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Original Research Article

Reliability Analysis of Gas Compressing System Using Cumulative Distribution Functions

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Abstract

This study evaluated the reliability of natural gas compressing system at Soku and Obigbo gas stations over a period of 4 years. Historical failure data of the compressing system at the gas stations were evaluated using exponential cumulative distribution function (ECDF) and Weibull cumulative distribution function (WCDF) to analyze the compressors reliability. The mean time between successive maintenance at the gas stations occurred within a short interval. This implies a high frequency of failures of the compressing system. The WCDF and ECDF established that the reliability of the gas compressing systems reduced with time. Within the investigation period, the probability of failure of the compressor components at Soku gas station ranged from 0.5301 to 0.6959 for WCDF and 0.3533 to 0.8251 for ECDF, while the reliability ranged from 0.4699 to 0.3041 for WCDF and 0.6467 to 0.1749 for ECDF. Similarly, the probability of failure of the compressor components at Obigbo gas station ranged from 0.5596 to 0.6818 for WCDF and 0.3986 to 0.8101 for ECDF, while the reliability ranged from 0.4404 to 0.3182 for WCDF and 0.6014 to 0.1899 for ECDF. The results indicated that the mean time between consecutive failures reduced the reliability of the compressors at the gas stations. Generally, the analysis revealed that effective maintenance practices are crucial for optimal performance and reliability of the compressing systems at Soku and Obigbo natural gas stations. Hence, WCDF or ECDF can be applied to improve the performance of the compressing system through evaluation of failure that will result in useful information on the system reliability.

Keywords: Natural Gas, Compressor, Reliability, Exponential and Weibull Distribution Functions.

1. INTRODUCTION

Oil and gas production systems consist of wells, flow-lines, manifolds, Christmas trees, risers, pipelines among other units. It is noteworthy that the operation of these facilities is associated with challenges such as pressure containment, maintenance and flow assurance in both onshore and offshore environment. Low temperature and high pressure are the common challenges that characterize oil and gas facilities, which often lead to high costs of maintenance and repair of systems on regular basis. Because of the large geographical coverage of oil production facilities, the task in risk assessment of oil and gas facilities is huge.

However, there are several different reliability methods that can be used to assess the performance of compressing systems, such as modelling approach. Models have been used as important tool to improving the accuracy and efficiency of gas compressor failure analysis (Bhujel *et al*., 2017; Aliyu & Bello, 2019; Gupta *et al*., 2022). Of course, several algorithms and modelling techniques have been developed for performing of reliability study on compression systems, which include predicting and preventing failures in gas compressors. Some of the notable failure prediction models applicable to oil and gas facility were developed based on fuzzy logic technique, Monte Carlo simulation, regression analysis and Bayesian network among others. Most of these models were developed using a variety of data sources, including sensor data, maintenance records, and historical failure data (Zakikhani, 2020).

Application of reliability model to critical analysis of failure and maintenance schedules in the industry is useful and importance for good operation and economy of a process plant (Woo *et al*., 2020). Reliability model can be helpful in maintenance planning, which will in turn lead to safety of plant facilities and reduction in cost (Zhang *et al*., 2002). Pourhosseini and Nasiri (2017) recommended the selection of components with superior effects on system failure during modelling in place of parameters with less impact on the system, as this will help to avoid over/under maintenance of components by considering their availability priorities.

The traditional approach of obtaining time based or historical failure data of a system for developing reliability model is well established in engineering. This approach enables a general long-range forecast of failure in a unit, and does not require any condition monitoring (Sigmundstad, 2018). For instance, Le Son *et al*., (2013) used reliability analysis based on available information to determine the process life efficiency with time. The reliability of a scroll compressor was evaluated by Chang *et al*., (2016) using a model developed based on data generated from equipment failure to evaluate the compressor lifetime. Barros (2017) also formulated a model for prediction of remaining useful lifetime for system based-maintenance. The model assumed a random variable, containing set of the greatest lower bound, current condition of the compressor, set of failed or unacceptable states and failure time to predict the expected time and future condition of the compressor.

Process data can also be used to develop stochastic models for reliability evaluation and performance of compressing systems, as have been demonstrated by some researchers while studying the degradation behaviour of mechanical systems (Ye & Xie, 2015; Yang, 2016). According to Ye and Xie, (2015), the performance of compressor parameter can be expressed as a linear function, which depends on the actual condition, time of assessment, and the error between the actual and predicted values of the performance parameter. The error between actual and predicted is usually assumed as normal distribution, which depends on mean and standard deviation. The time variable in this equation is often determined directly from the historical operating data of the unit under analysis at the discrete points in time. For a given critical threshold, the failure probability over the period can be calculated by incorporating linear function with error.

The failure mode technique is another method used for compressor reliability analysis. It involves identifying potential failure modes for each component of the system and assessing the potential impact of each failure on the overall system performance, whereby the information obtained can be used to identify and prioritize areas for improvement (Al-Ghamdi & Al-Hazmi, 2019). Guo *et al*., (2016a) used a predictive model to study the failure modes and effects analysis of compressors. Through the model, the weaknesses in the compressors were identified, while the finite element method was employed to calculate their reliability.

Several studies have also developed reliability model based on Bayesian and Markov chain models, with applications in the various aspects of safety and reliability of components of oil and gas systems have received attention such as the reliability and safety of oil and gas instrument systems (Jin *et al*., 2012) and wellhead compressor (Chomphu & Kijsirikul, 2020). Unlike some conventional probabilistic models that are made use of exact values for analysis or evaluation of system reliability in the oil and gas industry, the Bayesian and Markov models may use arbitrary values to study the investigated system. However, precise estimation of failure probabilities of some basic event may be impractical due to insufficient data (Khalil *et al*., 2012). Hence, it is often necessary to work with approximate estimates of probabilities in the absence of precise data. In such cases, it is appropriate to use 'possibility' instead of 'probability' (Cheliyan & Bhattacharyya, 2018).

While various modelling techniques are effective for reliability analysis of engineering systems, there are also deficiencies in some reliability models for compressor units using failure or performance data because of the high reliability of natural gas compressing systems. In order to overcome the deficiencies, Yu *et al*., (2022) utilized historical failure and performance data of a natural gas compressor unit to develop a data-driven methodology of reliability analysis. This approach considered two distinctive failure modes: degradation failure and catastrophic failure, as well as effects of external environment and operating conditions.

Overall, the reliability of gas compressors can be improved or predicted with the aid of models utilizing available past and current information about the compressing system. Adequate and precise use of data inputs to the models for the analysis of the compression system can significantly improve the optimal performance and longevity of the systems, thereby reducing maintenance and replacement costs.

2. MATERIALS AND METHODS

2.1 Compressor Failure Data

The previous records of compressor failures data at Obigbo and Soku gas plants were collated to perform the reliability analysis and optimization of the compressor operational variables. The data collected include the times and dates in which the failure occurred in each gas station for a total period of five (5) years. From the recorded failure dates and times, the time between the two successive failures were evaluated. The collated records of previous failures from the compressor unit of the two gas plants were arranged and tabulated as shown in Table 1.

Table 1: Compressor failure data from January 2018 to December 2022

Gas Station	Failure Time	Failure Date	Time between Failures (Day)
Obigbo Gas Station	Time of 1st failure	Date of 1st failure	—
	Time of 2nd failure	Date of 2nd failure	Record time between 1st and 2nd failures
	Time of 3rd failure	Date of 3rd failure	Record time between 2nd and 3rd failures
	Time of 4th failure	Date of 4th failure	Record time between 3rd and 4th failures
	Time of nth failure	Date of nth failure	Record time between (n-1)th and nth failures
Soku Gas Station	Time of 1st failure	Date of 1st failure	—
	Time of 2nd failure	Date of 2nd failure	Record time between 1st and 2nd failures
	Time of 3rd failure	Date of 3rd failure	Record time between 2nd and 3rd failures
	Time of 4th failure	Date of 4th failure	Record time between 3rd and 4th failures
	Time of nth failure	Date of nth failure	Record time between (n-1)th and nth failures

2.2 Reliability Analysis

The reliability analysis was performed using information obtained from the recorded compressor failures with times. Thus, the numbers of times the compressor fails in the respective gas stations were used as input to the reliability model. In order to choose the most suitable reliability model, two models were selected: exponential cumulative distribution and Weibull cumulative distribution. The reliability of the compressors in the gas plants were expressed in terms of probability cumulative distribution function (CDF). That is, the reliability of a component failing over time is related to the probability of the component failure within the specified time frame. This was generally stated as:

$$P(t) + R(t) = 1 \quad (1)$$

In other words, a component with high reliability implied that its probability to fail within the specified time frame will be minimized.

2.2.1 Reliability Based on Exponential Cumulative Distribution

The failure probability based on the exponential cumulative distribution function was adapted according to the work of Yu *et al*., (2022), and this is expressed according to Equation (2).

$$P_e = 1 - \exp(-\lambda t) \quad (2)$$

Form Equation (1), the reliability of the compressor based on the exponential cumulative distribution function can be expressed as:

$$R_e = \exp(-\lambda t) \quad (3)$$

Where: $P_e =$ Probability of failure based on exponential cumulative distribution function

$\lambda =$ Rate parameter

$t =$ The time of failure (days)

The rate parameter was obtained through the maximum likelihood estimation (MLE), by taking the reciprocal of the sample mean (Dass, 2018). That is,

$$\lambda = \frac{1}{\mu} \quad (4)$$

2.2.2 Reliability Based on Weibull Cumulative Distribution

The failure probability based on the Weibull cumulative distribution function is expressed according to the work of Yu *et al*., (2022) as given Equation (5).

$$P_w = 1 - \exp\left[-\left(\frac{t}{\beta}\right)^k\right] \quad (5)$$

Therefore, from Equation (1), the reliability of the compressor based on Weibull cumulative distribution can be expressed as:

$$R_w = \exp\left[-\left(\frac{t}{\beta}\right)^k\right] \quad (6)$$

Where: $P_w =$ Probability of failure based on Weibull cumulative distribution function

$k =$ Shape parameter

$\beta =$ Scale parameter

$t =$ The time of failure (days)

The shape parameter, k, and scale parameter, β, were obtained using the moment method in terms of the sample mean, μ, standard deviation, σ, and sample population, n, (Dass, 2018). That is,

$$k = \frac{\mu}{\sigma} \quad (7)$$

$$\beta = \frac{\mu}{\Gamma\left(1 + \frac{1}{n}\right)} \quad (8)$$

3. RESULTS AND DISCUSSION

The results so far evaluated from this study are presented in this chapter as shown in the Tables and Figures.

3.1 Reliability Results from the Historical Failure of Natural Gas Stations

The estimated probability and reliability of the compressors at the natural gas compression stations are tabulated in Table 2 for Soku Gas Station and Table 3 for Obigbo Gas Station.

Table 2: Probability and reliability of compressors at Soku natural Gas station

	P(t)		R(t)	
Time Ranking (days)	WCDF	ECDF	WCDF	ECDF
33	0.5301	0.35334	0.4699	0.64666
34	0.53359	0.36182	0.46641	0.63818
40	0.55268	0.41045	0.44732	0.58955
43	0.56124	0.43336	0.43876	0.56664
50	0.5792	0.48341	0.4208	0.51659
53	0.58618	0.50348	0.41382	0.49652
59	0.59906	0.54131	0.40094	0.45869
65	0.61072	0.57627	0.38928	0.42373
68	0.61616	0.59273	0.38384	0.40727
69	0.61792	0.59808	0.38208	0.40192
70	0.61966	0.60335	0.38034	0.39665
77	0.63117	0.63838	0.36883	0.36162
82	0.63876	0.6615	0.36124	0.3385
87	0.64591	0.68313	0.35409	0.31687
91	0.65133	0.69944	0.34867	0.30056
96	0.65778	0.71865	0.34222	0.28135
98	0.66026	0.72599	0.33974	0.27401
103	0.66625	0.7435	0.33375	0.2565
104	0.66741	0.74687	0.33259	0.25313
105	0.66856	0.75019	0.33144	0.24981
107	0.67082	0.7567	0.32918	0.2433
132	0.69591	0.82513	0.30409	0.17487

Table 3: Probability and reliability of compressors at Obigbo natural gas station

	P(t)		R(t)	
Time Ranking (days)	WCDF	ECDF	WCDF	ECDF
45	0.55962	0.3986	0.44038	0.6014
47	0.56405	0.41204	0.43595	0.58796
52	0.57439	0.44434	0.42561	0.55566
57	0.58382	0.47487	0.41618	0.52513
63	0.59414	0.50929	0.40586	0.49071
69	0.60354	0.54146	0.39646	0.45854
71	0.6065	0.5517	0.3935	0.4483
78	0.61624	0.5858	0.38376	0.4142
92	0.63336	0.6464	0.36664	0.3536
94	0.63559	0.65431	0.36441	0.34569
97	0.63885	0.66583	0.36115	0.33417
98	0.63991	0.66958	0.36009	0.33042
99	0.64097	0.6733	0.35903	0.3267
102	0.64406	0.68419	0.35594	0.31581
103	0.64507	0.68773	0.35493	0.31227
107	0.64902	0.70153	0.35098	0.29847
109	0.65094	0.7082	0.34906	0.2918
110	0.65189	0.71148	0.34811	0.28852
130	0.66917	0.76984	0.33083	0.23016
147	0.68182	0.81007	0.31818	0.18993

In analysing the probability and reliability of the compressor, the historical data obtained from Soku natural gas compression stations were unutilised. The data revealed that the total maintenance records collected over a period of approximately 4 years, from 11th April, 2017 to 16th November, 2021 was 23. The time between maintenance activities ranges from 33 days to 132 days, with an average of 70 days. Similarly, the historical records of maintenance activities resulting from of natural gas compression station failures at Obigbo over a period of 4 years from 3rd February, 2018 to 7th March, 2022, showed that a total of 21 maintenance records were recorded. The time between maintenance activities ranged from 47 days to 130 days. These historical data were used to perform the reliability analysis.

The data obtained from both stations gives an indication of the frequency of failures/maintenance required. Thus, shorter time intervals indicate more frequent maintenance needs, likely due to more failures occurring in that period. For instance, the lowest time between maintenance at Soku gas compression station was 33 days, and was recorded between 8th September, 2017 and 12th October, 2017. On the other hand, the longest time between two consecutive maintenances was 132 days, occurring between 7th March, 2020 and 18th July, 2020. The longer time intervals suggest less frequent failures. The maintenance records over time can help identify increasing or decreasing frequency of failures. Though, from the history of data obtained, it does appear that there are no obvious trends about the failure of the compressors. However, thorough analysis, the data can give an idea of the reliability of the compressors in the natural gas compression station over time. According to Yu *et al*., (2022), the time between consecutive failures influences the reliability and overall performance of compression stations.

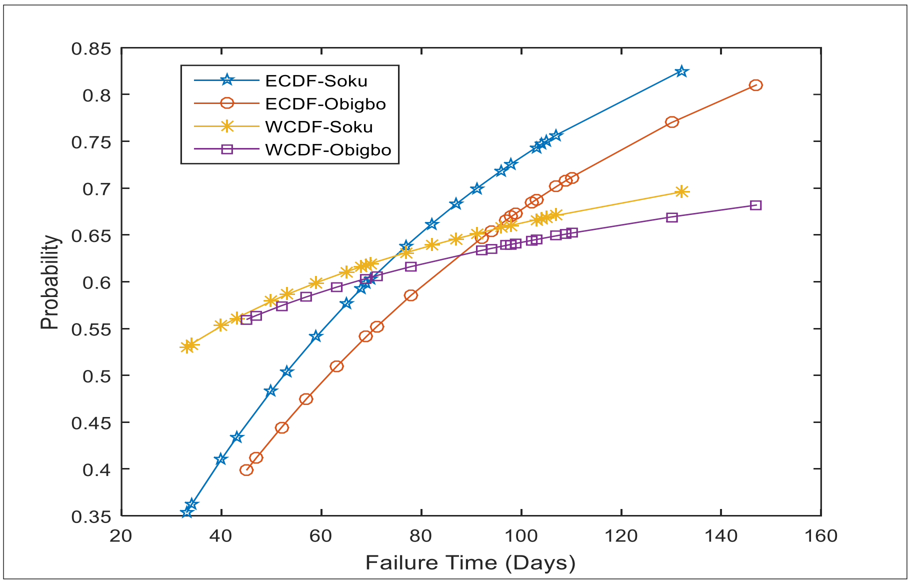

Figure 1: Probability of compressor failure at the gas station

Figure 1 shows the plot of probability of compressor failure at the Soku and Obigbo gas stations versus failure time, obtained using the exponential cumulative distribution function (ECDF) and Weibull cumulative distribution function (WCDF). The ECDF and WCDF curves follow similar trends, but WCDF gives a better fit to the data points, indicating Weibull distribution may better explain the reliability of these compressors. For both stations, the probability of failure increases with time, following the typical 'bathtub curve' behaviour where failures rise steadily with age/use after the initial break-in period.

At shorter times, the probability of failure estimated by ECDF was less than that WCDF at the initial times, but as the time increases, the ECDF curve for both gas stations crossed over the WCDF curve. At this point that the two distribution curves met, it implies that ECDF and WCDF predicted equal time for probability of compressors at Soku or Obigbo station to fail after several months of use. This analysis provided useful information about the probability of failure at the gas stations, which can be used for scheduling of preventive maintenance. As explained by Rahman *et al*., (2022), the probability of machine failure is a function of the mean time between successive failures of the machine. This is often quantified by mathematical expressions, utilizing historical data or information about an equipment.

Generally, the probability analysis is useful for maintenance/inspection schedules, particularly in determination of frequent actions that may be needed where failure probability is higher. Therefore, the effective maintenance of any mechanical equipment or its components can influence their optimal performance level and their reliability. Hence, based on the WCDF and ECDF analysis, this study established that compression systems at Soku station have higher probability of failure compared to Obigbo gas compression station.

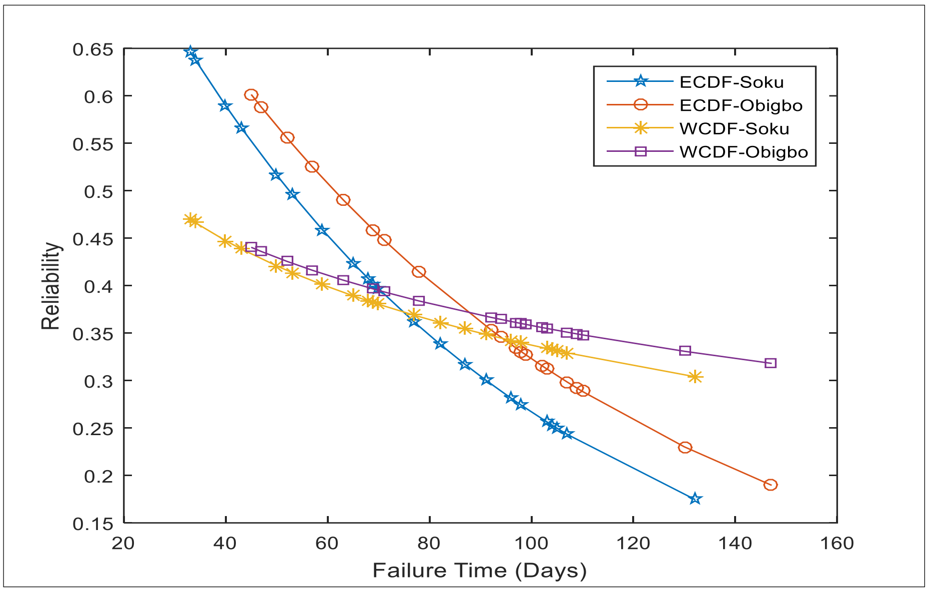

Figure 2: Reliability of compressor failure at the gas station

Figure 2 is the plots of reliability analysis generated from the exponential cumulative distribution function (ECDF) and Weibull cumulative distribution function (WCDF), utilizing data obtained from Soku and Obigbo gas stations against failure time. The results are presented in Tables 2 and 3. The profiles indicate that the reliability of the compressors at Soku and Obigbo stations decreased with increasing failure time for both ECDF and WCDF models. The results provided a quantitative measure of how reliable the compressors are at each station over different periods of operation. Thus, the decrease in reliability is an indication of decline in compressor performance. This is consistent with the study by Al-Duais *et al*., (2022), which found that a decreasing reliability of a mechanical system indicates its decline in performance efficiency.

The trends in the reliability results with respect to the failure data at the compression stations provided useful information that can be used for various purposes like maintenance scheduling, equipment replacement planning and reliability centred asset management. For example, the station may choose to schedule frequent preventive maintenance for equipment suspected to have lower reliability at a given time.

However, from the exponential cumulative distribution function (ECDF), the compressors at Soku and Obigbo natural gas stations are more reliable below 77 days and 92 days, while from 77 days at Soku gas station and 92 days at Obigbo gas station, the Weibull cumulative distribution function (WCDF) showed the compressors are more reliable. This implied that both cumulative distribution functions have periods for which their performance can be relied on. Nevertheless, the failure rates estimated by the Weibull distribution appears to be decreasing with increasing time. On comparison, the reliability curves showed that Obigbo gas compressors are reliable than compressor at Soku gas compressors.

Nevertheless, some studies have found that WCDF performed better than ECDF in terms of failure of mechanical equipment such as the natural gas compression stations. For instance, Yu *et al*., (2022) showed that the time to failure of gas compressor followed the Weibull distribution function more than exponential distribution function. Al-Duais *et al*., (2022) also found that the Weibull distribution function performed better for reliability analysis and description of failure rate. Conclusively, the application of the WCDF and ECDF highlighted the importance of distribution function for scheduling of preventive maintenance activities.

4. CONCLUSION

This study evaluated the reliability of natural gas compressing system at Soku and Obigbo gas stations in Rivers State of Nigeria based on historical data of failures using exponential cumulative distribution function (ECDF) and Weibull cumulative distribution function (WCDF). Based on the results, it was concluded that:

1. The frequency failures and maintenance activities at Soku and Obigbo natural gas compression stations varies over time. Thus, the mean time between most maintenance activities at the gas stations occurred within a short interval. This indicates a high frequency of failures in the compressing systems. Therefore, the mean time between consecutive failures influenced the overall performance and reliability of the compressors at the gas stations.
2. The historical data are significant for the reliability analysis and evaluation of the compressor failures, particularly in determining

maintenance and inspection schedules, especially in scenarios where the probability of failure is high.

3. The WCDF slightly showed a better performance in analysing the reliability of the compressing systems than ECDF. However, both models are suitable for application for scheduling of preventive maintenance activities in natural gas compression stations.

Generally, the analysis revealed that effective maintenance practices are crucial for optimal performance and reliability of compression systems at Soku and Obigbo natural gas stations. Hence, WCDF or ECDF can be applied to improve the performance of the compressing system through evaluation of failure that will result in useful information on the system reliability.

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