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Reliability-Centered Maintenance Analysis on a Single-Stage Water-Cooled Oil-Injection Screw Compressor

T. M. Odi-Owei, J. C. Ofodu, E. G. Saturday, M. S. Torbira
Department of Mechanical Engineering, University of Port Harcourt, Nigeria.

Abstract*— Reliability-centered maintenance (RCM) is applied to analyze a single-stage water-cooled oil-injected rotary screw compressor situated in one of Nigeria's offshore installations. Its eleven critical components were examined for a fifteen-month period from December 2020 to February 2022 with aggregated monthly running hours of 38723.993. Downtime period due to four significant component failures were in April, May, November and December 2021, during which the standby compressor of same model was put in service. This maintenance analysis is comprised of two sections: qualitative and quantitative (mixed method). First, the qualitative approach employed decisive tools like failure modes, effects, and criticality analysis (FMECA) and logic tree analysis (LTA) in accordance with Hinchcliffe and Smith's procedure to develop technically feasible maintenance tasks. Through these frameworks, answers to the seven RCM questions were demonstrated for conformance to SAE JA1011-specified standard RCM process. Second, the quantitative aspect studied critical components by incorporating reliability characteristics like failure rates, mean time between failures (MTBFs), reliability function, availability, maintainability with running hours from compressor in-service data. Evaluation of critical components with reliability characteristics enabled clear understanding, while considering whether or not failure(s) occurred. Altogether, the study analyzes the functionality of the compressor and suggests proactive maintenance tasks for improvement within its operating context via RCM.*

Keywords*— RCM, FMECA, LTA, MTBFs, reliability characteristics.*

I. INTRODUCTION

Compressors play important roles in diverse industries. The commonality of all compressors' working principle—increasing air or gas pressure while simultaneously reducing its volume—makes them prevalent [1]. As a device, they generate pneumatic energy from mechanical energy [2]. Due to their industrial significance, an effective maintenance philosophy like RCM is beneficial to preserve its function. RCM is a methodical and organized process for creating a maintenance schedule that mitigates likelihood of failures for an identified asset [3]. RCM of a single-stage water-cooled oil-injected air compressor installed in an offshore installation in the Niger Delta is the subject of this study. As with traditional reliability techniques, essential components constituting the screw compressor are analyzed qualitatively through an RPN-based FMECA and LTA. These critical components are control panel, electric motor, compressor element (airend), air filter, unloader, solenoid valve, air/oil separator, heat exchangers (aftercooler and oil coolers), oil filters, water separator and safety valve. The first objective is to provide answers to the seven RCM questions outlined in SAE JA1011 [4] to confirm that this RCM procedure complies with prescribed standards. The second is to develop a wide-ranging FMECA to aid achieve the third objective, which is the formulation of technically feasible maintenance tasks and intervals via LTA in Hinchcliffe & Smith's [5] approach. Through compressor in-service data, quantitative aspects of the analysis infer and show trends between failed and non-failed critical compressor components, together with some reliability characteristics. These characteristics are failure rates, MTBFs, reliability, availability, maintainability, probability density and cumulative distribution functions.

Several works on compressor maintenance have been published. The RCM methodologies and principles were applied by Narnaware *et al*. [6] to a specific thermal power plant's air compressor. Following the application and analysis of RCM, PM from RCM was created and compared with schedules of the presently operating plant. Compressor component failures and maintenance costs were seen to be reduced or eliminated as a result. The next failure time of a gas compressor was demonstrated using Markov's model, according to Cho *et al*. [7], who studied earlier literatures on offshore predictive plant maintenance. Cho *et al*. [8] investigated methods for predicting an offshore gas compressor's next time of failure. They envisaged that the analysis would be useful to offshore operation companies in improving maintenance planning and reducing machinery downtime due to unanticipated failures. A multipurpose outline for preserving and improving an industrial air compressor functionality while lowering the risk of failure(s) was offered by Verma & Singh [9]. The accomplished case studies demonstrated that air compressor maintenance and operational tasks can simultaneously be optimized. Spüntrup *et al*. [10] analyzed and demonstrated compressor reliability improvement using the offshore and onshore reliability data (OREDA) project. Maintenance prioritizations were, however, suggested with the aid of Pareto analysis. Seleiyi *et al*. [11] utilized Chi test technique, Lognormal model, Weibull probability distributions to conduct a reliability-based analysis of a process air compressor. According to their findings, incorporating closed-watch condition-based approaches to PM activities improved plant efficiency at the Indorama petrochemical company. Tupake *et al*. [12] adopted compressed air systems to implement an RCM procedure. They showed that there was less delay needed between a plant equipment failing and the possibility of an unplanned equipment failure. Elvian *et al*. [13] applied FMEA as well as LTA qualitative reliability tools to study the impact and timing of screw compressor component failures. Using sequence labeling technology, Chen *et al*. [14], established a standard dataset for extracting information from maintenance log sheets in order to diagnose air compressor faults. Their findings revealed significant promise for the fields of named entity recognition (NER) and sequence labeling (SL) in the identification of compressor anomalies. In order to identify impending compressor failures, Tahir & Akin [15] used condition monitoring and industrial internet of things (IIoTs). This helped to reduce compressor downtime and thereby improve reliability. A quick overview of an air compressor, its uses, overhauling, condition monitoring and the maintenance schedules for a reciprocating compressor was provided by Hussain [16]. Nithin *et al*. [17] presented an RCM-focused framework for asset cost optimization through statistical and probabilistic exploration by way of a centrifugal gas compressor.

II. METHODOLOGY

A. System Selection and Data Collection

It might be too radical and resource-intensive [18] to apply RCM to the entire screw compressor. Therefore, this analysis selects critical items. Component criticality covers failure consequences including operational performance, safety and environment. Nevertheless, BS EN 60300-3-11:2009 includes cost effectiveness. OEM literatures, competent personnel and operating data formed part of data collection methods. Pareto's 80/20 rule is also considered. Example, a compressor component (20%) can cause severe consequences like costly part damage, production interruption or even plant shutdown (80%). Thus, the compressor is critical and justifies an RCM program.

B. System Boundary Definition

Recognizing boundaries of critical components identifies input/output interfaces. Boundaries represent the item-surrounding interactions that make up the operational context of the system [19] and define its scope [20]. Boundaries support organization and preciseness of items in analysis. Figure 1 illustrates the compressor's boundary overview.

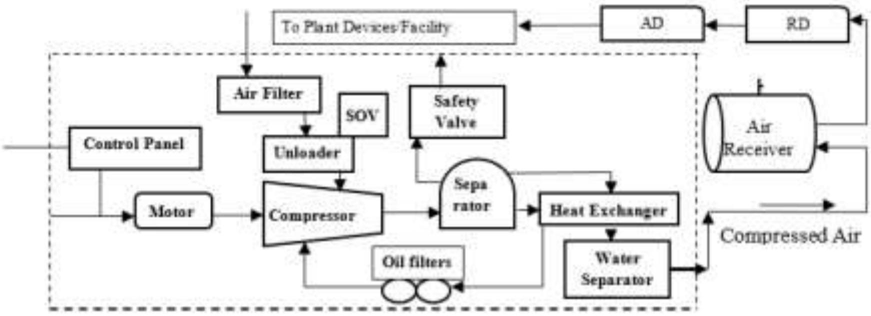

Figure 1: Boundary diagram of compressor assembly

C. System Description and Functional Block Diagram

The single-stage oil-injected screw compressor is a member of the marine compressed air system located in the engine room onboard the FPSO. Air is admitted through its filter to the compressor element, where it is compressed along with lube oil for sealing. Air and lube oil are then separated in the air/oil separator and then cooled by the heat exchangers – aftercoolers and oil coolers. Compressed air is now discharged and oil returns for the compression process again. It is designed to produce a maximum pressure of 13 bar(g) through a drive speed of 1784 r/min for 144/193 kW/hp via a 150kW electric motor. Figure 2 shows the functional block diagram of critical components.

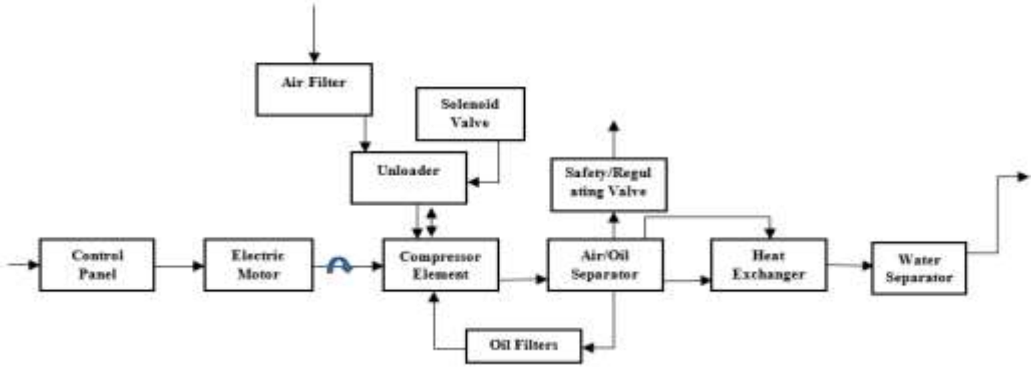

Figure 2: Functional block diagram of compressor components

D. System Function and Functional Failures

This step answers RCM questions 1 and 2 through understanding critical component's "functions" and "failures". As per NAVAIR 00-25-403, functions are the component's intended purpose. Failure of an item, as defined by BS EN 60300-3-11:2009, is the loss of ability to perform. This oil-injected screw compressor is designed to produce air to power pneumatic control devices in the FPSO installation. Table 1 represents component's functions and failures.

TABLE 1: Functional failures of critical components

S/No.	Components	Functions	Functional Failures
1.	Control panel	Electronic control/power source, PLC	Power trip; no signal; earth leakage
2.	Electric Motor	Drives compressor element at 1734 r/min, with 440V at 150kW	High current; unbalanced winding resistance; high temperature
3.	Compressor element	Compress air pressure to 13 bar (g) at 144 kW max.	Screw worn and jammed; leaks from oily seal; bearing noise
4.	Air filter	Filters air entering the compressor assembly	None or partial suction
5.	Unloader	Regulates air intake and compression	Immovable (fixed); oil entry
6.	Solenoid valve	Controls loader/unloader action	Actuation failure/no output; uncontrolled airflow; partial/non output control
7.	Air/oil Separator	Separates compressed air from lube oil; air/oil receiver	Blockage; minimum pressure valve failure
8.	Heat exchangers	Cools lube oil and compressed air	High temperature (no cooling of oil and/or air)
9.	Oil filters	Filter dirt from lube oil	Clogged up dirt
10.	Water separator	Traps water from compressed air line	Moisture; condensate passage in air line
11.	Safety valve	Protects air/oil separator from overpressure	Fail to open/close

E. Failure Modes, Effects and Criticality Analysis (FMECA)

This important qualitative tool answers RCM questions 1 to 5. They constitute critical component's "functions", "failure modes", "effects" and "consequences". FMECA are used for identification and documentation. RPNs are benchmarked at 70, with failed critical items having RPN > 70, implying maintenance prioritization. Action priority codes are more recently utilized than RPNs. The FMECA is presented in Table 2.

F. Logic Tree Analysis (LTA)

At this stage, failure modes of the components are further categorized using this qualitative procedure shown in Figures 3. Based on "YES/NO" answers, maintenance tasks are assigned. RCM questions 6 and 7 are addressed by this decision-making process. It answers these questions by determining if a proactive or default maintenance task(s) are to be assigned to the compressor component(s). This step aims to prioritize resources that could be applied to each failure mode [21]. Failure modes from FMEA serve as its input [22]. The LTA suggests proactive, default and sometimes failure-finding tasks. Considering hidden failures, failure-finding tasks are applied. Example is to the safety valve, since its failure may not be detected until it fails to protect the separator from overpressure. This is the phenomena of multiple failures. Though the later contrasts *occult* failures that happen without notice [23] to the crew.

G. Task Selection

This section is the result of answering and evaluating the entire RCM questions 1 to 7. After the above steps have been applied to compressor components, the LTA-recommended tasks are evaluated under three broad maintenance categories, which according to [24] are proactive, failure-finding and default. In light of RCM, they should all be technically feasible and worth doing. SAE JA1011 and JA1012 amplifies and clarifies tasks' technical feasibility. Task intervals are mostly based on OEM manuals, expert judgment, FMECA and component's operating contexts.

H. Quantitative Reliability Analysis

The following equations are applied to calculate values for the oil-injected screw compressor from the equipment's operating data. They are tabularized in 4 and 5.

Failure rate of critical components (λ) = $\frac{f}{T}$ (1)

Mean Time Between Failures (MTBF) = $\frac{T}{f}$ (2)

Mean Time to Repair (MTTR) = $\frac{Time\ to\ Repair\ (TTR)}{No.of\ Component\ Failures}$ (3)

Reliability Function $R(t) = \ Prob\ \{T\ \geq t\}$

For a given value of *t*, *R (t)* is the probability that the time to failure *T* is greater than or equal to '*t*'. We then define

$$F(t) = 1 - R(t) = Prob\ \{T\ <\ t\} = 1 - e^{-\lambda t} \quad (4)$$

Where F (0) = 0, and $\lim_{t\to\infty} F(t) = 1$, then $F(t)$ refers to the *probability of failure* occurring before time '*t*'. With *f* (*t*), the PDF is exponential, therefore, the various functions can be computed as per [25]:

$$f(t)\ = \lambda(e^{-\lambda t}) \quad (5)$$

The screw compressor reliability (or survival) function $R(t)$, can be calculated exponentially as:

$$R(t) = \int_t^{\infty} \lambda\, e^{-\lambda t}.dt\ =\ e^{-\lambda t} \quad (6)$$

Therefore, $R(t) =\ 1 - F(t)$

Correspondingly, $R(t) + F(t) = 1$ (7)

Incorporating MTBF, the reliability function applied to the oil-injected screw compressor is thus:

$$R(t) = e^{(\frac{-t}{MTBF})} \tag{8}$$

Further, hazard rate can be expressed as $z(t) = \frac{f\,(t)}{R\,(t)} = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda$ (9)

Compressor availability $Availability\ A(t) = \frac{Uptime}{Uptime+Downtime} = \frac{MTBF}{MTBF+MTTR}$ (10)

Compressor maintainability $Maintainability\ M(t) = 1 - e^{\left(\frac{-t}{MTTR}\right)} = 1 - e^{-\mu t}$ …(11)

Where, $Repair\ rate, \mu = \frac{1}{MTTR}$, and MTTR is a figure of merit

III. RESULTS AND DISCUSSION

A. Results from Qualitative RCM Analysis

FMECA with RPNs is illustrated in Table 2 and they provide the developed answers to RCM questions 1 to 5. The questions are: (1) What are the functions of the compressor in its operating context? (2) What are the functional failures? (3) What are the failure modes? (4) What are the failure effects? and (5) Failure consequences? The LTA in Figure 3 then answers RCM questions (6) and (7). Specifically, “What should be done to predict or prevent each component failure?” and “What should be done if no suitable task can be found?” Table 3 presents maintenance tasks and intervals based on OEM recommendations and expert judgment. This satisfies the third objective of the analysis.

TABLE 2: FMECA of screw compressor components

Component	**Function**	**Potential Failure Mode(s)**	**Potential Effect(s) of Failure**	**Severity**	**Potential Cause(s)/ Mechanism(s) of Failure**	**Occurrence**	**Detection**	**RPN**	**Recommended Action(s)**
Control panel (controller)	Powers compressor unit/electronic control source	Power trip; earth leakage	Loss of power; loss of all other functions; electric shock to operator (unsafe effects)	8	High current; loss of insulation on current conducting parts	2	3	**48**	Ensure ambient temperatures & humidity levels; monitoring; inspections
Electric motor	Drives compressor element at 1734rpm, with a 150-kW rated power	Short/open circuit; stud rotor; winding burnout	Inadequate/no compression; loss and/or damage to other functions	6	Low insulation on resistance; water ingress; high voltage; mechanical overload	1	5	**30**	On-condition monitoring; inspections
Compressor element	Compress/increase air pressure at max. 13 bar at 144 kW rated power.	Worn & jammed; screw stucked	No compression; damage to control devices; high noise level; high repair/replacement costs	8	Vibration; misalignment; poor lubrication	1	7	**56**	Yearly inspections by OEM/service reps.; correct lube oil
Air filter	Filters intake air from particles	Poor/no suction	Damage to compressor element; overheating; degraded air quality	7	Dirt; contaminated air; misalignment/adjustment	4	4	**112**	Timely replacements; ensure quality ambient air
Unloader	Regulates air compression	Fail to open/close	High temperature/pressure; damage to separator; compressor trip; operational hazard	8	Pressure switch; faulty solenoid; air filter problem	6	7	**336**	Regular PM; inspections
Solenoid valve	Controls loading/unloading operation	No discharge; no actuation; power loss	Loading/unloading failure; damage to other components; explosion	8	Faulty solenoid; coil damaged; electronic issue	5	8	**320**	Inspections & PM; spares availability
Oil separator/air receiver	Separates compressed air from lube oil	Blockage; minimum safety valve failure	High temperature/pressure; oil ingress in compressed air; damage to devices	9	Oil buildup; carbonization; faulty check valve or separator element	1	4	**36**	Replace 2-yearly; adhere to OEM maintenance schedules;
Heat exchangers (aftercoolers & oil cooler)	Cools compressed air and lube oil	No/insufficient cooling	Elevated oil/air temperatures, damage to oil filters; compressor trip	5	Dirt; blockages; corrosion; aging	1	5	**25**	Clean every 500 running hours; ensure quality fresh water
Oil filters	Filters dirt from lube oil	Damaged or worn out	Degraded component performance; cracked/ruptured/fracture	7	Insufficient/impro-per lubrication damaged oil filters; blockages	2	6	**84**	Timely replacements

			d compressor rotors; high temperature of components						
Water separator (condensate trap)	Removes moisture/water from compressed air line	Water/condensate retention	Water ingress in compressed air; damage to pneumatic control devices; FPSO shutdown	7	Pipe blockages; after-cooler failure; lack of constant drainage	1	6	**42**	Regular monitoring & draining
Safety valve	Protects separator from overpressure	Fail to open/close	Damage to oil separator; operator injury	9	Hidden/occult /power failures; lack of failure-finding tasks	2	3	**54**	Regular inspections; yearly testing; failure-finding

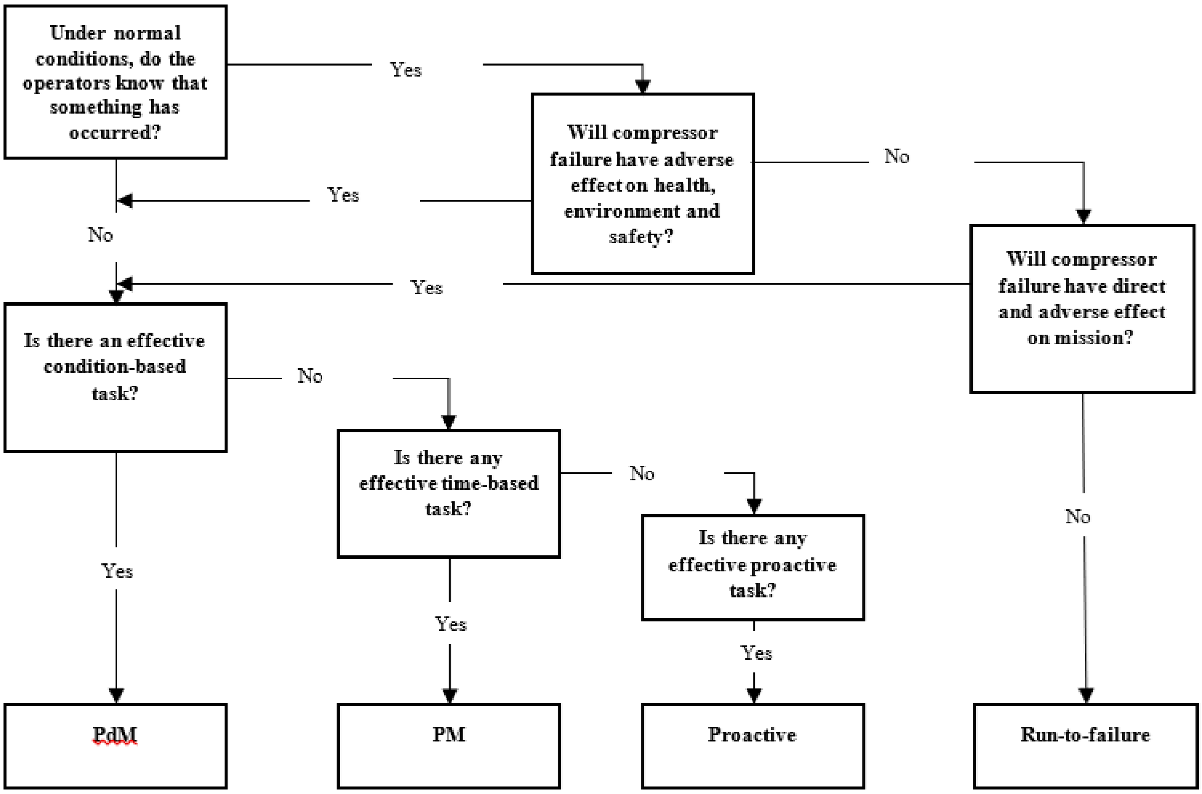

Figure 3: Logic tree diagram for screw compressor

TABLE 3: Proposed maintenance tasks and intervals for compressor components

Proposed Maintenance Task(s) and Intervals

Component	**Current Maintenance Type**	**Maintenance Task**	**Interval**	**Remark**
Control panel	CM	Monitoring and inspections	Weekly	Check connections and switches.
Electric motor	-	CdM and PM	6-Monthly	Regrease motor, check windings, rotor, shaft, etc.
Compressor element	-	Cleaning and inspections/CdM	3 to 6-Monthly	Check screw clearance, vibration, alignment
Air filter	Replacements	Replacements	Yearly or 4000 hours	Replace if damaged or blocked
Unloader	CM	Inspections/PM	Daily/3-monthly	Observe loading/unloading sequence/pressures
Solenoid valve	CM	Inspections/PM/FF	Daily/3-monthly	Inspect and check for faults
Air/oil separator	-	Monitoring/replacements	Daily or 2-yearly	Visual daily checks and replace yearly
Heat exchangers	-	Monitoring/cleaning	Weekly/3-monthly/500 hours	Ensure fresh water intake, check for blockage
Oil filter	Replacements	Inspections and replacements	Yearly/4000 hours	Scheduled replacements if aged or faulty
Water separator	-	Regular monitoring/draining	Daily	Regular cleaning and draining
Safety valve	CM	Inspections/testing/FF	Weekly/yearly/4000 hours	Inspect and test for hidden failures

CM - corrective maintenance; CdM – condition-monitoring; PM – preventive maintenance; FF – Failure-finding

3.2 Results from Quantitative RCM Analysis

Through the running times *T* from compressor operating data, reliability characteristics and indices of critical components were calculated. Individual critical components are compared with a reliability characteristic and indices to demonstrate a relationship within their operating context. Table 4 displays values of compressor reliability characteristics derived from the section on quantitative analysis and the compressor operating data. Table 5 shows further reliability metrics and indices for each critical component to be compared considering failure or no failure(s). Figures 4 through 7 demonstrates how the critical compressor components and reliability characteristics relate to each other in the context of its operation.

TABLE 4: Derived reliability data for critical components

Components	**No. of Failures (*f*)**	**Running Hours (*t*)**	**Failure Rate (λ)**	**Downtime (*Hrs.*)**	**MTBF**	**MTTR**	**[*R*(*t*)]**	**[*A*(*t*)]**	**[*M*(*t*)]**
Control Panel	0	38723.99	0.00000	0.000	38723.99	0.000	1.000	1.000	-
Electric Motor	0	38723.99	0.00000	0.000	38723.99	0.000	1.000	1.000	-
Compressor Element	0	38723.99	0.00000	0.000	38723.99	0.000	1.000	1.000	-
Air Filter	2	38555.99	0.00005	3.000	19277.99	1.500	0.130	0.999	0.991
Unloader	1	37565.99	0.00003	1158	37565.99	1158	0.360	0.970	0.669
Solenoid Valve	1	37307.99	0.00003	1480	37307.99	1480	0.370	0.962	0.616
Air/oil Separator	0	38723.99	0.00000	0.000	38723.99	0.000	1.000	1.000	-
Heat Exchangers	0	38723.99	0.00000	0.000	38723.99	0.000	1.000	1.000	-
Oil Filter	1	38721.99	0.00003	2.000	38721.99	2.000	0.312	0.999	0.632
Water Separator	0	38723.99	0.00000	0.000	38723.99	0.000	1.000	1.000	-
Safety Valve	0	38723.99	0.00000	0.000	38723.99	0.000	1.000	1.000	-

TABLE 5: Reliability metrics for critical components

			Reliability Measures			
Components	***t***	***Λ***	***f(t)***	***F(t)***	***R(t)***	***Z(t)***
Control Panel	38723.99	0.0000000	0.000000	0.000	1.000	0.000000
Electric Motor	38723.99	0.0000000	0.000000	0.000	1.000	0.000000
Compressor Element	38723.99	0.0000000	0.000000	0.000	1.000	0.000000
Air Filter	38555.99	0.0000500	0.000006	0.860	0.140	0.000050
Unloader	37565.99	0.0000266	0.000097	0.640	0.360	0.000258
Solenoid Valve	37307.99	0.0000268	0.000009	0.632	0.368	0.000026
Air/oil Separator	38723.99	0.0000000	0.000000	0.000	1.000	0.000000
Heat Exchangers	38723.99	0.0000000	0.000000	0.000	1.000	0.000000
Oil Filters	38721.99	0.0000258	0.000009	0.632	0.368	0.000025
Water Separator	38723.99	0.0000000	0.000000	0.000	1.000	0.000000
Safety Valve	38723.99	0.0000000	0.000000	0.000	1.000	0.000000

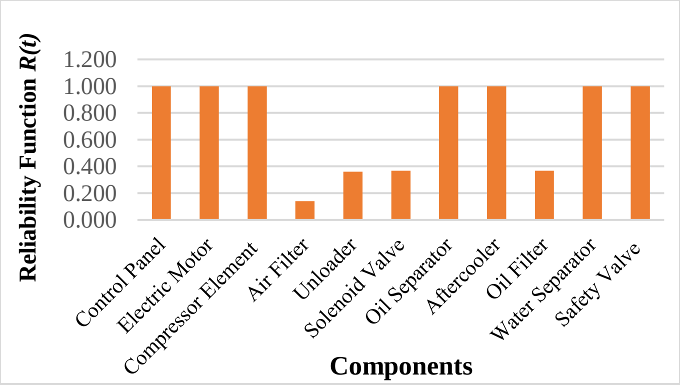

Figure 4: Reliability of components

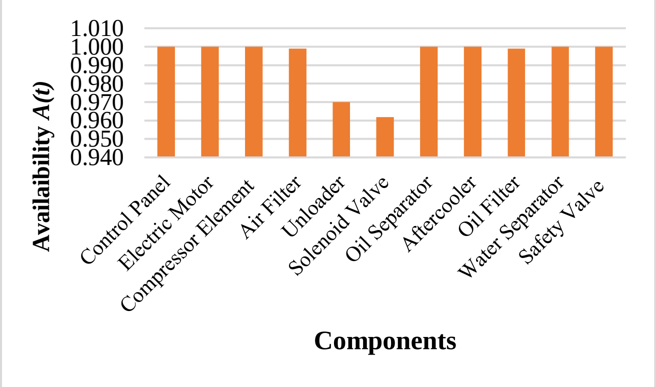

Figure 5: Availability of components

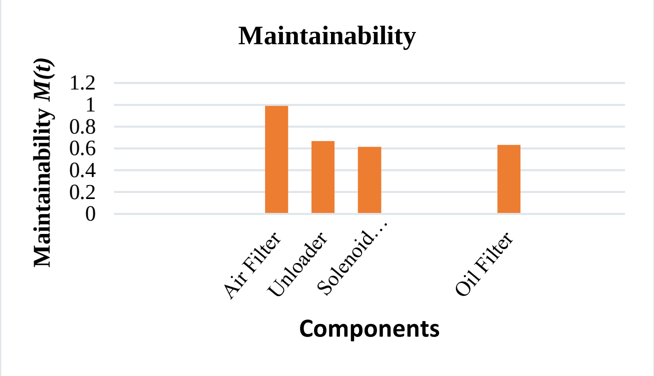

Figure 6: Maintainability of component

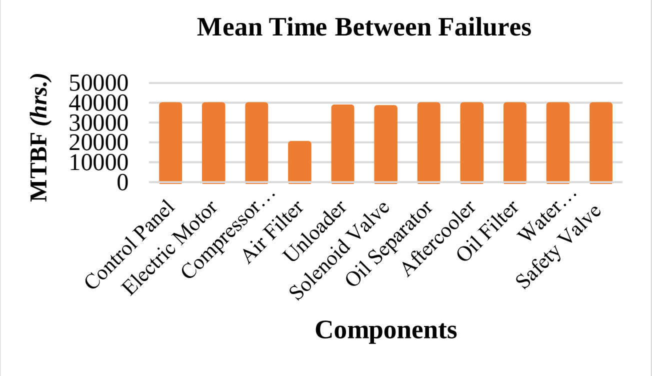

Figure 7: MTBF of components

IV. CONCLUSION

The FMECA and LTA methodology provided answers to the seven RCM decision questions. By examining component functions, functional failures, failure modes, effects, and consequences, an extensive FMECA was developed to address RCM questions 1 through 5. The LTA aided in maintenance task allocation(s), through its YES/NO decision framework, which specifically answered questions 6 and 7. These determined suitable maintenance tasks that should be adopted for the oil-injection screw compressor and served as the qualitative foundation for the RCM analysis through Hinchcliffe and Smith's procedure. Quantitative analysis established relationships between failed and non-failed components through reliability characteristics, such as failure rates, reliability (survivor) functions, availability, maintainability and MTBFs. Components having low reliability had high maintainability due to minimal MTTR and as reliability is concerned with "non-occurrence of complimentary events" [26] in contrast to maintainability. Non-failed component's maintainability was not considered as no failure(s), repair(s) or replacements occurred to measure MTTR. Failed components had low MTBF, reliability and availability. Thus, for reliable compressor performance, components MTBF should be as high as practically possible to achieve improved reliability, availability and maintainability (i.e. low component MTTR). Consequently, the functionality of the compressor will be preserved within its operating context.

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