Analysis of Optimal Maintenance Interval Determination For Liquid oxygen Pump Assembly P-805A At PT Gresik Gases Indonesia Using Reliability Centered Maintenance and Age Replacement Methods

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Abstract.
The Liq O2 Assy P-805A pump is a critical rotating equipment in the Air Separation Unit (ASU) plant of PT Gresik Gases Indonesia, which transfers liquid oxygen from tank T-80C to tank T-80D. Failure records show that the mechanical seal of the pump leaks repeatedly, causing downtime and disrupting product distribution to key customers such as PT Smelting. A previous study applied Reliability Centered Maintenance (RCM) to determine the maintenance policy but did not answer the question of the optimal replacement time. This study extends that analysis by adding the Age Replacement method based on downtime minimization. The data are failure records for 2022–2026, comprising eight failures and seven times between failures. The RCM analysis shows that mechanical seal leakage has the highest Risk Priority Number (RPN = 320) and is therefore the main priority for scheduled maintenance. The Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) are 5,033.14 hours and 15.5 hours, respectively. The data follow a Weibull distribution with a shape parameter (β) of 0.96 and a scale parameter (η) of 4,948.25 hours. A β value close to one indicates that failures of the pump tend to be random. Because the downtime-minimization model does not give a clear optimum under this condition, the preventive interval was determined from a reliability target. Taking the effective component lifetime into account, at a reliability level of 90% the pump is recommended to undergo early preventive renewal of the mechanical seal at an interval of ±478 operating hours (±20 days). This policy is considered economically efficient because it is equivalent to saving one cycle of component expenditure and maintenance labor wages.
Keywords: *Age Replacement, Component Lifetime, Mean Time Between Failures, Mean Time To Repair and Reliability Centered Maintenance.*

I. INTRODUCTION

PT Gresik Gases Indonesia is a company engaged in the production and supply of industrial gases, such as oxygen, nitrogen, and argon, which are produced through air separation in an Air Separation Unit (ASU) plant. The company operates the ASU plant continuously to supply the liquid oxygen demand of its customers in a stable manner. One of the products supplied to customers is liquid oxygen (LOX), so the transfer and distribution of liquid oxygen is an important activity that must run continuously so that customer demand, including that of PT Smelting, can be met reliably.

The distribution of liquid oxygen in the ASU plant of PT Gresik Gases Indonesia relies on the Liq O2 Assy P-805A pump. This unit is a rotating equipment in the form of a centrifugal pump that transfers liquid oxygen from tank T-80C to tank T-80D. As the only equipment supporting the transfer of the main product, a failure of this pump has a significant impact on the stability of the company's business. Whenever a failure occurs, the distribution of liquid oxygen to customers stops abruptly. This condition not only lowers the service reliability of the company but also causes operational losses through accumulated unscheduled downtime and rising emergency repair (corrective maintenance) costs. The characteristics and frequency of pump failures from January 2022 to January 2026 are presented in Table 1.

Table 1. Failure history data of the Liq O2 Assy P-805A pump (Source: internal data of PT Gresik Gases Indonesia)

No	Date	Type of Failure	Component	Downtime
1	10/01/2022	Mechanical Seal Leak	Mechanical Seal	32 hours
2	11/02/2022	Mechanical Seal Leak	Mechanical Seal	32 hours
3	08/03/2022	Mechanical Seal Leakage	Mechanical Seal	12 hours
4	15/04/2022	Mechanical Seal Leak	Mechanical Seal	12 hours
5	10/09/2022	Mechanical Seal Leak	Mechanical Seal	12 hours
6	27/07/2023	General Leak	Pump System	8 hours

No	Date	Type of Failure	Component	Downtime
7	06/05/2024	Oil Leak	Lubrication System	4 hours
8	17/01/2026	Seal Leakage	Mechanical Seal	12 hours
Average				**15.5 hours**

Table 1 shows that the pump failed eight times with a total downtime of 124 hours (about 5.2 days), an average of 15.5 hours per failure, and a longest repair time of 32 hours. Mechanical seal failures occurred in 6 of the 8 events (75%) and accounted for 112 of the 124 hours of downtime (about 90%), making the mechanical seal the component that fails most often. The leakage is attributed to poor cooldown, dry running, improper installation of components, the use of non-original parts, and insufficient inspection before operation.

Each failure of the pump reduces the flow of liquid oxygen to customers, so the continuity of product distribution is disrupted. With repairs lasting up to 32 hours on a system that operates continuously, the disruption lasts quite long. For the company, this condition may cause the supply to customers such as PT Smelting to go unfulfilled, reduce service reliability, and require emergency repairs by the maintenance team.

The maintenance system currently applied to the pump is still corrective maintenance, i.e., repairs are carried out only after a failure has occurred. This condition risks unscheduled downtime and higher repair costs than preventive action. An earlier investigation conducted on an identical system utilized a Reliability-Centered Maintenance (RCM) framework to determine operational behaviors, systemic malfunctions, and structural damage forms, while establishing subsequent preservation guidelines through Failure Mode and Effect Analysis (FMEA) along with Risk Priority Number (RPN) scores. That study recommended scheduled maintenance, condition-based maintenance, and routine inspection for several failure modes, but it did not answer the important operational question of when the critical component should be replaced.

Previous studies show that RCM has been widely applied to determine maintenance policies for various types of production machines [1], [2], [3], [4], [5], [6] , including pumps [7]. In continuous industries, RCM-based preventive maintenance has been shown to be effective for vital plant subsystems such as filter press machines, in order to determine optimal maintenance intervals and reduce unscheduled downtime [8]. Reliability-based preventive maintenance policies are also important for evaluating the root causes of production machine failures and for minimizing the accumulated downtime caused by mechanical damage [9]. Studies on the efficiency of RCM-based preventive maintenance are also often combined with performance indicators of machine effectiveness to see the overall impact of downtime reduction [10]. However, RCM essentially stops at determining the type of maintenance policy and does not quantify the optimal replacement interval. To overcome this limitation, several researchers have combined RCM with the Age Replacement method, which determines the replacement interval of a component based on its failure distribution [11]. Age Replacement has also been applied on its own to various machines to determine replacement intervals of critical components [12], including centrifugal pumps [13], [14]. RCM has likewise been shown to be effective for determining periodic maintenance policies for material handling equipment such as cranes [15], and for components of continuously operating plant utility systems in order to minimize the risk of production interruption [16].

Considering the impact of mechanical seal failure on the continuity of liquid oxygen supply and on company performance as described above, a measured determination of maintenance time is needed so that failures can be prevented before they occur. Hence, this investigation builds upon earlier research by integrating RCM frameworks with Age Replacement modeling specifically for the Liq O2 Assy P-805A equipment. The RCM scheme serves to map systemic operations and damage profiles while structuring core preservation tasks, whereas the Age Replacement application calculates the most efficient component swap frequencies centered on containing system outages, bypassing the need for corporate financial records. The primary academic contribution of this work stems from executing this hybrid maintenance approach on a cryogenic distribution pump within the industrial gas sector, a specific configuration that remains underrepresented in existing literature.

The primary targets of this academic work involve: (1) mapping out the operational behaviors, systemic functional drops, and specific failure categories of the Liq O2 Assy P-805A machinery via RCM execution; (2) establishing the most effective preservation strategy derived from the RCM evaluation; and (3) determining the most efficient component replacement timeline through Age Replacement models to optimize overall system availability.

II. METHODS

Research Design and Data

This research is a case study with a quantitative approach. The data consist of primary data (interviews and observations concerning the function of the machine, the causes of failure, and maintenance actions) and secondary data (the machine failure history for 2022–2026).

Research Stages

The research was carried out in the following stages: (1) identification of the machine functions and functional failures; (2) identification of failure modes and FMEA analysis to obtain the RPN values; (3) determination of the maintenance policy based on the RCM results; (4) calculation of MTBF and MTTR from the failure history data; (5) statistical evaluation of the Time To Failure (TTF) metrics across Weibull, lognormal, normal, and exponential frameworks, where selection follows the lowest AIC score alongside Kolmogorov–Smirnov (K-S) validation; (6) determination of the optimal replacement interval (t_p^*) using the downtime-based Age Replacement model, with T_f taken from the actual MTTR (15.5 hours) and T_p taken from the estimated time of a preventive replacement action, which is shorter than that of a corrective action; and (7) drawing conclusions and recommending the maintenance policy. Research limitation: the Age Replacement analysis was carried out using a downtime-minimization approach rather than a cost-minimization approach, so the company's maintenance cost data were not used.

Reliability Centered Maintenance (RCM)

The RCM architecture provides a systematic framework to construct optimized equipment preservation roadmaps derived from operational targets, failure characteristics, structural damage sources, and the systemic effects of outages [3]. This methodology encompasses a clear sequence of identifying system targets, functional declines, failure mechanisms, deploying FMEA evaluations, indexing RPN ranks, and establishing the final preservation tasks.

Failure Mode and Effect Analysis (FMEA)

FMEA functions as a diagnostic instrument designed to isolate and grade prospective machine faults along with their operational consequences, directly reinforcing the failure identification phase within RCM [6]. According to Sihombing et al. [17], this analysis evaluates three primary criteria: Severity (S) for indexing fault consequence intensity; Occurrence (O) for estimating failure probability; and Detection (D) for measuring the capability to intercept anomalies before damage materializes. These three criteria are indexed on a 1-to-10 rating metric utilizing the operational definitions defined in Table 2.

Table 2. Rating scale for Severity, Occurrence, and Detection (adapted from Sihombing et al. [17])

Rating	Severity (S)	Occurrence (O)	Detection (D)
1–2	Very low: does not affect operation	Very rare: almost never occurs	Very easy: failure is very easy to detect
3–4	Low: minor disturbance to operation	Rare: occurs occasionally	Easy: failure is fairly easy to notice
5–6	Moderate: production slightly disturbed	Moderate: occurs several times	Moderate: failure is sometimes difficult to notice
7–8	High: production significantly disturbed	Frequent: occurs often	Difficult: failure is hard to detect
9–10	Very high: machine stops completely or is hazardous	Very frequent: occurs very often	Very difficult: failure cannot be detected

The S, O, and D ratings were determined through collaborative discussion (brainstorming) involving operators and maintenance technicians who understand the operating conditions and maintenance activities of the Liq O2 Assy P-805A pump. Plant operators assigned scores drawing from their empirical insights in handling the equipment daily, whereas the engineering personnel determined their metrics from historical machine verification records, system upkeep logs, and technical restoration activities. Each failure mode was assessed using the historical failure data and the interview results, with the rating criteria in Table 2. If the ratings differed, further discussion was held considering the historical failure data, the experience of the operators, and the expertise of the maintenance technicians, and the final S, O, and D values were set by consensus. If consensus could not be reached, the highest rating was used as a precaution in determining the priority of failure risk.

The three ratings are multiplied to obtain the RPN as follows:

$$RPN = S \times O \times D \quad (1)$$

where S, O, and D are the Severity, Occurrence, and Detection ratings, respectively. The RPN is used as the basis for prioritizing each failure mode, so that the component with the highest RPN becomes the main priority in preparing the maintenance strategy [18].

Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR)

MTBF is the average operating time between failures, whereas MTTR is the average time required to repair the machine after a failure [19]. Both parameters are the basis of the reliability analysis of systems and components. They are calculated as follows:

$$MTBF = \frac{\sum_{i=1}^{n} TTF_i}{n} \quad (2)$$

$$MTTR = \frac{\sum_{j=1}^{m} TTR_j}{m} \quad (3)$$

where TTF_i is the time between failure i−1 and failure i (hours), n is the number of intervals between failures, TTR_j is the repair duration of failure j (hours), and m is the number of failures. A high MTBF indicates good reliability because the intervals between failures are longer [2], while a small MTTR indicates that repairs are carried out faster so that machine downtime can be minimized [20].

Age Replacement

Age Replacement is a method for determining the interval of preventive component replacement based on the age of the component, with the aim of minimizing downtime or maintenance cost [19]. The method assumes that a component is replaced preventively at an interval t_p (hours), or replaced correctively if the component fails before reaching t_p. The optimal replacement interval (t_p^*) is the value of t_p that minimizes the downtime rate $D(t_p)$. In the downtime-based Age Replacement model, $D(t_p)$ is formulated as follows [19]:

$$D(t_p) = \frac{T_p \cdot R(t_p) + T_f \cdot (1 - R(t_p))}{\int_0^{t_p} R(t)dt} \quad (4)$$

where $D(t_p)$ is the downtime rate, i.e., the hours of downtime per operating hour at replacement interval t_p; T_p is the downtime due to a preventive replacement (hours); T_f is the downtime due to a corrective replacement (hours); $R(t_p)$ is the reliability of the component at age t_p; and R(t) is the reliability function of the component as a function of time t (hours). R(t) is obtained from the failure distribution (Weibull, lognormal, normal, or exponential) that best fits the historical TTF data. The distribution is selected through goodness-of-fit tests such as the K-S test or by comparing AIC values among distributions [19].

If the estimated shape parameter of the Weibull distribution is $\beta \leq 1$, the failure rate of the component is constant or decreasing (not a wear-out pattern), so the downtime-minimization model does not necessarily yield an interior minimum. Under this condition, the preventive replacement interval can be determined in a practical way using a reliability-target approach, i.e., the interval t_p at a specified reliability level. The Weibull reliability function is given by [13], [14]:

$$R(t) = exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \quad (5)$$

where β is the shape parameter and η is the scale parameter (hours). The interval t_p at a target reliability $R(t_p)$ is obtained by solving Eq. (5) for t, which gives:

$$t_p = \eta\left[-ln\, R(t_p)\right]^{\frac{1}{\beta}} \quad (6)$$

III. RESULT AND DISCUSSION

Identification of Functions and Functional Failures

The Liq O2 Assy P-805A pump functions to transfer liquid oxygen from tank T-80C to tank T-80D continuously. Based on observations and interviews, the component that fails most often is the mechanical seal, whose main functional failure is the inability of the pump to transfer liquid oxygen optimally due to leakage at the mechanical seal.

FMEA and Risk Priority Number (RPN) Analysis

The RPN values were calculated with Eq. (1) from the S, O, and D ratings determined as described in Section II.D. The results of the FMEA of the Liq O2 Assy P-805A pump are presented in Table 3.

Table 3. FMEA of the Liq O2 Assy P-805A pump

Component	Failure Mode	Failure Effect	Cause	S	O	D	RPN
Mechanical Seal	Leakage	LOX flow decreases	Worn mechanical seal	8	8	5	320
Mechanical Seal	Leakage	Distribution disrupted	Worn mechanical seal	8	7	5	280
Mechanical Seal	Leakage	Pump downtime	Dry running	9	6	5	270
Lubrication System	Oil Leak	Pump system damage	Gasket/oil seal damaged	6	4	4	96
Pump System	General Leak	Fluid loss	System leakage	7	4	5	140

Table 3 shows that mechanical seal leakage caused by a worn mechanical seal has the highest RPN, 320, obtained from a Severity of 8, an Occurrence of 8, and a Detection of 5. The high RPN indicates a level of risk that needs to be prioritized in maintenance activities.

Mechanical seal leakage affecting distribution has an RPN of 280, while failure due to dry running has an RPN of 270. Both failures also show that problems with the mechanical seal need attention when preparing the maintenance policy of the pump.

Meanwhile, failure of the lubrication system in the form of an oil leak has an RPN of 96, and a general leak in the pump system has an RPN of 140. Although their RPN values are lower than those of the mechanical seal failures, both failure modes still need attention in inspection and maintenance activities.

Thus, the mechanical seal is determined to be the critical component based on the FMEA because it has the highest RPN. This component is then the focus of the Age Replacement analysis with the objective of formulating optimized preemptive swap frequencies derived from its failure characteristics and the reliability target.

Determination of the Maintenance Policy

Derived from the structured RCM evaluation, the suggested asset care strategies include proactive maintenance for the mechanical seal (highest RPN), condition-based maintenance, routine inspection, and preventive replacement of components of the lubrication system. The scheduled maintenance of the mechanical seal is then reinforced quantitatively by the Age Replacement interval calculation.

Calculation of MTBF and MTTR

Based on the history of 8 failures with a total repair time of 124 hours, the MTTR is 15.5 hours. Based on 7 intervals between failures with a cumulative operating time of 35,232 hours, the MTBF is 5,033.14 hours. The detailed data on the time between failures and the operating duration are presented in Table 4.

Table 4. Time To Failure (TTF) data of the Liq O2 Assy P-805A pump

No	Failure Interval (Time To Failure)	Duration (days)	Duration (hours)
1	10/01/2022 – 11/02/2022	32.0	768.0
2	11/02/2022 – 08/03/2022	25.0	600.0
3	08/03/2022 – 15/04/2022	38.0	912.0
4	15/04/2022 – 10/09/2022	148.0	3,552.0
5	10/09/2022 – 27/07/2023	320.0	7,680.0
6	27/07/2023 – 06/05/2024	284.0	6,816.0
7	06/05/2024 – 17/01/2026	621.0	14,904.0

Note: duration in days is converted to hours with the standard assumption of 1 day = 24 hours.

Table 4 shows a very significant change in the intervals between failures (Time To Failure) that calls for closer analysis of the actual conditions in the field. In the initial period (data 1 to 3), failures of the mechanical seal occurred within relatively short and consistent intervals of 600 to 912 hours (25 to 38 days).

However, a large increase in failure-free duration appears at the transition from data 3 to data 4, where the operating time of the pump before failure rose sharply to 3,552 hours (148 days), about 4.7 times the average of the initial period (760 hours). This increase in component reliability continues at data 5, where the operating duration reaches 7,680 hours (320 days), about 2.2 times that of data 4. The longest failure-free duration is recorded at data 7, at 14,904 hours (621 days), more than twice that of the preceding interval (6,816 hours).

Technically and operationally at PT Gresik Gases Indonesia, the increasingly long operating durations indicate a gradual improvement in the quality of maintenance handling of the Liq O2 Assy P-805A pump. In the first three periods, the high frequency of failure was triggered by fundamental technical problems such as poor cooldown before the pump was started, dry running, installation precision errors, and the use of non-original components.

The sharp increase in failure-free duration from data 4 to data 7 indicates that the maintenance team of the company has applied effective corrective actions in the field. These actions include tightening the cooldown procedure standards to prevent thermal shock to the pump, minimizing the risk of fluid loss (dry running), improving competence in the installation precision of the seal, and a commitment to consistently using original spare parts. This improvement in maintenance management explains why the mechanical seal was able to last much longer in the later years of the observation. In line with the theory in Section II.E, the increasingly long intervals represent an improvement in the reliability of the system.

In terms of component lifetime, the large increase in failure-free duration at the end of the period shows that the corrective actions, in the form of installation accuracy and the use of original parts, succeeded in extending the effective service life of the mechanical seal toward its optimal economic life limit. This is also supported by the MTTR of 15.5 hours, which suggests that repairs were carried out comprehensively to restore the component to its original reliability level (reliability growth) rather than as a quick fix. This extension of component life through quality maintenance intervention explains why the failure pattern of the pump eventually shifted to random failure.

Time To Failure Distribution Test

The TTF data in Table 4 underwent statistical evaluation using four unique probability functions (including Weibull, lognormal, normal, and exponential shapes) using Maximum Likelihood Estimation (MLE), with the best distribution identified through the minimum AIC score and subsequent Kolmogorov–Smirnov validation, followed by the comprehensive dataset display compiled inside Table 5.

Table 5. Results of the Time To Failure distribution test

Distribution	Parameter	AIC	K-S Statistic	K-S *p*-value
Weibull	$\beta = 0.96$; $\eta = 4{,}948.25$ hours	139.32	0.250	0.687
Lognormal	$\sigma = 1.19$; μ (scale) = 2,741.73 hours	139.17	0.251	0.686
Normal	$\mu = 5{,}033.14$; $\sigma = 4{,}849.74$ hours	142.68	0.231	0.776
Exponential	$\lambda^{-1} = 5{,}033.14$ hours	137.33	0.263	0.628

Table 5 shows that all distributions have K-S *p*-values above 0.05, so statistically all of them are acceptable for describing the TTF data. The Weibull distribution was chosen as the basis of the analysis because it is the distribution most commonly used in Age Replacement analysis and is more general (it approaches the exponential form at $\beta \approx 1$). The estimated shape parameter (β) is 0.96, which is close to 1. This value indicates that the failure rate (hazard rate) of the mechanical seal is relatively constant over time, so failures are dominated by random factors, such as installation errors, dry running, or the use of non-original parts, rather than by a wear-out pattern that increases with the age of the component.

This random failure characteristic is also consistent with the analysis in Section III.D, where the surge in the duration between failures in the later period resulted from periodic improvements in technical handling by the maintenance team, not from a linear wear pattern of the component.

This finding has an important implication for the application of Age Replacement: when $\beta \leq 1$, the downtime-minimization function $D(t_p)$ in Eq. (4) does not yield a clear interior minimum (the downtime rate tends to decrease as t_p increases), so determining the preventive replacement interval purely by downtime optimization is less relevant under random failure. Therefore, the maintenance interval in this study was determined with the reliability-target approach, i.e., the interval t_p at a specified reliability level, using Eqs. (5) and (6).

Maintenance Interval Based on the Reliability Target

The preventive maintenance interval was calculated using the Weibull reliability function in Eq. (5) with $\beta = 0.96$ and $\eta = 4{,}948.25$ hours, at several specified reliability levels. The results are presented in Table 6.

Table 6. Preventive maintenance intervals at several reliability targets

Reliability Target R(t)	Interval (days)	Interval (hours)
95%	9.4	226.4
90%	19.9	478.1
85%	31.2	749.9
80%	43.4	1,042.3

Considering the considerable operational impact if the pump fails (disruption of liquid oxygen distribution to PT Smelting), this study recommends a reliability target of 90% as the reference for the preventive replacement policy, namely replacement or comprehensive inspection of the mechanical seal at an interval of ±478 operating hours (±20 days). This interval is much shorter than the actual mean time between failures (MTBF = 5,033.14 hours), so theoretically it can reduce the risk of unexpected failure, although the consequence is a higher frequency of preventive maintenance activities.

According to the standard specifications of the manufacturer, the economic life of a mechanical seal under ideal conditions is generally designed to be much longer (in the range of thousands of hours). Nevertheless, the ±20-day interval resulting from the reliability-target calculation remains important for the company to apply as a conservative preventive maintenance measure. In terms of component lifetime, early replacement at an interval of ±20 days aims to renew the physical condition of the component before it enters the critical phase of random failure, so that the accumulated reliability of the pump remains high without waiting for the component to reach the end of its physical service life.

Although this study is based on a downtime-minimization approach without processing the financial data of the company, the preventive action time (T_p) scheduled at this interval indirectly represents operational cost efficiency equivalent to one cycle of expenditure on purchasing a new component and on

maintenance labor wages. Such scheduled preventive replacement is expected to be far more advantageous economically than the large financial losses caused by a sudden breakdown. The risk of loss from unscheduled failure includes loss of revenue opportunity during long repairs and potential penalties for interrupting the continuity of liquid oxygen supply to major customers such as PT Smelting. On this basis, the company should consider the trade-off between the frequency of periodic preventive maintenance and the potentially large impact of operational losses when setting its final maintenance policy in the field.

IV. CONCLUSION

Culminating from the systemic evaluation, the empirical evidence demonstrates that the failure mode with the highest risk in the Liq O2 Assy P-805A pump is mechanical seal leakage caused by a worn mechanical seal, with an RPN of 320, for which the recommended maintenance policies are scheduled maintenance, condition-based maintenance, and routine inspection. The MTBF and MTTR are 5,033.14 hours and 15.5 hours, respectively, and the Time To Failure data show a marked increase in failure-free duration, reaching 14,904 hours at the end of the observation period. This trend represents good component lifetime characteristics and indicates that the comprehensive repair quality and the corrective actions of the field maintenance team restored the reliability of the system and delayed physical failure before the standard economic life limit of the manufacturer was reached.

The distribution test shows that the historical breakdown records are best characterized by a Weibull mathematical profile showing parameters $\beta = 0.96$ and $\eta = 4{,}948.25$ hours, which indicates a tendency toward random failure. Therefore, the preventive maintenance interval was determined from a 90% reliability target, namely ±478 operating hours (±20 days). This conservative renewal policy is expected to benefit the company by saving estimated expenditure equivalent to one cycle of component cost and technician wages, while mitigating the risk of large financial losses from a potential interruption of liquid oxygen supply to major customers. Future research is recommended to complete the data with the actual downtime of preventive actions and to consider a cost-based Age Replacement approach when maintenance cost data are available.

V. ACKNOWLEDGMENTS

The author expresses his deepest gratitude to the Department of Industrial Engineering within the Engineering Faculty at Universitas Muhammadiyah Gresik for offering institutional resources that enabled this academic study to be successfully finalized. The author expresses his deep appreciation and respect to. Elly Ismiyah, S.T., M.T., as a supervisor who always takes the time to provide direction, constructive criticism, and very valuable guidance during the manuscript preparation process. The author also expresses his gratitude to the leadership, maintenance department staff, and all operators of the Liq O2 Assy P-805A Pump at PT Gresik Gases Indonesia who have provided permits, technical assistance, and access to historical data on machine damage which is very crucial for the smooth analysis in this study. The author's infinite gratitude and highest appreciation are offered to his parents and the entire beloved extended family, who always provide prayers, outpourings of affection, moral support, and endless motivation during the process of compiling this work. Not to forget, the author expresses his appreciation to his fellow Industrial Engineering students of the University of Muhammadiyah Gresik and all comrades who have provided technical assistance, enthusiastic support, and constructive discussion space during the lecture period and the completion of this research.

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