service, and faults in components like the piston, valves, gas packing, etc. By employing Markov processes and regenerative processes, the analysis provides a detailed examination of the compressor's stochastic behavior over time. Key reliability metrics, including mean time between failure (MTBF) and system availability, are obtained to evaluate the compressor's performance, utilizing real compressor data on failures and repairs. The analysis reveals the significant impact of operating conditions and various faults on compressor unavailability. A sensitivity analysis further evaluates how variations in compressor failure and repair rates influence overall reliability, providing valuable insights into the determinants of compressor reliability. The study concludes by offering critical insights into the factors affecting the reliability and robustness of gas compressors. The findings form the basis for enhancing system robustness by addressing key determinants of compressor reliability. Additionally, the paper opens the directions for future research to further explore and mitigate reliability challenges in gas compressors, thereby contributing to the development of more reliable and resilient oil and gas infrastructure.

II. Model Description

The following operating conditions and assumptions are considered:

- The system consists of a single gas compressing unit.
- The unit undergoes five types of maintenance, i.e., repair due to piston failure, repair due to valve failure, repair due to gas packing failure, major overhauling, and normal service.
- The unit undergoes repair upon failure.
- Major overhauling and normal service are carried out as per schedule.
- After each maintenance, the unit is restored to its original operational condition.
- Only one maintenance facility is available.
- Only one maintenance is carried out at a time.
- If needed, the maintenance team may decide on extending the repair work to normal service or major overhauling.
- The failure times and repair times are assumed to be exponentially distributed.

Figure 1 shows the state transition diagram of the gas compressor.

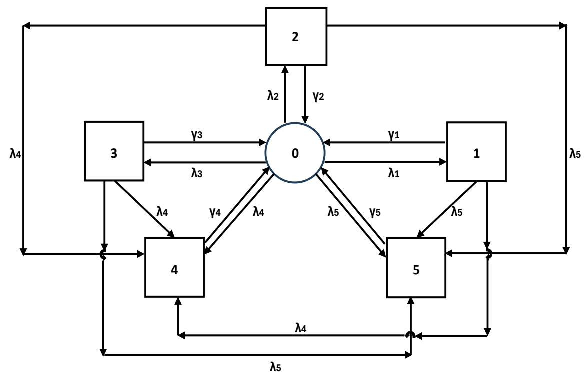

Fig 1. State transition diagram of the gas compressor

Transition states of the gas compressor are described below:

State 0: the gas compressor is in an operative state.
State 1: the gas compressor is undergoing repair due to piston failure.
State 2: the gas compressor is undergoing repair due to valve failure.
State 3: the gas compressor is undergoing repair due to gas packing failure.
State 4: the gas compressor is undergoing normal service.
State 5: the gas compressor is undergoing major overhauling.

Here, S_0, S_1, S_2, and S_3 are regenerative states, whereas S_4 and S_5 are non-regenerative states.

Table 1 gives the estimated values of failure rates and repair rates for the gas compressor.

Table 1 : Estimated values of rates for the gas compressor

Rate (per hour)	Estimated value (per hour)
λ_1, Constant failure rate (piston failure)	0.002
λ_2, Constant failure rate (valve failure)	0.004
λ_3, Constant failure rate (gas packing failure)	0.001
λ_4, Constant failure rate (normal service)	0.001
λ_5, Constant failure rate (major overhauling)	0.00002
γ_1, Constant repair rate (piston failure)	0.07
γ_2, Constant repair rate (valve failure)	0.09
γ_3, Constant repair rate (gas packing failure)	0.07
γ_4, Constant repair rate (normal service)	0.21
γ_5, Constant repair rate (major overhauling)	0.04

III. Mathematical Analysis

Abbreviations and Acronyms

λ_1	Constant failure rate (piston failure).
λ_2	Constant failure rate (valve failure).
λ_3	Constant failure rate (gas packing failure).
λ_4	Constant failure rate (normal service).
λ_5	Constant failure rate (major overhauling).
γ_1	Constant repair rate (piston failure).
γ_2	Constant repair rate (valve failure).
γ_3	Constant repair rate (gas packing failure).
γ_4	Constant repair rate (normal service).
γ_5	Constant repair rate (major overhauling).
S_i	State i
q_{ij}	probability density function from S_i to S_j
Q_{ij}	cumulative distribution function from S_i to S_j

*	Laplace transform
**	Laplace Stieltjes transform
Ⓢ	Laplace convolution
©	Laplace Stieltjes convolution
MTBF	Mean time between failures
A_0	Availability of the system

Transition Probabilities and Mean Sojourn Times

Transition probabilities and the mean sojourn times are evaluated based on the system's transitions to different possible states.

Using the definition of transition probabilities q_{ij} [III], we get:

$$q_{01}(t) = \lambda_1 e^{-\lambda t}$$
$$q_{02}(t) = \lambda_2 e^{-\lambda t}$$
$$q_{03}(t) = \lambda_3 e^{-\lambda t}$$
$$q_{04}(t) = \lambda_4 e^{-\lambda t}$$
$$q_{05}(t) = \lambda_5 e^{-\lambda t}$$
$$q_{10}(t) = \gamma_1 e^{-(\gamma_1+\lambda_4+\lambda_5)t}$$
$$q_{20}(t) = \gamma_2 e^{-(\gamma_2+\lambda_4+\lambda_5)t}$$
$$q_{30}(t) = \gamma_3 e^{-(\gamma_3+\lambda_4+\lambda_5)t}$$
$$q_{40}(t) = \gamma_4 e^{-\gamma_4 t}$$
$$q_{50}(t) = \gamma_5 e^{-\gamma_5 t}$$
$$q_{14}(t) = \lambda_4 e^{-(\gamma_1+\lambda_4+\lambda_5)t}$$
$$q_{15}(t) = \lambda_5 e^{-(\gamma_1+\lambda_4+\lambda_5)t}$$
$$q_{24}(t) = \lambda_4 e^{-(\gamma_2+\lambda_4+\lambda_5)t}$$
$$q_{25}(t) = \lambda_5 e^{-(\gamma_2+\lambda_4+\lambda_5)t}$$
$$q_{34}(t) = \lambda_4 e^{-(\gamma_3+\lambda_4+\lambda_5)t}$$
$$q_{35}(t) = \lambda_5 e^{-(\gamma_3+\lambda_4+\lambda_5)t}$$
$$q_{0^40}(t) = q_{1^40}(t) = q_{2^40}(t) = q_{3^40}(t) = \left[\lambda_4 e^{-\lambda_4 t} © 1\right]\gamma_4 e^{-\gamma_4 t}$$
$$q_{0^50}(t) = q_{1^50}(t) = q_{2^50}(t) = q_{3^50}(t) = \left[\lambda_5 e^{-\lambda_5 t} © 1\right]\gamma_5 e^{-\gamma_5 t}$$

Where,

$$\lambda = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5$$

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

$$p_{01} = \frac{\lambda_1}{\lambda}$$
$$p_{02} = \frac{\lambda_2}{\lambda}$$
$$p_{03} = \frac{\lambda_3}{\lambda}$$
$$p_{04} = \frac{\lambda_4}{\lambda}$$

$$p_{05} = \frac{\lambda_5}{\lambda}$$

$$p_{10} = \frac{\gamma_1}{\gamma_1 + \lambda_4 + \lambda_5}$$

$$p_{20} = \frac{\gamma_2}{\gamma_2 + \lambda_4 + \lambda_5}$$

$$p_{30} = \frac{\gamma_3}{\gamma_3 + \lambda_4 + \lambda_5}$$

$$p_{40} = 1$$

$$p_{50} = 1$$

$$p_{14} = \frac{\lambda_4}{\gamma_1 + \lambda_4 + \lambda_5}$$

$$p_{15} = \frac{\lambda_5}{\gamma_1 + \lambda_4 + \lambda_5}$$

$$p_{24} = \frac{\lambda_4}{\gamma_2 + \lambda_4 + \lambda_5}$$

$$p_{25} = \frac{\lambda_5}{\gamma_2 + \lambda_4 + \lambda_5}$$

$$p_{34} = \frac{\lambda_4}{\gamma_3 + \lambda_4 + \lambda_5}$$

$$p_{35} = \frac{\lambda_5}{\gamma_3 + \lambda_4 + \lambda_5}$$

$$p_{0^{4}0} = p_{1^{4}0} = p_{2^{4}0} = p_{3^{4}0} = 1 - \frac{\gamma_4}{\gamma_4 + \lambda_4}$$

$$p_{0^{5}0} = p_{1^{5}0} = p_{2^{5}0} = p_{3^{5}0} = 1 - \frac{\gamma_5}{\gamma_5 + \lambda_5}$$

The following relations can easily be verified:

$$p_{01} + p_{02} + p_{03} + p_{04} + p_{05} = 1$$

$$p_{10} + p_{14} + p_{15} = 1$$

$$p_{20} + p_{24} + p_{25} = 1$$

$$p_{30} + p_{34} + p_{35} = 1$$

$$p_{40} = 1$$

$$p_{50} = 1$$

Using the definition of unconditional mean time m_{ij} [III], we get:

$$m_{01} = \frac{\lambda_1}{\lambda^2}$$

$$m_{02} = \frac{\lambda_2}{\lambda^2}$$
$$m_{03} = \frac{\lambda_3}{\lambda^2}$$
$$m_{04} = \frac{\lambda_4}{\lambda^2}$$
$$m_{05} = \frac{\lambda_5}{\lambda^2}$$
$$m_{10} = \frac{\gamma_1}{(\gamma_1 + \lambda_4 + \lambda_5)^2}$$
$$m_{20} = \frac{\gamma_2}{(\gamma_2 + \lambda_4 + \lambda_5)^2}$$
$$m_{30} = \frac{\gamma_3}{(\gamma_3 + \lambda_4 + \lambda_5)^2}$$
$$m_{40} = \frac{1}{\gamma_4}$$
$$m_{50} = \frac{1}{\gamma_5}$$
$$m_{14} = \frac{\lambda_4}{(\gamma_1 + \lambda_4 + \lambda_5)^2}$$
$$m_{15} = \frac{\lambda_5}{(\gamma_1 + \lambda_4 + \lambda_5)^2}$$
$$m_{24} = \frac{\lambda_4}{(\gamma_2 + \lambda_4 + \lambda_5)^2}$$
$$m_{25} = \frac{\lambda_5}{(\gamma_2 + \lambda_4 + \lambda_5)^2}$$
$$m_{34} = \frac{\lambda_4}{(\gamma_3 + \lambda_4 + \lambda_5)^2}$$
$$m_{35} = \frac{\lambda_5}{(\gamma_3 + \lambda_4 + \lambda_5)^2}$$
$$m_{0^{4}0} = m_{1^{4}0} = m_{2^{4}0} = m_{3^{4}0} = \frac{1}{\gamma_4} - \frac{\gamma_4}{(\gamma_4 + \lambda_4)^2}$$
$$m_{0^{5}0} = m_{1^{5}0} = m_{2^{5}0} = m_{3^{5}0} = \frac{1}{\gamma_5} - \frac{\gamma_5}{(\gamma_5 + \lambda_5)^2}$$

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

$$\mu_0 = \frac{1}{\lambda}$$
$$\mu_1 = \frac{1}{\gamma_1 + \lambda_4 + \lambda_5}$$
$$\mu_2 = \frac{1}{\gamma_2 + \lambda_4 + \lambda_5}$$

$$\mu_3 = \frac{1}{\gamma_3 + \lambda_4 + \lambda_5}$$
$$\mu_4 = \frac{1}{\gamma_4}$$
$$\mu_5 = \frac{1}{\gamma_5}$$

The following relations can easily be verified:

$$m_{01} + m_{02} + m_{03} + m_{04} + m_{05} = \mu_0$$
$$m_{10} + m_{14} + m_{15} = \mu_1$$
$$m_{20} + m_{24} + m_{25} = \mu_2$$
$$m_{30} + m_{34} + m_{35} = \mu_3$$
$$m_{40} = \mu_4$$
$$m_{50} = \mu_5$$

Mean Time Between Failures

Using probabilistic arguments and the definition of $\phi_i(t)$ [III], the following recursive relation is obtained:

$$\phi_0(t) = Q_{01}(t)+Q_{02}(t)+Q_{03}(t)+Q_{04}(t)+Q_{05}(t) \quad (1)$$

Mean time between failures when the system started at the beginning of state 0 is given by:

$$\text{MTBF} = \lim_{s\to 0} \frac{1-\phi_0^{**}(s)}{s} = \mu_0 \quad (2)$$

System Availability

Using probabilistic arguments and the definition of $A_i(t)$ [III], the following recursive relations are obtained:

$$A_0(t) = M_0(t)+q_{01}(t)©A_1(t)+q_{02}(t)©A_2(t)+q_{03}(t)©A_3(t)+q_{0^40}(t)+q_{0^50}(t) \quad (3)$$

$$A_1(t) = q_{10}(t)©A_0(t)+q_{1^40}(t)+q_{1^50}(t) \quad (4)$$

$$A_2(t) = q_{20}(t)©A_0(t)+q_{2^40}(t)+q_{2^50}(t) \quad (5)$$

$$A_3(t) = q_{30}(t)©A_0(t)+q_{3^40}(t)+q_{3^50}(t) \quad (6)$$

Where,

$$M_0(t) = e^{-\lambda t} \quad (7)$$

In steady state, the availability of the subsystem is given by:

$$A_0 = \lim_{s\to 0} s\, A_0^{*}(s) = \frac{N_1}{D_1} \quad (8)$$

Where,

$$N_1 = m_{0}{}^{4}{}_{0} + m_{0}{}^{5}{}_{0} + p_{01}(m_{10} + m_{1}{}^{4}{}_{0} + m_{1}{}^{5}{}_{0}) + m_{01}(p_{10} + p_{1}{}^{4}{}_{0} + p_{1}{}^{5}{}_{0}) + p_{02}(m_{20} + m_{2}{}^{4}{}_{0} + m_{2}{}^{5}{}_{0}) + m_{02}(p_{20} + p_{2}{}^{4}{}_{0} + p_{2}{}^{5}{}_{0}) + p_{03}(m_{30} + m_{3}{}^{4}{}_{0} + m_{3}{}^{5}{}_{0}) + m_{03}(p_{30} + p_{3}{}^{4}{}_{0} + p_{3}{}^{5}{}_{0}) \quad (9)$$

$$D_1 = \mu_0 \quad (10)$$

IV. Sensitivity Analysis

The concept of sensitivity analysis assists in determining the extent to which a parameter (independent variable) affects an obtained measure (dependent variable), whereas the relative sensitivity analysis further helps in assessing the impact of different parameters due to significant differences in the numerical values of various parameters [IV]. Sensitivity analysis for MTBF and availability of the gas compressor are presented in Tables 2 and 3, respectively.

Table 2: Sensitivity analysis for MTBF of the gas compressor

Parameter	Sensitivity analysis	Relative sensitivity analysis
λ_1	-15547.167	-0.249376559
λ_2	-15547.167	-0.498753117
λ_3	-15547.167	-0.124688279
λ_4	-15547.167	-0.124688279
λ_5	-15547.167	-0.002493766

Table 3: Sensitivity analysis for availability of the gas compressor

Parameter	Sensitivity analysis	Relative sensitivity analysis
λ_1	29.5355	0.062010288
λ_2	26.9142	0.113013647
λ_3	29.5355	0.031005144
λ_4	-115.9119	-0.121679509
λ_5	-80.1549	-0.001682866
γ_1	-0.3347	-0.024594793
γ_2	-0.4106	-0.038792778
γ_3	-0.1674	-0.012301071
γ_4	-0.026	-0.005731682
γ_5	-0.0297	-0.001247113

Thus, the order in which the parameters (failure rates/repair rates) influence the MTBF and availability of the gas compressor is given below:
For MTBF: $\lambda_2 > \lambda_1 > \lambda_3 = \lambda_4 > \lambda_5$
For availability: $\lambda_4 > \lambda_2 > \lambda_1 > \gamma_2 > \lambda_3 > \gamma_1 > \gamma_3 > \gamma_4 > \lambda_5 > \gamma_5$

It can be observed that the MTBF is most influenced by λ_2 and least influenced by λ_5. Whereas, the availability is most influenced by λ_4 and least influenced by γ_5.

Furthermore, the values of the MTBF and availability can be estimated from the expressions obtained in (2) and (8), which are reflective of the important reliability

indices of the system:
MTBF: 125 hours
Availability: 0.95

The trend of MTBF with respect to λ_5 and λ_2 is shown in Figure 2.

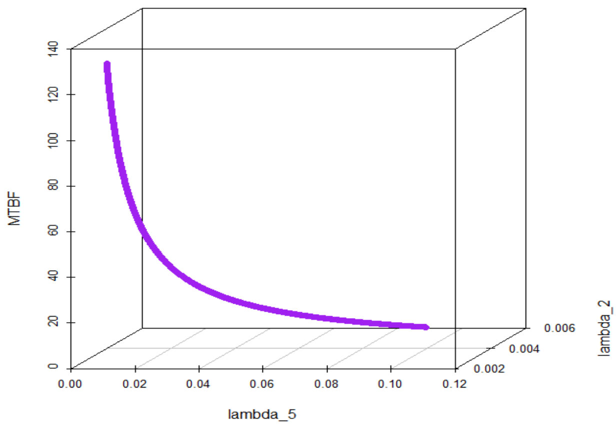

Fig 2. Trend of MTBF with respect to λ_5 and λ_2

The trend of availability with respect to γ_5 and λ_4 is shown in Figure 3.

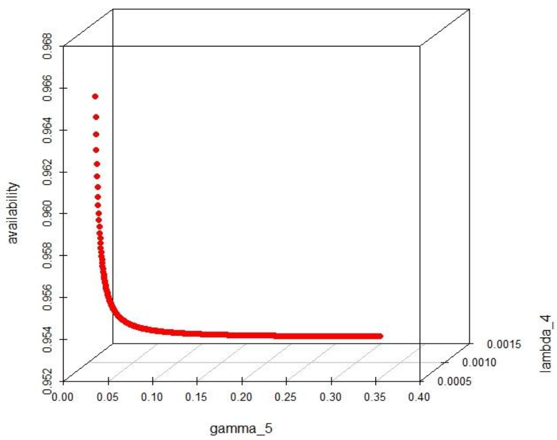

Fig 3. Trend of availability with respect to γ_5 and λ_4.

Clearly, the trends shown in Figures 2 and 3 are in line with the results of the sensitivity analysis.

V. Conclusion

The study has effectively demonstrated the significant impacts of operating conditions and various faults on the reliability of a gas compressor in an oil and gas company. The sensitivity analysis conducted as part of the research emphasizes how variations in failure and repair rates critically influence the overall system reliability.

Results of the relative sensitivity analysis help the maintenance managers in identifying the most critical type of failure, thus helping the maintenance team in updating the existing maintenance strategy. These improvements can significantly extend the mean operational hours and boost system availability, thereby optimizing overall operational capabilities. Thus, this study provides essential insights into the determinants of compressor reliability, guiding strategies for enhancing the robustness of gas compressors. This work enriches the existing body of knowledge and provides practical insights that enhance system reliability and maintenance strategies.

Additionally, the paper recommends avenues for future research to continue exploring and mitigating reliability challenges, aiming to develop a more resilient oil and gas infrastructure. Integration of deep learning into compressor fault detection may be explored, possibly leading to a paradigm shift offering higher accuracy, real-time processing, and adaptability to various data types. Continuous evolution of these techniques may promise further enhancements in the maintenance and reliability of gas compressors, reducing the risk of gas lift failures.

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Conflict of Interest:

There was no relevant conflict of interest regarding this article.

References

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

II. G. Taneja, V. Khurana and S. M. Rizwan, "Economic analysis of a reliability model for two programmable logic controller cold standby system with four types of failure," Pure Applied Mathematika Sciences, vol. 63, no. 1-2, pp. 65-78, 2006.

III. K. B. Misra, Handbook of Performability Engineering, 1st ed. Springer: London, 2008.

IV. K. Sachdeva, G. Taneja and A. Manocha, "Sensitivity and economic analysis of an insured system with extended conditional warranty," Reliability: Theory & Applications, vol. 17, no. 3(69), pp. 315-327, 2022.

V. N. Padmavathi, S. M. Rizwan, A. Pal and G. 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.

VI. Nabila Al Balushi, S. M. Rizwan, S. Z. Taj and Waleed Al Khairi, "Probabilistic analysis of power transformers in a power distribution company with six types of failures and inspection," International Journal of Engineering Trends and Technology, vol. 72, no. 4, pp. 15-22, 2024.

VII. S. M. Rizwan, J. V. Thanikal, N. Padmavathi and H. 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.

VIII. S. Z. Taj, "Performance and cost benefit analysis of reliability models for a cable plant," Ph.D. dissertation, Glasgow Caledonian University, Glasgow, Scotland, U. K., 2023.

IX. S. Z. Taj, S. M. Rizwan and K. Sachdeva, "Reliability and sensitivity analysis of a wastewater treatment plant operating with two blowers as a single system," in Reliability Engineering for Industrial Processes: An Analytics Perspective. Cham: Springer Nature Switzerland, 2024, pp. 19-39.

X. Yaqoob Al Rahbi, S. M. Rizwan, B. M. Alkali, A. Cowell and G. Taneja, "Reliability analysis of a rodding anode plant in aluminum industry with multiple units failure and a single repairman," International Journal of System Assurance Engineering and Management, vol. 10, pp. 97-109, 2019.