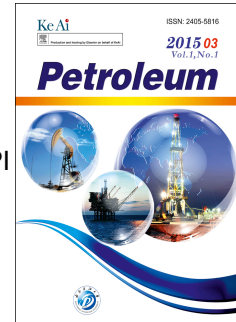


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Reliability, Availability, Maintainability (RAM) study, on reciprocating compressors API 618

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Abstract: The Oil & Gas industry has continuously increased its requirements and together with the high complexity of technological systems and the higher competitiveness of markets, has compelled providers to implement adequate management strategies for these systems in order to improve their availability and productivity to meet those more demanding criteria.

In this context, the complex of RAM factors constitute a strategic approach for integrating reliability, availability and maintainability, by using methods, tools and engineering techniques (Mean Time to Failure, Equipment down Time and System Availability values) to identify and quantify equipment and system failures that prevent the achievement of the productive objectives. The application of such methodologies requires a deep experience and know-how together with the possibility of acquiring and processing data in operating conditions. This paper presents the most relevant aspects and findings of a study conducted for assessing the operational performance of a reciprocating compressor system package installed and used in the oil and gas' industries. The study was based on the analysis of the behaviour of states defined for each individual parts and component of reciprocating compressor and also aimed to identify and evaluate the effects of RAM-type factors and was conducted in collaboration with a private company that, for privacy reasons, will be named RC company. The Methodologies procedures used in this descriptive study were the bibliographical research, documentary and content analysis of the main literature. Adopting the most suitable maintenance strategy is one of the main challenges that maintenance managers face. The main purpose of this work is to propose a new approach to evaluate maintenance strategies.

In this study, three criteria called reliability, availability and maintainability (RAM) have been employed to compare to future maintenance strategies.

Keywords: RAM, reciprocating compressors, maintenance, oil & gas.

1. Introduction

The complex of maintenance activities, methodologies and tools aim to obtain the continuity of the productive process; traditionally, this objective was achieved by reviewing and substituting the critical systems or through operational and functional surplus in order to guarantee an excess of productive capacity. All these approaches have partially shown inefficiencies: redundant systems and excess capacity immobilise capitals that could be used more profitably for the production activities, while carrying out revision policies very careful means to support a rather expensive method to obtain the demand standards [1] (Bevilacqua et al., 2013).

The complex of maintenance activities is transformed from a simple reparation activity to a complex managerial task which main aim is the prevention of failure.

An optimal maintenance approach is a key support to industrial production in the contemporary process industry and many tools have been developed for improving and optimising this task.

The evaluation of components reliability is a fundamental aspect for proper maintenance execution; existing reliability evaluation methods are based on the availability of knowledge about component states. However, component states are often uncertain or unknown, especially during the early stages of the development of new systems. In such cases, it is important to understand how uncertainties will affect system reliability assessment. Reliability of systems often depends on their age, intrinsic factors (dimensioning, quality of components, material, etc.) and conditions of use (environment, load rate, stress, etc.).

In this context, RAM factors constitute a strategic approach for integrating reliability, availability and maintainability, by using methods, tools and engineering techniques (such as Mean Time to Failure, Equipment down Time and System Availability values) to identify and quantify equipment and system failures that prevent the achievement of its objectives.

The majority of industrial systems have a high level of complexity, nevertheless, in many cases, they can be

repaired. Moreover historical and or benchmarking data, related to systems failure and repair patterns, are difficult to obtain and often they are not enough reliable due to various practical constraints. In such circumstances, it is evident that a good RAM analysis can play a key role in the design phase and in any modification required for achieving the optimized performance of such systems. However, it is difficult to estimate the RAM parameters of these systems up to a desired degree of accuracy by utilizing available information and uncertain data [2] (Komal et al., 2010).

Reciprocating Compressor are very sophisticated systems that go beyond traditional RAM analysis due to specific capabilities needed for performing a range of working operations that can ensure the required production efficiency and reliability in the Oil and Gas industry.

The main aim of this research work was to assess the availability of reciprocating compressors plant designed, configured, and eventually compared against End User Site Project that should be as minimum $>$ of 96% during normal production. Another important goal was the identification and ranking of the equipment and sub-systems which are major contributors towards unavailability. Ranking is based on the estimated equipment and sub-system contribution towards unavailability. The final objective was to propose and assess potential cost-effective optimization options to ensure the achievement of the target availability, where appropriate, and perform Equipment Criticality Assessment for the systems and equipment assessed as part of the RAM study.

This work was carried out in collaboration with Newmann Esser, a company leader in the production of reciprocating compressors for the Oil & Gas industry and has established as one of its mission a continuous improvement of its products quality in terms of availability and reliability in accordance with the standards of the specific sectors in which the produced systems are applied.

2. Literature review

Among various methods for systems performance modelling (Root Cause Analysis, RCA; Failure Mode and Effect Analysis, FMEA; RAM; Quality Control Tools), RAM is an engineering tool that evaluates the equipment performance at different stages in design process. It addresses both operation and safety issues and aims to identify areas with in the system or process where improvement actions can be initiated. With RAM analysis of the system key performance metrics such as Mean Time to Failure (MTTF), Equipment down Time (EDT) and System Availability values (A_{sys}) can be ascertained. The information obtained from analysis helps the management in assessment of the RAM needs of system [3] (Sharma and Kumar, 2008).

In the Oil & Gas Industry risk-based maintenance programs to improve safety, reliability and availability of the plants have been applied for a long time now.

RAM is one of the risk evaluation models that are applied in Maintenance and Safety Integrity Management System.

Eti et al., 2006 [4] demonstrated an approach for the integration of RAMS and risk analysis as a guide in maintenance policies to reduce the frequency of failures and maintenance costs.

Depending on the information delivered by different indicator decision-making models, managers who are in charge of maintenance can take measures to review operational management, maintenance management and safety management, so that the indicators mentioned above can better satisfy management needs. The decision-making model which is used to improve equipment reliability, availability and maintainability are called RAM procedure, and it is also a sustained and close-loop management system. Dynamic risk rank indicator, predictive maintenance indicator and RAM indicator constitute the intelligent maintenance indicator decision-making system. [5] (Qingfeng et al., 2011).

RAM is considered to be one of the two most significant areas for profitability improvement (William, 2001). Moreover, RAM modelling will contribute to an increased safety and environmental performance, which is an important factor in maintaining the license to operate, by providing real and up-to-date data concerning the actual state of the plant. Herder at al. (2208) [6] described the feasibility and prerequisites for implementing RAM simulation modelling in industrial practice, by means of developing, implementing and using a RAM simulation model for the GE Plastics Lexan® plant in Bergen op Zoom, The Netherlands.

Lundteigen et al. (2009), [7] in their paper outline a new approach to reliability, availability, maintainability, and safety (RAMS) engineering and management. The new approach covers all phases of the new product development process and is aimed at producers of complex products like safety instrumented systems (SIS). The article discusses main RAMS requirements to a SIS and presents these requirements in a holistic perspective. The approach is based on a new life cycle model for product development and integrates this model into the safety life cycle of IEC 61508.

Saraswat and Yadava (2008) [8] emphasised the role of reliability, availability, maintainability and supportability (RAMS) aspects for improving performance of engineering systems.

Rajiv and Poja (2012) [9] developed a methodology to permit the system reliability analysts/managers/engineers/ practitioners to conduct RAM analysis of the system to model, analyse and predict the behaviour of industrial systems in a more realistic and consistent manner through a Markovian approach. They demonstrated that with RAM analysis of the system key performance metrics such as Mean Time between Failure (MTBF), Mean time to Repair Time (MTTR) and System availability values are ascertained.

3. Reciprocating Process Compressor in Oil and Gas Industry

The target duty of reciprocating process compressors is the export of produced gas from a small oil / gas field into a common manifold system.

The back pressure in the manifold varies depending on the total gas rate.

The gas is a hydrocarbon mixture of variable molecular weight, including inert gases such as Nitrogen, and may contain corrosive/ toxic components such as Hydrogen Sulphide.

In such system the gas is compressed in a series of discontinuous steps by coaxing a fixed volume of gas into a chamber or cylinder for compression.

Then the compression of the gas mechanically reduces the size of this cavity. At the end of the compression cycle the chamber opens and discharges the high-pressure gas.

Due to the compression process the temperature of the process gas increases; for this reason, in some cases separate stages of compression with intercooling of the gas between them are applied for limiting the temperature and loads on the compression cylinder.

It is not rare that only one or two stages of this compression process are needed. This kind of compressors do not allow an open gas passage from delivery to suction, even do back flow is possible by leakage through the clearances between moving parts.

Reciprocating compressors can achieve high pressure ratios per stage at low volume flows.

With respect to centrifugal and screw compressors, the reciprocating ones are used for smaller flow; they also allow a greater flexibility of duty.

They are built with materials that can stand suitable mechanical loads and when in contact with the process gas are also chemically resistant.

Hydrocarbon compressors API 618 are generally horizontal and designed with opposed pairs of cylinders, in order to meet the mechanical balance and gas sealing requirements.

To achieve reasonably practical shaft alignment and permit thermal expansion, flexible couplings are used between co-axial shafts.

Horizontal reciprocating compressors require particularly robust base-frames as the cylinders are supported separately from the crankcase. This is particularly true offshore with the baseplate having to provide the necessary stiffness for alignment and dynamic stability on the offshore installation where the structure itself is too mobile.

Compressors require suitable piping, Interstage vessels and coolers with associated control systems. Together with baseplate and driver this forms the "Compressor System".

A general scheme of the compressor main elements/components is shown in Figure 1.

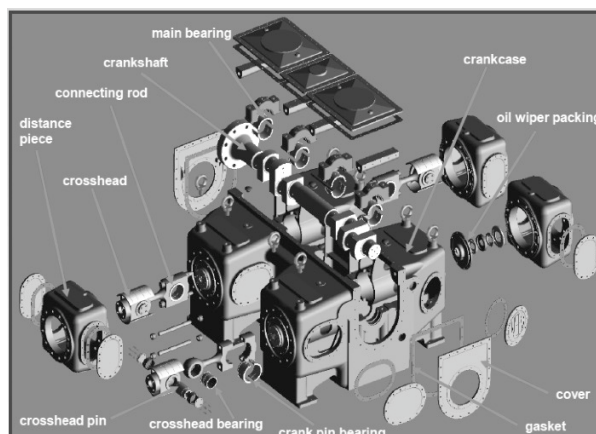


Figure 1: Components of horizontal reciprocating gas compressor (scheme provided by RC company)

The vast majority of compressors are shaft driven by a separate electric motor, gas turbine or diesel engine. A drive gearbox may be required to match the compressor and driver speeds. Reciprocating compressors are not normally variable speed as there are a number of ways to modify the output from such machines including :- reducing cylinder efficiency using clearance pockets, control on suction valve opening, and offloading cylinders.

The safety of reciprocating compressors handling hazardous materials is dominated by their piston rod sealing systems. These require appropriate design, maintenance and operator attention.

3.1 Operating requirements

Reciprocating compressors are generally designed for long periods of steady operation, up to perhaps 3 years' service without major overhaul. Valves and seals require service at perhaps 12/24 or more monthly intervals.

- **Continuous Duty**

Selecting equipment for continuous operation, requires steady, efficient and reliable operation. Reciprocating compressors cannot run continuously for more than a maximum of about 12/24 months before valve and seal wear becomes unacceptable, and the motion work may only be able to run for up to 3 years between major overhauls. Sophisticated monitoring will give the best information to permit maintenance intervention to be well-planned and of the shortest possible duration. Chemical additives may be used to control fouling. Materials are selected for negligible corrosion in service.

- **Variable / Intermittent Load Duty**

Reciprocating compressors are tolerant of duty changes, but, being positive displacement machines, recycle control is normally used to manage flow changes. Some machines are fitted with unloading systems, these can be complex and may cause local high temperatures. Reciprocating compressors can be started up very quickly, provided that detailed checks are carried out and, above all, no liquid is present in the compressor or suction system

- **Emergency Duty**

Reciprocating compressors are not ideal for emergency duty as they require operator checks and attention during starts. It is practical to have a set running on full recycle at low power and perhaps reduced speed, ready to pick up load in a few seconds. Again, the potential presence of liquid in the suction line would pose a major hazard.

3.2 Maintenance requirements

Maintenance requirements for reciprocating compressors are a combination of preventative maintenance of the motion work and major components and essential predictive maintenance based on measured performance such as valve temperatures, rod drop, vibration.

Valves, gas seals, bearings can be accessed by removal of local covers. Removal / maintenance of seals and bearings requires lifting equipment to support and position motion work as required. The pistons and rod are normally removed as an assembly by unscrewing the cross-head nut. Only then can the gas seal, and the piston rings, be inspected and changed. Reciprocating compressors are thus relatively maintenance-intensive, reducing the availability compared to centrifugal units.

The alignment and levelling of cylinders to crankcase should be checked periodically, particularly after any cylinders have been disturbed. Any misalignment or movement will result in increased fatigue loads on cylinder supports and fasteners. Movement is often shown up by "panting" of the oil film in mechanical joints.

Special fasteners permit the tension or stretch of fasteners to be checked in service. Hydraulically tensioned fasteners are often fitted to ensure accurate tightening in confined spaces.

The motion works bearings will be white metal, possibly of shell construction that would simplify maintenance. A high level of fitting skill is required to work on these machines.

The piston rod and gland arrangements are precisely engineered to avoid gas leakage, assembly and installation of these components requires some of the highest levels of quality engineering and attention to detail to provide reliable operation.

The control and remote isolation valves will be large and very heavy, often posing a difficult lifting problem. It is important that the full operation of these valves be tested before the plant is returned to service. It may be necessary to carry out in-service operating tests on valves to ensure their reliability. They also often have inter-coolers and water cooled cylinder jackets. Hence liquid may well be condensed inside the compressor. Some process compressors are of a "lubricated" design, where a process-compatible lubricating oil is injected in small quantities into the cylinder. This oil lubricates the piston rings and gas seals. The oil provides a significant degree of corrosion protection. The main corrosion potential is if the lubricating oil supply stops, while condensation continues. This might occur when a set was stopped, but not isolated and purged with dry gas. Light hydrocarbon condensate will wash off the oil film, leaving surfaces exposed to trace corrosive elements in the gas.

The worst corrosion occurs if process deposits (salts, oxides) are exposed to damp air under poor ventilation conditions. This may occur if there is a failure that prevents a normal process clean out. The system is then opened for inspection, and left open while parts / resources are obtained. This can be avoided by proper cleaning / venting activities after the inspection, and even by applying corrosion inhibitors.

The crankcase and cross-head areas should be completely separate from the process, with clean lubricating oil in a dry gas (ideally Nitrogen) atmosphere. There should be no potential for corrosion here, although it is very wise to periodically test the oil for water, chlorides and light hydrocarbons.

4. Materials and methods

In this work the RAM analysis method has been applied; it is an assurance activity for safety critical systems in aerospace, nuclear power and industries. For the process industries (e.g., oil and gas, power plants), RAM analysis is rapidly developing and becomes a mandatory deliverable for the conceptual design phase.

In this study the RAM analysis has been performed based on the following documents:

- Maintenance Strategy;
- Piping and Instrument Diagrams;
- Process Flow Diagrams;
- Process Operations and Control Philosophy;
- Maintenance Policy;

The RAM methodology is presented in detail in the following scheme.

The RAM study was based on failure rate and model data that are developed and compiled from a number of sources, including ERM experience and publicly available process equipment failure rate databases such as OREDA 2009 5th edition SINTEF and NPRD. When using the generic failure database, a review of the data set has been performed and some modifications to the data were applied based on the experience of the application and operating environment. These modifications and assumptions have been reviewed and agreed upon with the project team prior to conducting the RAM model.

For large multi-component equipment such as compressors and turbines, the failure modes are divided into trip, minor and critical failures.

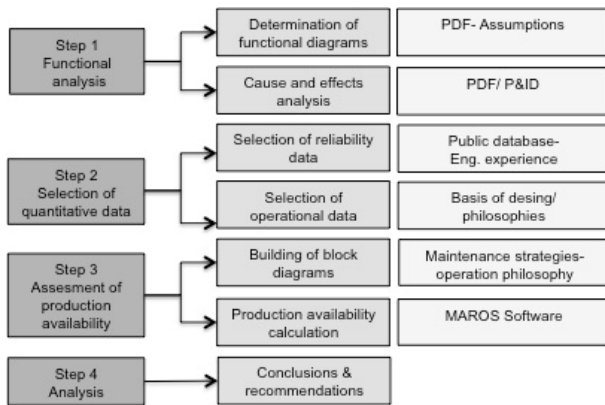


Figure 2: Scheme of RAM methodology (scheme provided by RC company)

Trip failures generally represent an upset of the process and/or instrument failures and can be rectified during the operating shift. Minor failures are generally related to equipment failures in case repair would be needed and performed within a short period of time.

Critical failures refer to multiple component failures or major part failure which would require a significant repair time.

This allows a more accurate modelling of the failure-maintenance cycle.

To assess the time needed to repair non functional equipment in case of corrective maintenance application, it as to be taken into account the time required for isolation, depressurization, on-site mobilization, actual repair time, and restart ramp up time.

Time spare equipment procurement time, off-site logistics or administrative processes which are outside the optimization of the equipment configuration design in the context of RAM study.

Reliability block diagrams were developed for the major equipment to allow production availability to be quantified. The analysis was performed using Monte Carlo analysis technique.

Following the assessment of production availability, the equipment/ sub-systems that were found to be the major contributors to unavailability were ranked with respect to the estimated contribution towards unavailability.

Specific Software RAM tools can also be used as Process Reliability Modelling, Plant Wide Performance Modelling or simply RAM Modelling. In this case it has been chosen the software MAROS for Upstream and Midstream analysis propriety of DNV.

4.1 Reliability Data Collection

The goal of RAMS is to create input data for the assessment of the suitability of a system in a life cycle. That is, to provide data on failure rates of the system, possible failure modes, MDT, maintenance operations, hazards and their consequences, etc. This output of RAMS simulations enables the life cycle specialists to calculate costs and to perform Cost-Benefit Analyses (CBA). But before the RAMS simulation at system level, input on known component failure data must be

provided. There are then 3 different steps in the application of RAMS, all of which are interlinked.

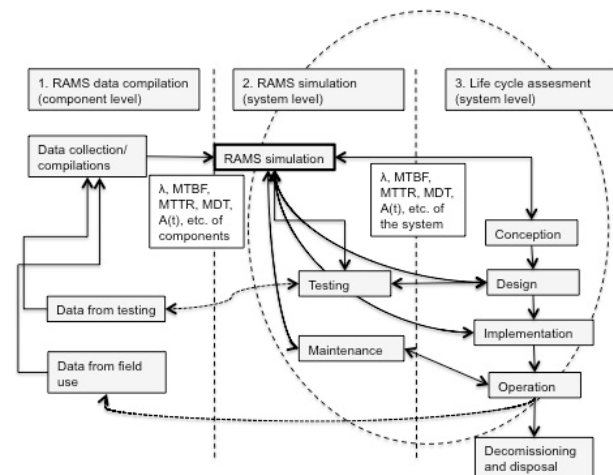


Figure 3: Scheme of RAMS steps and Life Cycle assessment (scheme provided by RC company)

- Step 1: RAMS data compilation (component level)

Failure data compilation stands as the foundation of any RAMS simulation or process. Whether it is made through testing or through observed field operation and maintenance feedback, the study of individual component failure provides data on failure rate and all other reliability parameters. This data is used as input for step 2, RAMS simulation.

This is of utmost importance, for as stated above, a great number of authors state that the use of more complex reliability models (in step 2) does not necessarily mean there is a better result, for there is generally a lack of relevant reliability data (step 1). Reliability data has more impact on the RAMS simulation results than the RAMS simulation models themselves.

- Step 2: RAMS simulation (system level)

In this step, the goal is to model the system in terms of reliability aspects. That is, from values of failure rate, MTBF, MDT, among others from individual components, be able to compute values which refer to the same components but while interacting with each other in a system and a stated environment. The first methods developed to do so – like the Preliminary Hazard Analysis and the Failure Modes and Effects Analysis – are of qualitative nature and are mainly intended to identify failures at system level. Other methods which appeared later on are of quantitative nature and enabled the reliability engineers to predict through mathematical formulations several values for failure rate and related parameters in systems. These simulation result values are termed design or expected reliability.

- Step 3: Life cycle assessment (system level)

In the life cycle step, the goal is to assess the benefits the system will bring. In order to do so, costs and incomes must be assessed. Another part to quantify is costs. RAMS

parameters will play a very big role in determining the costs, since as stated above, failures will bring costs to the system, i.e. the cost of a compressor system to be stopped due to a failure, the cost of a corrective maintenance operation on a compressor system which forces the impediment the cost of accidents which might involve serious injuries or death, among others.

So at this step, the idea is to take RAMS simulation results and create targets for the system studied. The targets will influence the system's mission profile and the life cycle's CBA, and the results of the CBA might indicate that the RAMS targets need to be revised. This is thus an iterative process, for the RAMS targets influence the CBA and the CBA influences the RAMS targets. It is then needed to go back to step 2, and rerun the simulations in order to revise RAMS targets. Finally, the testing and operation steps in the life cycle will influence step 1, for data can be collected through the testing and operation phases of the life cycle. This is a way to achieve reliability growth.

5. Reliability & Availability Results

The data collected and compiled in phase 1 have then been used to assess the reliability of the reciprocating compressor: failure rate, MTBF, MDT and other parameters were calculated and in relation to the interaction of the system under analysis with other components.

Based on a 10 simulation cycle run with a 20 year life, the average production efficiency is 97,8% within a standard deviation of +/- 0.104%. The average volume produced over life is 463059000 sm³ starting with 23149606 sm³ in 2015 and rising to 23196428 sm³ in 2034.

The average loss over life is 9980840 sm³ averaging at 499042 sm³ per year.

Figure 4 shows the results of the criticality analysis applied to compressors subsystems components: the most critical elements in terms of reliability of the entire system are the guide and the piston ring; the trust bearings and the gas pressure packing. The values defined in the analysis for the different types of valves are almost the same and range around 5% ensuring a suitable level of reliability.

In Figure 5 a breakdown of the components criticality for the selected subsystems is presented; the subsystem that shows the major vulnerability is given by the electric motor followed by the guide and piston rings.

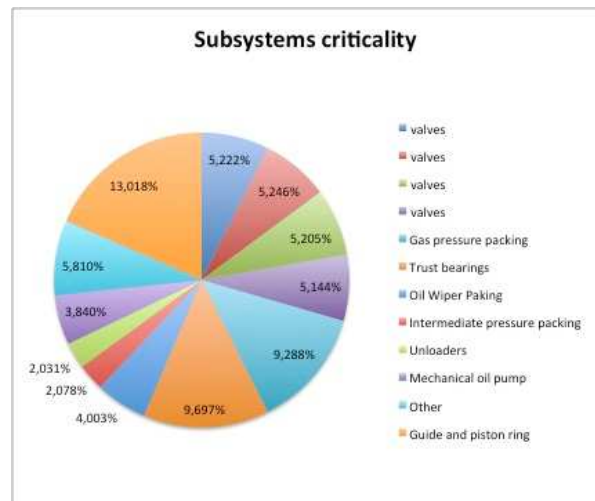


Figure 4: Results of subsystems criticality analysis

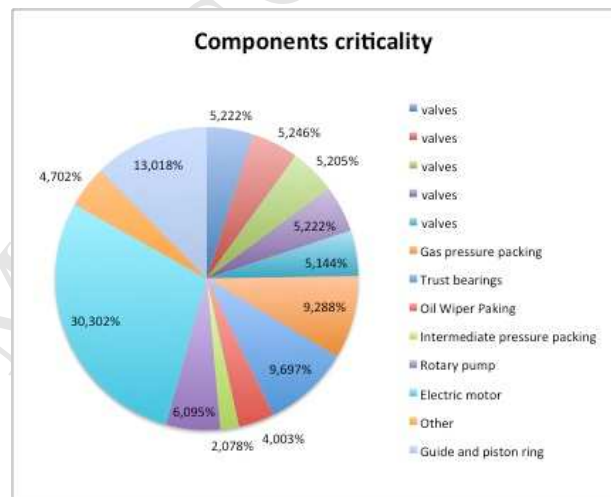


Figure 5: Results of components criticality analysis

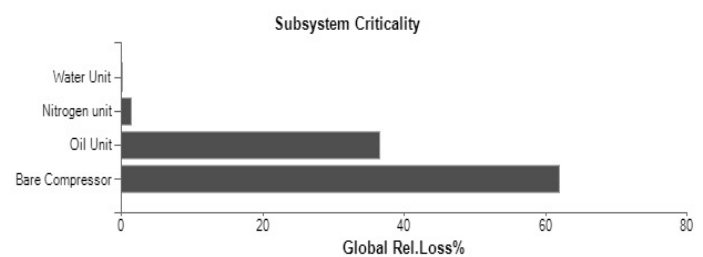


Figure 6: Global relative loss % for each main subsystem

Table 1 reports, for the analysed subsystems, the mean failure and the relative mean time between failure.

Description	Global Rel Loss %	Local Rel Loss %	Mean failure	Abs Loss Mean %	MTBF (years)	Unique ID
Bare Compressor	61,896	61,897	590,9	1,306	0,0338	48
Oil Unit	36,560	36,561	597,5	0,771	0,0335	50
Nitrogen Unit	1,3904	1,3904	25,9	0,029	0,7722	49
Water Unit	0,1519	0,1519	947	0,003	0,0211	151

Table 1: Results of components criticality analysis

The average number of outages per year was 11.47 with an average duration of 12339 hrs. The longest outage lasted 59.141 hrs and the shortest 0.051 hrs.

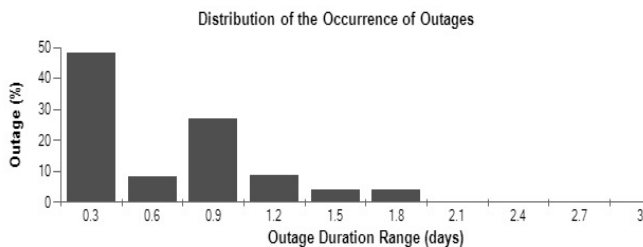


Figure 7: Frequency of outages

There have been analysed 9 main events contributing to the outages each one identified by an ID.

In Table 2 the number of occurrence of each event contributing to outages is reported.

Figure 8 shows a breakdown of the principal events contributing to the outages.

Contributor	Event ID	Contribution Count	Relative Contribution %
Critical	10	93	4.0541
Critical	17	562	24.4987
Critical	11	192	8.3697
Critical	13	88	3.8361
Critical	15	257	11.2031
Critical	16	619	26.9834
Critical	14	71	3.095
Critical	12	184	8.0209
Critical	9	200	8.7184

Table 2: Occurrence of each event contributing to outages

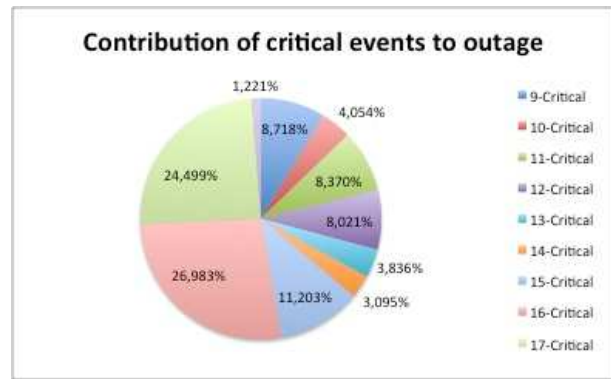


Figure 8: Principal events contributing to outages

6. Conclusion

This study was carried out in cooperation with a company leader in the production of reciprocating compressors with a mission of continuous quality improvement. They have a consolidated experience in the application of RCM methodology since it has a great impact on the preventive maintenance tasks.

The main aim of this research work was the assessment of the availability of reciprocating compressors plant designed, configured, and eventually compared against End User Site Project. The target value to reach for the availability was greater than 96% during normal production.

Moreover the quality team needed to define and rank the equipment and sub-systems which are major contributors towards unavailability. Such elements were correctly identified. Finally potential cost-effective optimization options to ensure to achieve the target availability were proposed and assessed.

The results of the RCM study applied on reciprocating compressor API 618, showed that the preventive maintenance proposed tasks and planning are generated.

The criticality analysis of components allowed to have a time window for programming effective maintenance activities and outlined failures and main events contributing to jeopardize the production process.

The present work recognizes the need for a structured approach whereby quantitative RAM targets are set at the conceptual design stage and used throughout the plant life cycle to control and review the RAM performance.

To enhance the credibility of the ideas presented in this work and the other formulations that are exists in the literature, it is necessary to work on real case studies.

This would in turn require industry to share some of its operational data with the academics.

These case studies would demonstrate the usefulness of the methods and could also be used by process engineers to learn how to apply RAM principles in process design.

The importance of this study was the possibility to collaborate with the company and to start a measurement campaign collecting field data that will allow the prosecution of the research and to increase the reliability and usefulness of results.

Future research will be devoted to on-site measurements and real data acquisition in working conditions.

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