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Reliability improvement of compressors based on asset fleet reliability data

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Abstract: Physical assets of the process industries include compressors, pumps, heat exchangers, batch reactors and many more. A large company that operates over many sites typically manages such assets in a coordinated way as an asset fleet. Strategic planning of maintenance and scheduling requires information about reliability, availability and maintainability of the assets in an asset fleet.
The work presented in this paper assesses the reliability of centrifugal compressors based on the data collected in OREDA (Offshore and onshore REliability DAta project). The fault tree (a top-down approach to illustrate all subsystems in a system) has been modeled by focusing on the six main subsystems of the compressor (power transmission, compressor, control and monitoring, lubrication system, shaft seal system, and miscellaneous). All the maintainable items described in ISO 14224 are considered. Based on the failure rates collected in OREDA, the most prevalent failures have been identified via a Pareto analysis. The article gives recommendations which subsystems should be prioritized for maintenance and which types of faults are likely to occur. The main contribution of this paper is an industry-based statistical analysis of the failure mechanisms in centrifugal compressor systems. It is expected to improve the reliability of centrifugal compressor systems and can be implemented in industrial settings with a similar documentation system like OREDA.

Keywords: Reliability analysis, Information processing and decision support, Fault tree analysis, Maintenance Scheduling and planning

1. INTRODUCTION

This paper is about improving the reliability of compressors based on asset fleet data from a reliability database. Improving the reliability of equipment in the process industry has a major impact on aspects such as environment, safety, production availability and maintenance costs. The technical integrity of the complex systems is mandatory to ensure safe and reliable operations (World Economic Forum, 2017). Achieving knowledge about the likelihood of failures and their consequences is a key activity. In companies of the oil and gas industry the current economic situation is putting tight constraints on the operations and optimizing life cycle cost while reducing maintenance cost. At the same time, reliability of equipment is not just correlated to profit, but high reliability also reduces the risk for the environment and the work force which is inherent with every machine failure.

This article refers to assets in the meaning of engineering assets (Beebe, 2010). This includes all the physical assets in a process plant, such as mechanical, process or electrical equipment. A large number of assets of a similar type and function can be aggregated and called an asset fleet. Usually they also have at least one common stakeholder (Schulze Spüntrup and Imsland, 2018). This stakeholder might be an engineer who is responsible for the maintenance of all assets in the fleet or a manager who aims to reduce carbon emission for the entire asset fleet. Fleet assets are not necessarily located in one place. From an operational point of view, these assets are in one company. For improved data collection, multiple companies may form a consortium to collect and share data with the purpose to make better decisions with higher statistical significance. The data is created from the assets. This could concern process data from the operation of the equipment or information about failures and maintenance of the specific asset. This data is collected and stored for later use.

Maintenance in the context of asset fleets reveals benefits in terms of the economies of scale and to identify assets that benefit most from it (economically), but from a maintenance perspective challenges may also arise as the objective is to maintain the entire fleet as good as possible.

A thorough analysis of the data collected from asset failures and maintenance actions can give insights on where

to improve maintenance systems. This study aims to analyse the failures of topside centrifugal compressors used in offshore applications by the oil and gas industry. The findings will show where improvements in the maintenance actions have the largest impact on the reliability of current systems. Furthermore, condition monitoring systems are just able to predict failures from the first signs of failure. Research on predictive maintenance tries to predict failures even before these first signs and to obtain information about the likelihood of failure beforehand. Section 2 will show that there are open questions about how information from past failures can be used to achieve insights into the reliability of a compressor systems. This paper aims to fill that gap. The data from the Offshore and onshore REliability DAta project, OREDA (SINTEF Technology and Society et al., 2015), is used an an example, but the applied methods can be applied to similar data, too.

Section 2 in this paper gives necessary background about the OREDA project, the topics of reliability and maintainability and other work related to this article. Section 3 presents the methodology used in this paper, namely for the Pareto analysis and the reliability model. Section 4 presents briefly the data of OREDA that makes up the foundation for the analysis. Section 5 presents the results of the analysis including the outcome from Pareto and statistical reliability analysis. Some findings indicate critical points that reveal serious safety risks. Furthermore, mitigating strategies are developed based on the analyses. Section 6 concludes the work and gives an outlook for future work.

2. BACKGROUND

2.1 Key terms of reliability engineering

A failure mode is the manner in which an equipment or a part of an equipment can fail. By listing all failure modes for all maintainable items in a system, a failure mode and effects analysis (FMEA) can be performed.

In reliability engineering, faults in complex systems are often displayed by using the fault tree method. It reflects the structure of the equipment by representing the different subsystems of an asset down to individual components. For each component it is possible to identify different failure modes. Ultimately, all possible ways that a system can fail based on the individual components should be represented in such a fault tree. The fault tree breaks a complex system down into subsystems down to a level, where no further segregation is possible. A fault tree analysis is a form of deductive failure analysis. It uses a fault tree as a top-down approach to describe the system. The failure events at the lower level are then combined by Boolean logic and a undesired state of the system is explained.

2.2 The OREDA project

A reliability analsis of assets such as compressors, requires a comprehensive amount of data, preferably from an entire compressor fleet. The project organization OREDA (Onshore & Offshore Reliability Data) has been set up to collect and exchange industrial reliability data in the oil and gas industry for the participating companies operating worldwide. The database resulting from the OREDA
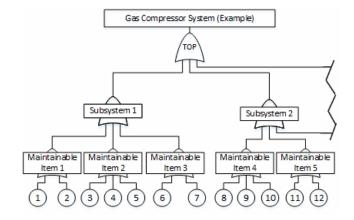

Fig. 1. Example of a fault tree. It can be extended to a higher number of branches and also more levels. The numbered circles denote the events that cause failure.

project comprises reliability and maintenance data for various types of equipment that are used in the exploration and production in various geographic areas, installations and operating conditions. There exists a wide range of literature based on the data from the OREDA project.

2.3 Work based on OREDA

Turan et al. (2011) conducted a study of the reliability and criticality for the case study of diving support vessel. This is done with the background of the OREDA handbook and other maintenance standards and procedures, such as the ALARP and the KP3 initiative, or the basic reliability-centered maintenance (RCM) and risk-based inspection (RBI) principles. The reliability assessment of Turan et al. (2011) is done by utilizing two reliability importance measures. Similar to our approach, the reliabilities of the main system and the subsystems are identified and suggestions are made how to improve the overall reliability of the various systems. This work by Turan et al. (2011) is referenced since it works with the same database, looks into the subsystems and takes information to estimate the reliability.

Langseth and Lindqvist (2006) chose a statistical approach to analyze a data set from the OREDA database. The model explains the different parts of the system that can fail (termed *competing risks*) and assumes that the preventive maintenance is imperfect and does not result in a total repair of the equipment. The authors conclude that the model has the capability to describe the data set that they used set as well. However, the authors state they are facing a non-identifiability of the competing risk problems and cannot claim to have found the correct model but rather that the data does not reject the developed model. The main outcomes of that work are therefore likelihood parameters (such as the eagerness and thoroughness of the maintenance crew) to describe the quality of the maintenance that has been performed.

Rausand and Oien (1996) used OREDA to illustrate the interpretation of basic concepts in failure analysis using an example of a gate valve. During their analysis they point out limitations in OREDA and propose enhancements, e.g. to record failure causes, failure mechanisms or root causes. Until now, this information are still not collected

in OREDA. The reason for discussing this reference is that there are already improvements suggested to OREDA. This is also part of the outcome of our work.

Sandtorv et al. (1996) share their practical experience of the OREDA project (e.g. that not always the personnel with the needed knowledge is available for data collection or that it is hard to agree on specifications for complex equipment). They make recommendations for future data collection projects. On the other hand, Hameed et al. (2011) named OREDA as the state of the art for data collection in the industry and they try to identify challenges regarding reliability and maintainability data collection for other industries, such as offshore wind turbines. In the failure analysis of Haugen et al. (1997) both critical failures and degraded failures, followed by critical failures, are considered. The OREDA project supplied the necessary data for this purpose. These paper demonstrate that OREDA is a useful database, and has been used successfully for research in areas such as failure analysis and reliability.

2.4 Work with a similar purpose

Choi and Chang (2016) try to improve reliability of subsea production systems. They analyse the reliability of a seabed storage tank based on a fault tree. The data is taken from components of the lowest level of the seabed storage tank. Active repair times from OREDA were taken into account and other databases were used to supplement the study. This work is relevant, since their approach is based on a fault tree and shows similarities to the method described in this article. However, they merge failure rates from different systems. This work uses data which is specific to a compressor system. A synergetic approach is chosen by Ebrahimipour and Suzuki (2006). Principal component analysis is coupled with importance analysis to improve equipment performance. The leading causes and common-cause events are identified. The topic of this paper is to identify main causes for failures, similar to the work of our article, but with different methods.

Another work with an relative approach for assesing the reliability of assets is given by Corvaro et al. (2017). The authors are using a RAM methodology (Reliability, Availability, and Maintainability) for the case of reciprocating compressors. The reliability is done with a RCM study from a private company. The availability calculation is performed by means of block diagrams. The input are failure rates, which is similar to the approach in the model developed by our work. The maintainability corresponds to maintenance activities suggested by the RCM analysis. These activities are assigned to criticality values that have been calculated before. Even though Corvaro et al. (2017) use RCM to build their model and the used equipment boundaries are not given by ISO 14224, the results of the work are comparable to the method presented in this paper.

3. METHODOLOGY

The work presented in this paper uses statistical reliability analysis and Pareto analysis. Fig. 2 illustrates the methodology and how these two different analyses work together. The dashed boxes indicate the logical next steps, which are outside the scope of this paper.
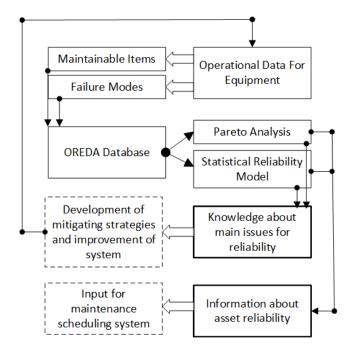

Fig. 2. Methodology for the statistical reliability analysis; dashed boxes indicates work that goes beyond the scope of this paper

3.1 Selection of data from OREDA

The taxonomy classification of ISO 14224:2016 for equipment used in the petroleum, natural gas, and petrochemical industry is used as well as the failure mode records for each component as described in the OREDA database. ISO 14224:2016 "Petroleum, petrochemical and natural gas industries – Collection and exchange of reliability and maintenance data for equipment" specifies the equipment to be included when studying a compressor system. Tab. 1 presents a list of compressor subsystems and the related equipment.

3.2 Pareto analysis

The Pareto principle or the 80/20 rule, states that the majority (roughly 80%) of the effects come from a minor part (roughly 20%) of the causes. A tool called Pareto analysis is build on this principle.

A Pareto analysis works by listing possible causes and ordering them, usually by their estimated benefit or by their impact on a problem. In the next step, a number of the most effective actions or most promising opportunities for countermeasures are selected. This is done by the Pareto principle, approaching 20% of the action items and expecting 80% of the benefit. In the case of OREDA, the information about the maintainable items and the failure modes must be sorted, based on the number of events when a specific maintainable item failed or when a specific failure mode occurred. Next to the contribution of the items the accumulated contribution in a descending order (from high contribution to low contribution) is indicated. The focus is on the action items that reach a cumulative contribution of 80%. A Pareto analysis has been conducted on the OREDA data (failure rates for each maintainable item and each failure mode). Focusing on the causes that
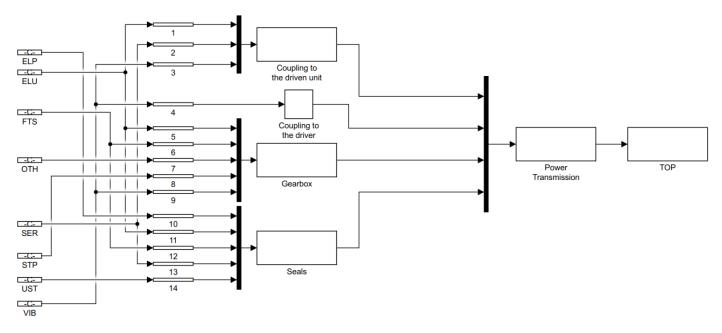
Fig. 3. Example of the Simulink model for the power transmission subunit; the calculation blocks are explained in Section 3.3.

result in the majority of failures will help to improve the reliability of the system.

3.3 Statistical reliability model

The statistical reliability model utilizes a fault tree analysis. The compressor subunits shown in Tab. 1 and all the maintainable items listed in the OREDA database are used to create a model.

Based on the reliability data from the offshore compressors a fault tree is modeled in Simulink. This is done taking the six subsystems into account individually and all maintainable items for each subsystem.

The common assumption that a failure is total and partial failures are not taken into account is applied (Baig et al., 2013). A failure in one of the subsystems leads to a failure of the entire compressor system.

Reliability is the "ability of an item to perform a required function under given conditions for a given time interval" (ISO 14224:2016). The relevant information in the OREDA database is in a table in OREDA (SINTEF Technology and Society et al., 2015). This table gives failure rate λ_i due to each of the failure modes i, and fractions $p_{i,j}$ of the total failure rate for each combination of failure mode i and maintainable item j. The failure modes such as ELU (External Leakage - Utility Medium) are listed in Tab. 2, and the maintainable items are listed in Tab. 1. Fig. 3 illustrates the calculation procedure for the power transmission system, which is comprised of maintainable items such as *Gearbox* and *Coupling to the driven unit*. The calculation proceeds as follows:

(1) The blocks labelled as 1, 2, 3 ... 14 calculate $r_{i,j} = e^{-\lambda_i p_{i,j} t}$ where t is time. For instance, in block 5, λ_i is the failure rate per hour for failure mode ELU, and $p_{i,j}$ is 0.001, being the fraction of failures for failure mode ELU reported in OREDA for the *Gearbox*

maintainable item. Since *Gearbox* has five possible failure modes, blocks 6 to 9 in Fig. 3 calculate $r_{i,j}$ values for the other four failure modes.

(2) The $r_{i,j}$ values are inputs for calculations of reliability of the maintainable items. For instance, the $r_{i,j}$ values from blocks 5-9 go into *Gearbox* which calculates reliability of the *Gearbox* maintainable item over all its failure modes as $r_j = 1 - \Pi_i(1 - r_{i,j})$.

(3) Similarly, the overall reliability r of the Power Transmission system is given by combining the reliability of the individual maintainable items in the Power Transmission system, i.e. $r = 1 - \Pi_j(1 - r_j)$.

Fig. 3 illustrates the Power Transmission system, which is one of the six subsystems of a compressor as listed in Tab. 1. Similar reliability calculations are carried out for all the subsystems. The results are combined to give an overall system reliability.

3.4 Steps beyond the scope of this work

The development of mitigating strategies and the improvement of the system are not covered in this paper. However, it is intended that the results of this work are used as input for those steps.

4. CASE STUDY

Currently, data from 278 installations, 17,000 equipment units with 39,000 failure and 73,000 maintenance records are stored in the database. The OREDA handbook described this database, currently in the sixth edition which has been published during the twelfth phase of the project.

OREDA data being relevant to this study comprises data from from 22 offshore turbine-driven centrifugal compressors in eight different installations. Tab. 1 lists the six subsystems of compressors and all the maintainable items for each subsystem. Tab. 2 lists all the different failure modes that have been considered.

Table 1. Subdivison of a compressor into subunits and the maintainable items of each subsystem

Compressors					
Power Transmission	Compressor Unit	Control and Monitoring	Lubrication System	Shaft Seal System	Miscellaneous
-Gearbox/Variable drive -Seals -Lubrication -Coupling to the driven unit -Coupling to the driver	-Antisurge System -Casing -Cylinder liner -Instruments -Shaft seals -Radial Bearing -Thrust bearing -Interstage seals -Valves -Internal piping -Balance Piston -Packing -Rotor w/ impellers	-Wiring -Control unit -Actuating device -Monitoring -Internal power supply -Seals -Piping -Sensors -Valves	-Reservoir w/ heating system -Pump w/ motor -Filter -Cooler -Valves and Piping -Oil -Instruments -Seals	-Dry gas seal -Filters -Gear -Mechanical seal -Reservoir w/ heating system -Pump -Motor -Scrubber -Seal oil -Valves	-Base frame -Flange joints -Control valves -Magnetic bearing control system -Isolation valves -Coolers -Piping, pipe support and bellows -Purge air -Silencers

Table 2. List of all considered failure modes for compressors and their acronyms

Acronym	Failure Mode
AIR	Abnormal instrument reading
BRD	Breakdown
ERO	Erratic output
ELP	External leakage - Process medium
ELU	External leakage - Utility medium
FTS	Fail to start on demand
STP	Fail to stop on demand
HIO	High output
INL	Internal leakage
LOO	Low output
SER	Minor in-service problems
NOI	Noise
OTH	Other
OHE	Overheating
PDE	Parameter deviation
UST	Spurious stop
STD	Structural deficiency
UNK	Unknown
VIB	Vibration

5. RESULTS OF THE ANALYSIS AND DISCUSSION

5.1 Pareto analysis

The Pareto analysis for the maintainable items (Fig. 4) reveals that the main contributing maintainable item is *Unknown* (The *Unknown* category will be further explained in section 5.4). Further, 10 other maintainable items contribute to 80% most frequently failing items.

Similarly, the Pareto analysis for the failure modes (Fig. 5) gives the insight that the most common failure mode in the boundaries of the compressor system is abnormal instrument reading. This contributes for more than 30% of all failures. In addition, seven other items contribute to 80% of the total failures. The Pareto principle is in this case not exact with about 40% of the failure modes making up 80% of the failures. However, this can be explained by the small numbers of failure modes. The results show that maintenance engineers should take care if they are basing maintenance decision on the 80/20 rule, because the analysis of the OREDA shows that this rule could be misleading in some situations. The main message of the Pareto analysis is that abnormal instrument reading should be the main focus of further improvements.
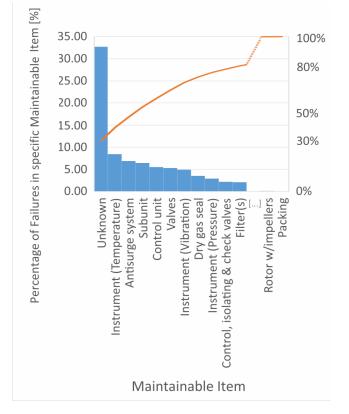

Fig. 4. Pareto analysis of the failures for specific maintainable items; the orange line denotes the accumulated percentage if failures, the dashed region contains minor contributors to the failures that have been removed from the graph

5.2 Statistical Reliability Analysis

Fig. 6 shows the results of the statistical reliability model. It gives an insight into the reliability of each sub-unit of the centrifugal gas compressor over time based on failure rates from the OREDA. It is evident over time, that the shaft seal system, the power transmission system and the lubrication system are impacting the reliability of the system very little. Their reliability value does not drop as much as other values do. This is mainly because the raw data in the database shows the failure rate for the shaft seal system and lubrication system are small.
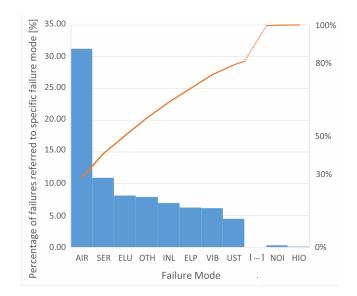
Fig. 5. Pareto analysis of the failures for specific failure modes; the orange line denotes the accumulated percentage if failures, the dashed region contains minor contributors to the failures that have been removed from the graph
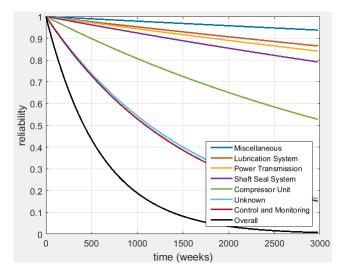

Fig. 6. Reliability of gas compressor subunits over time; the calculation blocks are explained in section 3.3.

On the other hand, the Control and Monitoring sub-unit has the largest influence on reliability. The effect is by far larger than the reliability decrease of the sub-units power transmission, the compressor itself and miscellaneous other items in the compressor system. Also, the degradation process of the Control and Monitoring sub-unit starts faster.

The overall reliability of the system reaches 80% after about 2.56 years. According to the OREDA data this would happen if there was no maintenance at all.

5.3 Knowledge about main issues for reliability

During the analysis of the data from OREDA two observations were made that have a serious safety risk linked to them.

The database reports external leakage of process medium as a failure mode that occurs in 6.25% of all failures. Leakage of process medium is unwanted in any case. This failure mode is the most frequent of the maintainable item category *Unknown* (2% of all failures). This means that there is a leakage, but it is unclear which maintainable part causes this leakage.

Another critical failure mode is *Fail to stop on demand*. In 0.5% of the cases this is due to an *Unknown* maintainable item.

From an external perspective the high number of *Unknown* that are documented seem to be an error in the data collection because with an investigation after the machine failure it should be possible to find out where e.g. a leak was. Since these two combinations are reported often, it should be a goal to reduce the amount of failures in the *unknown* category to support the industry.

Usage of results   While the information obtained through the Pareto analysis is qualitative and suggests where to take actions and where to improve the existing systems, the statistical reliability model gives information about how the reliability of the specific sub-unit changes over time.

Maintenance planning and scheduling requires such information for deciding what to do and when to take actions. Information is needed for background tasks such as ordering of spare parts, managing the inventory of spare parts, and getting the spare parts to where they are needed.

The results in this paper can be useful for the following activities:

- Qualitative information from the Pareto analysis to identify the maintainable items that should become part of the maintenance plan
- Quantitative information from the statistical reliability model such as the change of reliability over time within statistical boundaries can increase the priority for scheduling maintenance compared to an asset with a lower likelihood of degradation.
- Based on the statistical reliability model, thresholds can be set. When the reliability reaches this thresholds, maintenance shall be performed for these items. This is useful for assets that are difficult to perform predictive maintenance on.

The results in this paper are based on the OREDA data. However, companies operating large asset fleets typically also have their own databases. The findings in this paper suggest that it is very important to have accurate information about the different failure modes and maintainable items of an asset. The results also show that a large number of *unknown* faults reduces the usefulness of asset fleet data. It would be useful for further development of the methods to investigate reliability to reduce the numbers of faults categorized as *unknown*.

A challenge in maintenance is often the absence of information. Condition monitoring data would help to predict failures several months before the asset fails. However, for long-term planning and even for scheduling with a time horizon of six months such information is not available.

The reason for these comments is that condition monitoring systems are becoming more prevalent, and they enable predictive maintenance.

Predictive maintenance aims to predict machine failures even before the first signs are there, e.g. vibration or noise from the asset. With the statistical rating of the reliability it is possible to define thresholds and if the assumed reliability decreases below this threshold maintenance can be expected within the coming months. This is valuable information with the potential to improve existing maintenance planning systems.

5.4 Observations about the OREDA database

The *Unknown* maintainable item is the biggest contributor to compressor failures within all maintainable items. The authors acknowledge that this category is important and often the only option to categorize something to. Nonetheless, from an operational point of view there are also a few cases with combinations listed that are not logical. The combination of the maintainable item unknown with a known failure mode (*other*) means that there is knowledge about how something failed (otherwise the failure mode *unknown* would be the appropriate category) without knowing which item shows this failure mode.

Also, the failure mode *unknown* appears very often. An example for another unlogical combination that is reported it the maintainable item is unknown, but the failure mode is an abnormal instrument reading. If it is known that a reading is abnormal, it must also be known where the reading comes from.

In operations it might be difficult to track the history of equipment reliably. This has various reasons. The personal that is conducting this is changing over time. So the categorization of similar incidents might be deviating a lot regarding the categorization. Labels are based on the understanding of who reports a production loss or failure. This missing objectiveness arises also from the fact that there is different maintenance personnel in the different companies that contribute to OREDA. Even within one company it is very likely that failures are categorized by different personnel.

The reason for highlighting these points is that the results of the conducted analysis are sensitive to every documented failure event. If an unknown error is documented or an error in an unknown maintainable item, no suggestions for future actions can be made and the statistical reliability model becomes less accurate. Therefore, a finding of the paper is that a company maintaining an asset fleet should take pains to reduce the number of unknowns in its database since this will help to improve future reliability.

6. CONCLUSION

Compressor failure data from the OREDA database was used to conduct a reliability analysis and a Pareto analysis. These analyses help to understand the offshore compressors and their reliability better. The most prevalent failures have been identified. Main drivers for failure are the subunits control and monitoring and the power transmission, followed by unknown items. Abnormal instrument reading is the most common failure mode. Main contributors can be identified and proposals can be made of how to cope with some of the challenges in daily operation of the equipment.

Recommendations were made on how to improve data collection projects. The high number of *unknown* failures, with some of them not being logical, is critical and companies need to investigate if and why this is happening. However, the authors are aware of the challenges in the collection of the failure events and appreciate the way of improving reliability systems within a company by data collection. Aggregating data over the boundaries of a single company helps to collect data from a broader range of operating conditions and external factors such as climate. In the long run this will help the entire industry to become safer and more reliable which on the other hand will results in higher profit margins.

The output of the reliability analysis is an important input for future developments of maintenance scheduling and planning tools, as the information about the decrease of reliability within a subunit is an important decision factor.

Further study is recommended for the other identified parts of the compressor system that contribute to the most failures. Within the limitations of this work possible solutions for the control and monitoring systems were introduced. From the proposed methodology in Fig. 2 the improvement to the system need to be implemented. This will result in new operational data and the benefits of the changed system will become evident. Another point for further study is a more detailed assessment of the reliability.

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