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A study of the efficacy of a reliability management system- with suggestions for improved data collection and decision support

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Acknowledgment

This master thesis is written, as a requirement to my master's degree in offshore technology in the specialization of Risk Management at the University of Stavanger during the spring semester of 2017. The title of the thesis is "A study of the efficacy of a reliability management system- with suggestions for improved data collection and decision support".

The main objective is to analyze reliability management system (RMS) of Petroleum Technology Company (PTC) and also assessing its data quality. Basic knowledge of risk and reliability analysis, International Standard Organization (ISO) standards, and Offshore & Onshore Reliability Data (OREDA) project can help the readers to better understand the thesis.

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Stavanger, June 15, 2017
Amna Ali Khan

Abstract

Product reliability is very important especially in the perspective of new product development. Making highly reliable drilling and well equipment is an expensive and time-consuming process. But ignoring the product reliability could prove even more costly. Thus the manufacturers need to decide on the best reliability performance that succeeds to create a proper balance between time, cost and reliability factors to ensure the desired results. A reliability management system is a tool that the manufacturers can use to manage this process to produce reliable equipment. However, if this system is not well structured and lacks some important features, it can affect the outcomes of reliability analysis and decision making.

A lot of research has been done on creating a good reliability and maintenance database to improve systems reliability in the petroleum industry. Offshore & Onshore Reliability Data (OREDA) and ISO 12224 are part of such research projects. The main objective of this research is to analyze the existing reliability management system (RMS) in Petroleum Technology Company (PTC) in terms of its structure, features, functionality, and the quality of data being recorded in RMS and how it affects decision making.

The research was motivated by following issues 1) Reliability Management System of PTC is not automated in terms of extracting data from other sources within company, 2) PTC is missing a specified platform for failure reporting of their equipment, 3) the activities related to data collection and management are not well-organized hence demanding more effort. To analyze these issues, a literature study is performed to review the existing standards in the industry. ISO 14224 and OREDA define a very structured database to get easy access of reliability and maintenance data. OREDA database has well-defined taxonomy, boundaries and database structure. Also it has a well-organized procedure in place to collect, and store reliability data. Quality assessment of the data being collected is done through predefined procedures guideline. OREDA have very consistent list of codes to store language in coding form in the reliability and maintenance database.

By reviewing the existing standard in the industry, a few shortcomings have been identified both in the RMS and PTC failure reporting procedures. It is observed that data from the sources is collected by the responsible person but the collection method is usually not tested and planned. Data collection sources, methods and procedures within company or outside the company lack well-defined criteria and data quality assurance processes. Currently, the company is using Field Service Reports (FSR) and company's other databases as data sources for RMS. Company cannot access client's system that contains equipment utilization and process-related information. This can lead to missing information or ambiguous data because the data-entry responsible person needs to make assumptions sometimes to complete the missing operational and environmental data.

The RMS database structure lacks well-defined taxonomy, design parameters, and adequate failure mode classification. The Failure modes is an important aspect of high quality database since it can help in identifying the need for changes to maintenance periodicities, or the need for additional checks. The Offshore & Onshore Reliability Data (OREDA) project participating companies e.g. Statoil can calculate failure rates for selected data populations of within well-defined boundaries of manufacturer, design and operational parameters. These features are missing in RMS database.

It is recommended that PTC consider developing a failure reporting database to handle their failure event data in an organized way. For this purpose, failure reporting, analysis, and corrective action system (FRACAS) technique is suggested. FRACAS data from FRACAS database can be used effectively to verify failure modes and failure causes in the failure mode effect and criticality analysis (FMECA). Failure review board in the FRACAS process includes personnel from mix disciplines (design, manufacturing, systems, quality, and reliability engineering) as well as leadership (technical or managerial leads), to make sure that a well-rounded discussion is performed for particular failure related issues. The Failure Review Board (FRB) analyzes the failures in terms of time, money, required corrective actions. And finally management makes the decisions on basis of identified corrective action.

As data quality has high impact on the outcomes of reliability analysis through reliability management system. To have a good data quality, data collecting procedures and process management should be well-organized. It is crucial to performed data quality assessment on collected data. A data mining technique is discussed as a part of suggestion to improve data quality in RMS database. Once data is stored in RMS database a data mining method; data quality mining can help to assess the quality of data in database. This is done by applying a data mining (DM) tool to look at interesting patterns of data with the purpose of quality assessment. Various data mining model are available in the market but PTC needs to select DM model which suits best their business objectives.

RMS database is hard-wired so it is difficult to change its features and database structure. However, if PTC emphasize on improving failure reporting procedures and data quality in data sources locating within the company, it will directly and positively affect the data quality in RMS and the results of data analysis in RMS. This in turn, can improve their decision making process regarding new product development and redesigning the existing products.

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Chapter 1

1. Introduction

1.1. Background

Petroleum Technology Company (PTC), an oil and gas service Company, would like to improve the effectiveness of collecting, managing and accessing data related to their product performance. Today, the company has procedures and processes in place to perform these tasks. PTC has been using a web-based reliability management system (RMS) provided by ExproSoft. RMS is customized by ExproSoft according the PTC requirements. However, PTC is interested in reviewing alternative methods which could mitigate the chances of error, increase reliability of data input and increase overall evaluation of product portfolio. The Company would also like to implement methods by which they can combine production, servicing and operational history in one platform and can connect reliability database with this platform.

The goal of the master thesis is to evaluate the PTC reliability management system, analyze different elements of current system on the basis of existing standard in industry such as ISO 14224 and OREDA. Furthermore, the thesis presents some suggestions which could help PTC in improving the failure reporting structure within the company and improvement in quality of data being recorded in RMS.

1.2. Purpose

The purpose of the thesis is to analyze the efficacy of PTC Reliability Management System-with suggestions for improvement in data quality and decision making. The analysis is categorized into:

- The literature review of the standards for the existing database structures and methods with special attention to the failure data treatment.
- Analyze the efficacy of existing Reliability Management System with more advance standards currently in-use in the industry.
- Propose methods for improved data quality and data collection procedures to improve product reliability.
- Propose a more suitable technique for failure reporting and corrective actions to help better decision making to re-design more reliable equipment.

1.3. Scope and limitations

The scope of the thesis is to discuss Reliability Management System of PTC which has been in use for the last several years. The thesis provides an overview of database taxonomy, different features of database and workflow of RMS. Furthermore, efficiency and effectiveness of PTC

RMS is analyzed in accordance to ISO 14224 and OREDA by comparing RMS database structure to OREDA database structure. An important feature *Categories of Failure Modes* of the RMS is analyzed thoroughly on the basis of ISO 14224 and OREDA database.

The thesis also recommends suitable techniques to improve failure reporting structure and data quality assessment. If implemented, these techniques could help to improve data collection and reporting management procedures within the company. As a result company's data related to failure events could be less ambiguous as compared to its current state. This in turn, can improve decision-making process regarding new product development and redesigning the existing one.

The Reliability Management System of PTC relies on data quality in internal and external source systems. However, the data sources, their data quality, and data consolidation in the other sources such as production database, engineering database, and inspection database is beyond the scope of the thesis.

1.4. Thesis structure

To make the thesis more understandable, it is divided into the following chapters:

Chapter 1 – Introduction: Provides background information of the thesis, its purpose, scope and limitations.

Chapter 2 – Theoretical background: Provides a brief explanation of a reliability management system and some common reliability terms which have been used throughout this thesis

Chapter 3 - Reliability Management System of PTC: Provides an overview of the RMS workflows, its Taxonomy, structure and its main features.

Chapter 4 - ISO 14224 and OREDA databases and their data quality: The thorough literature review of ISO 14224 and OREDA database is conducted in the chapter. Data quality aspects and management of OREDA and ISO is discussed briefly.

Chapter 5 - Analysis of efficacy of PTC Reliability Management: The chapter provides a comparative study between PTC RMS and ISO 14224 and OREDA standards. Analysis of failure reporting procedures, quality of database and data quality in RMS is performed.

Chapter 6 - Suggestion for improved data collection and decision support: The chapter includes suggestions for improved data quality in the RMS database and improved failure reporting procedures for better decision making in PTC. The suggestions are categorized into minor, moderate and some major suggestions.

Chapter 7 – Discussions: The major findings of the study and how the suggested approaches can help PTC to improve those problems are discussed in the chapter.

Appendixes: Appendix A includes the list of abbreviations and appendix B includes screenshots of the reports and analysis results from PTC RMS to give the reader a better understanding of the RMS report structure.

Chapter 2

2. Theoretical background

This chapter provides a theoretical explanation of the common reliability terms which have been used in the thesis.

2.1 Reliability management system

A reliability management system (RMS) is a tool that helps the manufacturers to analyze the reliability performance of their products. They can use reliability management system to develop reliability specification for equipment improved performance and achieve desired results. (Murthy et al., n.d)

According to (Iordache, 2011, p.193) "*The RMS includes the software allowing the reliability predictions, the reliability test mini-coupon design, the software for failure mode identification by classification, and the tests correlation software.*"

The key elements of a reliability management system are: (Murthy et al., n.d)

- A data collection system
- Tools and techniques for data analysis
- A user interface to support and guide the equipment's manufacturer in making effective decision

It is beneficial, if a reliability management system is connected to the other computerized management systems within the company to make the process efficient. This is illustrated in figure 1. (Murthy et al., n.d)

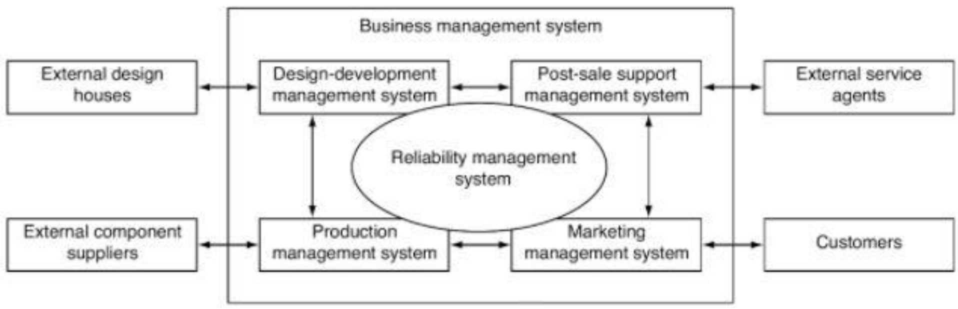


Figure 1 : *A reliability management system (Murthy et al., n.d)*

A reliability management system is the system of three interconnected modules: (Murthy et al., n.d)

i. Data and information module
ii. Knowledge module
iii. Interface module

These modules are shown in figure 2.

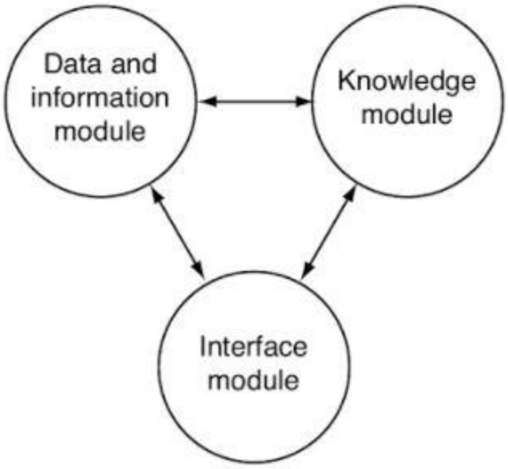


Figure 2: *Modules of a reliability management system (Murthy et al., n.d)*

Data and information module: Data for RMS can be taken from different sources. These sources can be within organization or external. RMS must be able to combine and merge all data from these sources in the required format. Data can be collected either from laboratories or field. Data is in the form of either discrete value or continuous value, in the latter case it can be failure time or censored time. (Murthy et al., n.d)

Knowledge module: A reliability management system should have a knowledge module which can offer either of following three categories of software; (Murthy et al., n.d)

- for general reliability analysis,
- for specific reliability analysis or
- Statistical software that involves general reliability analysis.

Interface module: A reliability management system should have a user interface i.e. it should allow user to set target and objectives and look at the output. A reliability management system should have two interface module; a user interface and application interface. A user interface provides possibility of the data input and output to RMS. While the application interface provides connection between variety of external program and database. (Murthy et al., n.d)

A basic reliability management system offers a calculation of basic reliability parameters such as mean time to failure (MTTF), failure rate (λ), survivor function ($R\ (t)$), probability of failure on demand (PFD). It also performs lifetime distribution analysis both parametric and non-parametric, such as exponential distribution, Weibull distribution, and Kaplan- Meier estimation. We will describe these terms in detail in the next section.

2.2 Basic reliability theory

This section, includes some basic reliability terms used in reliability management system which have been discussed in this thesis.

2.2.1. Failure function, $F(t)$ and Survival function, $R(t)$

Mathematically reliability is measured as the probability that a system continue to function successfully during a specified time interval$(0, \mathrm{t})$, under given operating condition and environment. (Todinov, 2005)
The reliability function given as $R(t) = P(T > t)$, is the probability that component will not fail before the specified time or will work more than specified time t. This also called survival function. This function is monotonic non-increasing function means it is always unity at start of life of component. (Todinov, 2005)
This function is connected to cumulative distribution function $F(t)$ of time to failure such that;

$$R(t) = 1 - F(t)$$

Let us consider a component with its life time from installation until it fails. We denote lifetime with T and it is a stochastic variable since we cannot predict when component will fail. Denoting life time distribution with $F(t), F(t) = P(T \leq t)$, gives the probability that the component will fail before specified time t. It is also known as failure probability or unreliability function.(Todinov, 2005) (Aven, 1992)
Often, reliability analysts are more interested in survivor function rather than failure function. Probability density function and unreliability function are linked together. (Aven, 1992)
Assume, T has continuous distribution, such that

$$F(t) = \int_0^t fs).ds$$

$f(t)$ is probability density of T that is, it describes how failure probability is spread over time. Figure 3 illustrates relationship between $F(t)$ and$f(t)$. (Todinov, 2005) (Aven, 1992)

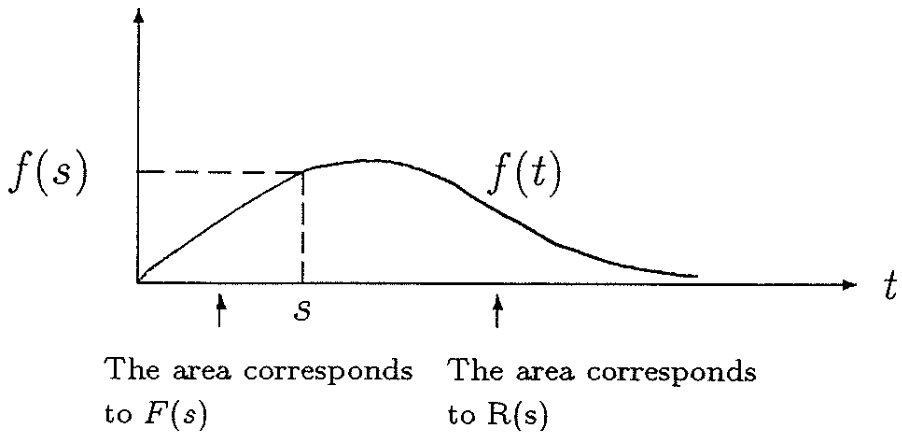


Figure 3: *Relationship between $F(t)$ and $f(t)$ (Aven, 1992)*

2.2.2 Failure rate, λ(t)

Failure rate expresses that how fast or slow a component can approach towards the failure at time t. A high failure rate indicates towards a high probability that component will fail soon. A low failure rate represents low probability that component will fail soon. (Aven, 1992)

It can be given as

$$\lambda(t) = \frac{f(t)}{R(t)}$$

Where,

$$f(t) = \frac{dF(t)}{dt}$$

Often failure rate takes shape of bath tub as shown in figure 4.

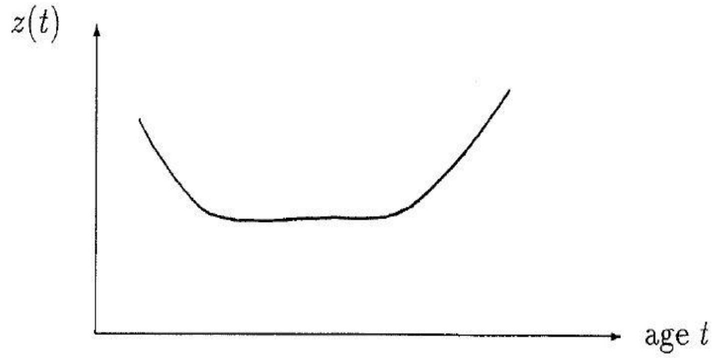


Figure 4: Bath tub shape of failure rate (Aven, 1992, p.265)

In the first phase failure rate is decreasing. This phase is called burn-in phase. Most often the units are tested before sending to the customer. That is why it is common practice that burn-in period is not included when reliability analysis is performed. Failure rate for component in next phase i.e. useful life phase is constant. If failure occurs in this phase it is "purely by chance". In the next phase i.e. fatigue phase, an increasing failure rate is due to fatigue or age limit of a component but proper maintenance strategies can eliminate the problem before it occurs due to aging. (Aven, 1992)

A Distribution with increasing failure rate represents IFR (increasing failure rate) as shown in figure 5.

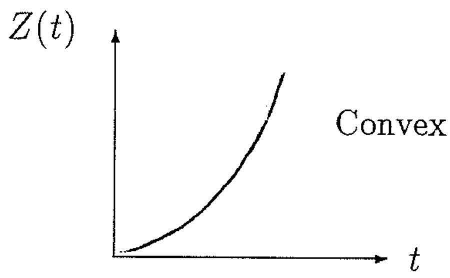


Figure 5: IFR distribution (Aven, 1992)

A distribution with decreasing failure rate represents DFR (decreasing failure rate) illustrated in figure 6.

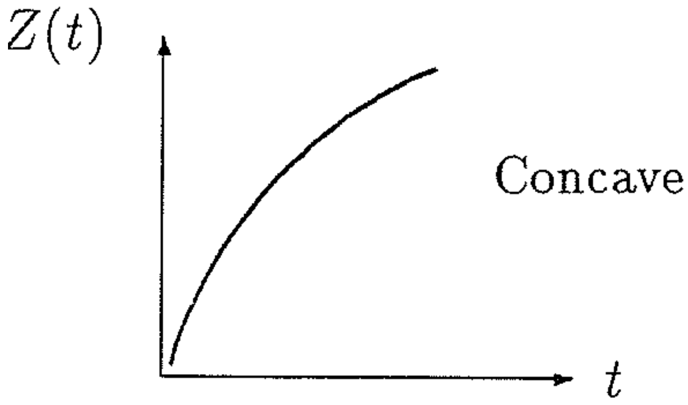


Figure 6: *DFR distribution (Aven, 1992)*

A constant failure rate gives linear hazard illustrated in figure 7.

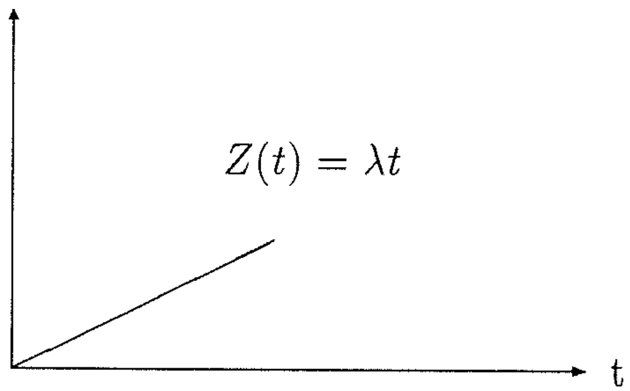


Figure 7: *Hazard for exponential distribution (Aven, 1992)*

2.2.3 Mean Time To failure (MTTF)

MTTR is an area below the survival function $R(t)$ between zero to infinity and is also referred as mean expected life time. (Aven, 1992)

MTTF is defined as *"Mean time to failure (MTTF) of a system is the expected time until the occurrence of first system failure. If T is a random variable that represents the time to occurrence of system failure, then*" (Grassmann, 2000, p.447)

$$MTTF = E(T)$$

Given the system reliability $R(t)$, the MTTF can be represented as

$$MTTF = \int_0^\infty R(t)d(t)$$

MTTF calculation is very popular among many industries because this estimate helps to understand that how much capability a component design has, to meet the reliability goals required for customer satisfaction. Also this calculation guides in determination of design trade-offs thus helps in selecting the best possible design approach. (Crowe and Feinberg, 2001)

2.2.4. Life time distributions

The plot shape of $f\ (t)$ and thus $F(t), R(t), z(t)$ depends on the type of selected lifetime distribution ("model") and the parameter values in the distribution. There are many types of lifetime distribution models such as exponential, Weibull, Gamma. However, the most popular life distribution models in reliability engineering are exponential life time distribution and Weibull lifetime distribution. (Aven, 1992)

a. Exponential distribution

The exponential distribution can be expressed as (Aven, 1992)

$$f(t) = \lambda e^{-\lambda t}, t \geq 0$$

Exponential distribution model has a constant failure rate.

$$z(t) = \lambda$$

A component that follows exponential failure time distribution can fail any time independent of the age of that component. Exponential distribution is memory-less and this property simplifies mathematical modelling. In practical, application reliability analysis is performed for a lifetime of component for limited period of time so exponential distribution also applicable for large values of t. (Aven, 1992)

The mean and variance in exponential distribution is given as (Aven, 1992)

$$ET = {}^{1}/_{\lambda} \ and\ VarT = \frac{1}{\lambda^2}$$

The exponential distribution is used for lifetime of electrical and electronic components. Sometimes it is also useful for lifetime of large mechanical units such as pumps, when unit continues to operate for large period of time and maintenance performed on unit causes different aging for various components in unit. (Aven, 1992)

b. Weibull distribution

When the failure rate is increasing or decreasing then Weibull lifetime distribution is used. Weibull distribution can be expressed as (Aven, 1992)

$$f(t) = \lambda^{\beta} \beta t^{\beta-1} e^{-(\lambda t)^{\beta}}, t \geq 0$$

Weibull distribution model give the failure rate as

$$z(t) = \lambda^{\beta} \beta t^{\beta-1}$$

If $\beta = 1$, then failure rate becomes constant, and Weibull distribution becomes exponential distribution.

If $\beta > 1$, the failure rate is IFR (increasing failure rate).

If $\beta < 1$, the failure rate is DFR (decreasing failure rate).

The expected lifetime and variance of Weibull distribution is given as: (Aven, 1992)

$$ET = \frac{1}{\lambda}\Gamma\left(1+\frac{1}{\beta}\right) and\ VarT = \frac{1}{\lambda^2}[\Gamma\left(1+\frac{2}{\beta}\right) - \Gamma^2\left(1+\frac{1}{\beta}\right)]$$

Weibull distribution is effectively used in reliability analysis of ball bearings, electrical insulation etc. The Weibull distribution is extensively used in maintenance analysis for the purpose of test optimization and replacement intervals. (Aven, 1992)

2.2.5. Kaplan-Meier estimator

The Kaplan-Meier estimator is used to perform non-parametric estimation of the survival function. Kaplan-Meier plots helps to estimate the survival probability for both censored and complete datasets.(Rausand and Høyland, 2004)

(Cleves, 2010, p.93) defines Kaplan-Meier estimator as *"it is a non-parametric estimate of survivor function $R(t)$, which is the probability of survival past time t or, equivalently, probability of failing after t. for a dataset with observed failure times, $t_1, \dots\dots\dots, t_k$, where k is the number of distinct failure times observed in data, the Kaplan- Meier estimate at any given time t can be given as:"* (Cleves, 2010)

$$\hat{S}(t) = \prod_{j|t_j \le t} \left(\frac{n_j - d_j}{n_j}\right)$$

Where,

n_j= number of an individual at risk at timet_j.

d_j= number of failure at timet_j.

The Kaplan-Meier is very sensitive at early and middle stage of product lifecycle but not very sensitive at later stage (right tail of distribution).(Rausand and Høyland, 2004)

Kaplan measure plots are used to show time-to-event data by a group of interest. Here the event of interest could be anything positive or negative, for example failure or survival. The Kaplan Meier plot is drawn with survival function on y-axis and time on x-axis. It produces graph in form of stair case either going downward or upward. When the Kaplan-Meier plot goes down it is showing probability of being event-free over time or increasing rate of failure event with the curves going up. Kaplan measure plots are helpful in summarizing the survival experience of any product. (Krause and O'Connell, 2012)

2.2.6. Average probability of failure on demand, PFD_{avg}

The average probability of failure on demand (PFD_{avg}) is a reliability measure which is often used for safety critical system or components. Safety critical systems must function when a dangerous condition is detected. For example fire and gas detection systems, nuclear reactor control systems or railway signaling and control systems. (Aven, 1992)

PFD_{avg} is mathematically expressed as:

$$PFD_{avg} = \frac{\int_0^t F(t).dt}{\tau}$$

With the following assumptions:(Aven, 1992)

- System is tested and repaired at regular time intervals of lengths τ. After repair, system should be as good as new.
- Time required for testing and repair is very negligibly small.
- Components start operation at $t = 0$ and state of components is only identified at test.

PFD_{avg} is also called the mean fractional dead time (MFDT). MFDT is average proportion of time system is not functioning. (Aven, 1992)

That is why,

$$PFD_{avg} = MFDT.$$

PFD_{avg} can also be expressed as:

$$PFD_{avg} = \frac{\int_0^t \bar{A}(t).dt}{\tau}$$

$$\bar{A}(t) = Average\ unavailability\ of\ system$$
$$= P(\ a\ failure\ has\ occurred\ at, or\ before, time\ t) = P(T \leq t) = F(t)$$

$\bar{A}(t) = F(t) = PFD(t)$

2.2.7. Failure modes

A failure mode describes the fault, which means, how we can observe the fault. It may be more suitable to call it fault mode but the term "failure mode" is being widely used in the literature. (Rausand and Høyland, 2004)

(ISO14224, 2006) defines failure mode as *"the occurrence of an abnormal physical phenomenon through which the loss or the risk of loss of the function of a given unit of equipment is observed."*

A method failure mode, effects, and criticality analysis is used to classify possible failure modes for each of component of a unit. Also, the effects of these failures on the system are studied. FMECA is mostly used by designers. Often, this provides basis for maintenance planning. (Rausand and Høyland, 2004)

- **Identification of failure modes:** Failure mode is identified by studying the output of various functions. A function can have one or multiple outputs. Depending on the effect some outputs have strict definition and some output may have target value with an acceptable deviation. (Rausand and Høyland, 2004)

- **Failure mode categories:** A failure mode is an observation of the failure from the outside, such as a component stops performing desired function. "Internal leakage" is a failure mode of a shutdown valve but wear of the valve seal is not a failure mode rather it is cause of failure. Failure mode can be classified as follows: (Rausand and Høyland, 2004)

  1. **Intermittent failures:** causes loss of function only for a very short period of time.

2. **Extended failures:** causes loss of function that will not be resumed until some part of the functional block is replaced or repaired.

Extended failures further have two categories: (Rausand and Høyland, 2004)

a. **Complete failures:** cause complete loss of a desired function.
b. **Partial failures:** cause loss of some function but do not cause full termination of a required function.

Both the complete failures and the partial failures may be further classified: (Rausand and Høyland, 2004)

a. **Sudden failures:** It is not possible to predict such failures by prior testing or examination.
b. **Gradual failures:** These failures can be forecasted by testing or examination. This is usually done by comparing actual device performance with a performance specification. However in some cases, it is difficult to perform this task.

The extended failures are further split into following: (Rausand and Høyland, 2004)

a. **Catastrophic failures:** Such failure is both sudden and complete.
b. **Degraded failure:** Such failure is both partial and gradual.

A reliability management system has inbuilt software for failure mode identification by classification. A high- scored reliability management system has adequate definition and classification of failure modes integrated to built-in software.

Chapter 3

3. Current Reliability management system of PTC

This chapter is prepared using PTC Reliability Management System (RMS) software and discussions with PTC personnel. To help reader in understanding the literature along with RMS software functionality, some additional screenshots from RMS software are added in appendix B.

PTC has reliability management system (RMS). The RMS provides the following data: (Andersen, 2012)

- Current and historical installation
- Operational experiences (positive and negative)
- Investigations report
- Reliability data and failure cause analysis

RMS has been applied for all equipment made by PTC which are in operational phase. The RMS system can register failure modes related to the installation, operation and retrieval phases. The system has further control if the failure mode is a safety-critical or non-safety critical mode. (Andersen, 2012)

3.1. Introduction to PTC RMS

The purpose of PTC reliability management system is to bring improvement in the equipment design and reduce the risks of critical failures, hence improving their services for the customers. The customers expect the products to meet the specified parameters upon delivery as well as complete their reasonable lifetime. The target of the product development is not just to complete a task that starts from design to installation of any equipment. The reliability activities are not beneficial for program management unless the outcomes are used either for design improvements or reliability assessment. Assessments, analysis, and test tasks are performed to get the results which are then used by management for improved decision making. (Flamm and Luisi, 1992)

The reliability design of an equipment is expressed in terms of its cost, schedule and performance, the customer needs, and marketing the competitive advantage for the product. Reliability values are used in marketing and warranty material. This reliability management system is an integral part of overall PTC system. Reliability activities start early in the design process and employed continuously through the product life cycle. This is to minimize or eliminate the chance of a product failure. Reliability management system of PTC is based on collecting data such as Installation time, failure time, pull time, failure modes, then reliability data is made through data analyses such as mean time to failure (MTTF), failure rate (λ), survivor function ($R\ (t)$), probability of failure on demand (PFD). Finally, fact-based decisions such benchmarking, product improvements, and system risk analyses are made on the basis of performed reliability analysis. (Flamm and Luisi, 1992)

3.2. Main features of PTC RMS

The key features of PTC RMS are:

- Installations data
- Investigation reports
- Failure analysis

Figure 8 shows PTC RMS home page and different elements of the system.

Figure 8: RMS system home page

3.2.1. Installations data

Installation database of RMS provides details for installed equipment, which has been delivered to the customers. Operational status is displayed either as sent, installed or operating, depending on the equipment status. Installation section (c in figure 9) of RMS displays following contents:

- Equipment type
- Region (where equipment is installed)
- Field (platform where equipment is located)
- Well (well number)
- Depth
- Customer (client’s name)
- SN (serial number of equipment)
- Installation date
- Status (sent , installed or pulled)

Let us consider an example (see figure 9) of equipment type WI-valve (water-injection valve)[a] at field Ekofisk B[b]. The customer is ConocoPhillips in the region, Norway. The system displays current operational status of the equipment in terms of pulled, operating or installed. An equipment having the pulled status is either failed or its operation is completed and it is sent back to the customer's storage place at PTC inventory. RMS System calculates service time details according to status of equipment. The system is displaying total service time[d] as 5.6 years for one unit in the example. One of the unit is not installed yet while the one unit which has been operating is pulled after giving service of 5.6 years.

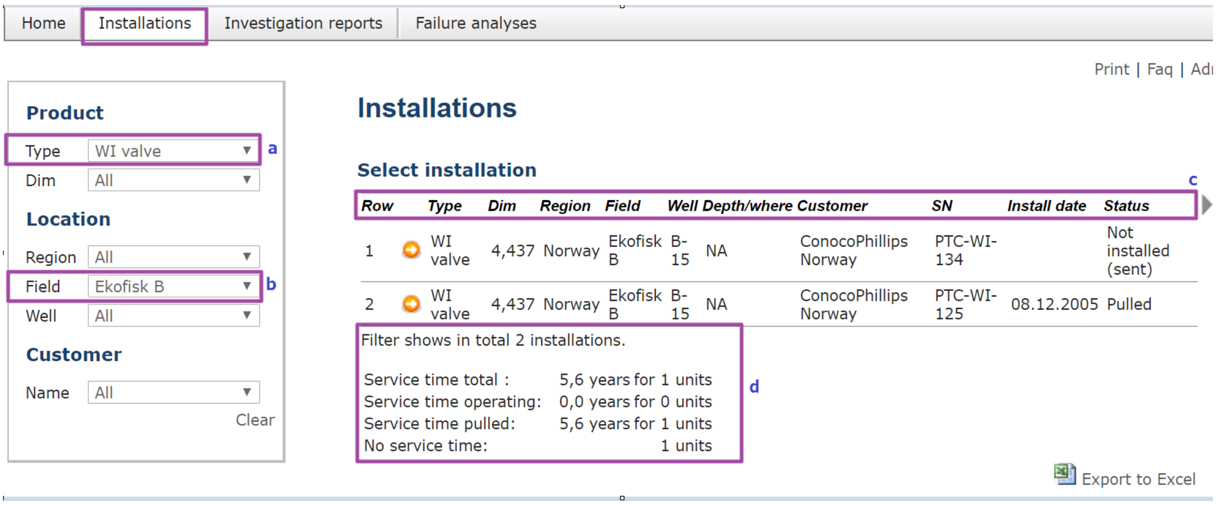


Figure 9 : *Two WI valves with status as not-installed and pulled and their total service time*

3.2.1.1. Installation reports

For an installed equipment, an installation report is prepared. Appendix B contains screen shot from RMS for a complete installation report for WI valve. The installation report contains following details:

- History of equipment
  - Sent date
  - Installed dated
  - Pulled date
- Design features
  - Primary or backup equipment
- Remarks
  - Type of lock (RNT lock)
  - PL-0025 is referring to 'PakkeListe' / Delivery ticket number 0025 (figure in appendix B)
  - Depending on the operating status of equipment, some remarks are given by the person who prepares the report.

When a client places an order for a product, PTC sends a set of two of the same equipment. One is primary and other is for the backup purpose. This is done to tackle the situation where some equipment is critical to continue production on oilfields and delay in shipment of new equipment can cause critical losses.

This information is also recorded in installation report if equipment in operation is primary or back up. Since, back up product is used in the case of failure of primary equipment and this information is to be used in reliability analysis. Finally, the remarks section of installati on report contains the general information about how failure occurred and the location where failed equipment is placed in PTC storage.

3.2.2 Investigation reports

When a component failure occurs, PTC is informed. PTC suggests customer to pull and investigate the equipment visually on platform. If required, some formal methods (for example, flushing with solvent or methanol) are used on-site to eliminate the failure cause. If failure persists, equipment is sent back to PTC. As soon as failure is confirmed, the responsible person update the status of the equipment to 'failed' in RMS system. The investigation reports in RMS are based on the information from the installation reports. When an equipment is marked as 'failed', the installation report will be transformed into an investigation report, and pulled out of the failure statistics until the report is approved / rejected by a third party (i.e. ExproSoft).

An investigation report is prepared through formal meeting with the customer representative(s). Investigation report section in RMS displays following contents, illustrated in figure 10:

- Report number
- Failure date
- Approval date

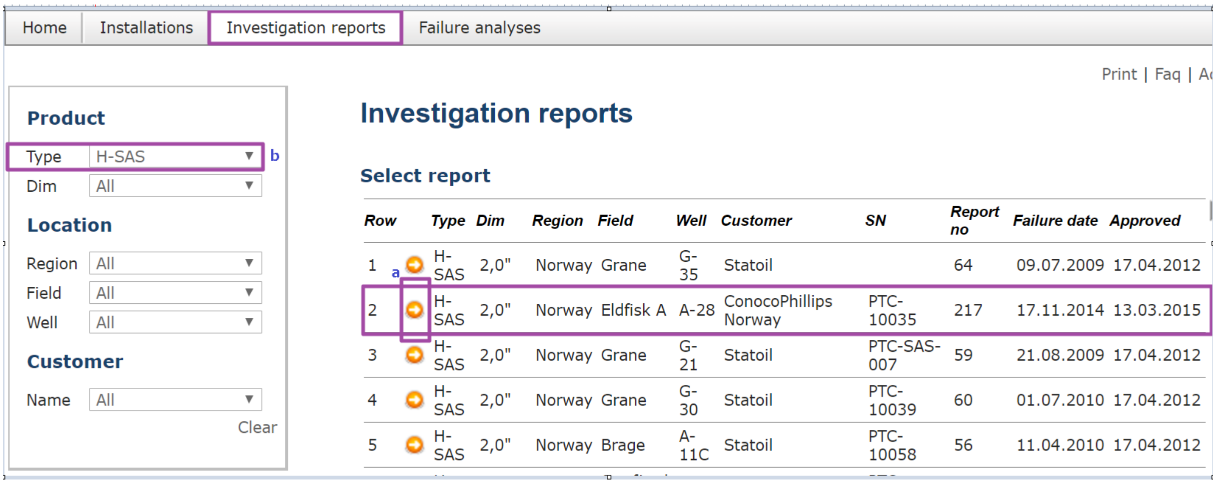


Figure 10 : investigation section of RMS displaying list for all H-SAS

The information for investigation report is collected from the inspection report prepared through a meeting with the client arranged by PTC person responsible for inspection reports. This is arranged to discuss the failure event details.

Figure 11 shows format of the investigation report for H-SAS (Safety and Automation System) in RMS database. The investigation report provides following elements (The superscript characters represent different section of the report in the figure 11).

- Report data [a]
    - Report number
    - Revision number
    - Revision date
    - Classification (restricted/open)
    - Serial number (SN)
- Events sequence [b]
- Failure cause [c]
- Consequences [d]
- Long term remedial actions [e]
- Failure categories [f]
- Appendix (some pictures of equipment being investigated)

In the investigation report, all the sequences of failure events are recorded for the product lifecycle from the installation to the failure. If the on-site corrective actions have been performed on the equipment and re-installation is done, it is also recorded. The equipment supervision is revised periodically. The number of supervisions and date of latest supervision is recorded investigation report.

Investigation report

a

Report data

Report no	217
Revision no	2
Revision date	12.03.2015
Classification	Restricted
SN	PTC-10035

Event sequence b » more

19/07-2006: The H-SAS system was installed and tested OK.

17/11-2014: 01/12-14: The valve did not pass the barrier test. COP tried to wash the valve several times, without any luck.

01/12-2014: Valve was pulled and changed with a new H-SAS. Jan

08/12-2014: Visually inspected. Looks good after over 9 years in operation. Photos on the server.

03/03-2015: Visually inspected Seal area. Damages on back up soft seal. This could result in the valve not closing properly.

Failure cause c » more

It looks like the back up soft seal has some damages, and that this damage could result in the valve not closing properly.

Consequence d » more

The H-SAS was changed With a New H-SAS, in the same spool.

Long term remedial actions e » more

The damaged soft seal has been upgraded to an other material.

Failure categories f

Failure type (when)	Operational failure	» more
Failure mode (how)	Leakage in closed position (LCP)	» more
Failure cause category (why)	Component degradation by operational conditions	» more
Root cause (why)	Uncertain	» more
Reporting	Operator	» more
Warranty	No	» more
Long term remedial actions	Product changes	» more

Figure 11 : *An example of investigation report for H-SAS in RMS*

Here is the explanation of the above mentioned sections of the report.

- **Event sequences**

PTC RMS has set following criteria to create an event sequence. Entire event sequence should be described a step by step with the date and time if possible. The event sequence should include all relevant issues prior to the failure, failure detection, failure escalation and remedial actions taken at the platform. Examples of remedial action taken on the platform are:

- Replacing the valve with dummy or with new valve.
- Full workover
- Flushing with solvent to remove grease from valve seat
- Flushing with methanol to remove shoot from valve seat
- Pressure testing three times without leakage the third time
- Open/close valve three times to restore function

The observed leak rate should be included in event sequence if it's relevant and available. Event sequence for equipment type H-SAS (Safety and Automation System) are shown in figure 11[b].

- **Failure cause**

The person who collects data for failure events (inspection team and responsible person for data collection for RMS) interprets the failure cause through meeting and discussions with the client's representatives. System demands an accurate failure cause description including direct cause and root cause. For a particular H-SAS type component failure cause is shown in figure 11[c].

- **Consequences**

In this section, the consequences are defined as a chain reaction after the failure. It is described if the failure resulted in HSE (Health Safety and Environment) losses, loss of production/ operation, loss of market reputation, material damages on nearby equipment. Potential consequences scenarios that easily could occur if conditions were slightly different are also discussed here. Figure 11[d] shows the consequences for a particular H-SAS type component.

- **Long term Remedial actions**

In this section, those actions are defined which are taken after the incident in an attempt to prevent recurrence or to reduce the consequences upon recurrence. These actions could be installation changes like design material or surface treatment changes. These actions could also be change in the procedure of manufacturing, assembling or operational. The actions to reduce severity upon recurrence could be changed in operational procedures describing what to do if a similar failure is detected or introduction of physical barriers. An example of Long term remedial action performed for a particular H-SAS is shown in figure 11[e].

- **Failure categories**

Following failure categories are recorded in RMS:

- Failure type (when) describes if the failure occurs during installation, operation or retrieval. Operational failures are really important to know since they are included in reliability analysis.
- Failure mode (how) for every installation are pre-registered for each installation in the admin dialog.
- Failure cause category (why) is an overall reason to have failure modes.
- Root cause (why) falls into two categories. Vendor failures or not a vendor failure. Product failure which is not a vendor failure can be cascading failure, operational use outside the product specifications or deposit failure caused by e.g. scale. Product failures

that are a vendor failure can be wrong design, manufacturing failure, human errors during installation, operational use within the product specification.
- Reporting section describes who reported the failure. Failure reports are either received from operators or there are multiple sources of failure reporting. The failure report source is made with the intention to have a filter making a fair comparison of different vendors when reliability numbers are calculated.
- Warranty describes if this is a documented warranty case or not. This is only for in-house statistics.

An example of Failure categories for component H-SAS is shown in figure 11[f].

3.2.3. Failure analysis

In RMS system failure analysis has following sections

- Reliability analysis
- Unavailability analysis
- Failure type analysis
- Failure mode analysis
- Failure cause analysis
- Warranty analysis
- Long-term remedial actions analysis

3.2.3.1.Reliability analysis

To perform the reliability analysis, following information is given in the system:

- Installation dates- Analysis will only include the product installed after and before the mentioned date.
- Burn in period: The reliability analysis only includes the operational failures. The burn in period is mentioned to neglect failures during the first period of successful installation.
- Estimated wear out- This is used to make a realistic estimate of expected time to failure by using Weibull distribution.
- Failure modes: This section allows to choose if the analysis should include all failure mode or only safety critical modes. Since some failure modes have a safety critical effect upon failure.
- Failure type: The reliability analysis only includes operational failures.
- Root cause: Used if a non-vendor failure needs to be excluded.
- Reporting: Failure which is not reported by operators can be excluded in the analysis if required.

RMS performs both parametric and non-parametric data analysis. We will discuss details of lifetime data distribution analysis in RMS in section 3.3.5. The results of the reliability analysis are displayed with following parameters:

- Mean failure rate; calculated as Number of failure/total service time.
- Mean time to failure-industry standards; the industry standard for making MTTF estimate is by inverting failure rates. Calculation of MTTF by using exponential distribution will

normally produce very optimistic and often unrealistic estimate of MTTF. Such MTTF is merely a performance indicator. However, it is most commonly used in the industry and is often referenced in bidding and benchmarking.

- Expected time to failure-observed; it is estimated from defined dataset by considering the area under its associated Kaplan-Meier survivor function plot. This is found by numerical integration with trapezoid sums. This plot can only be established up to the highest operational time found in the dataset.
- Expected time to failure-realistic estimate; true MTTF can be estimated by fitting a Weibull distribution and estimated wear-out time. It will produce a fair model for extrapolation of component survivor function to the time of wear out. True MTTF can be calculated as area under the Weibull distribution function. The wear-out time is selected based on testing, experience or physical modeling of dominant wear out mechanism e.g. fatigue or corrosion calculations.

Figure 12 shows the reliability analysis section of RMS, with following values are chosen in analysis filter: (figure 12[c]

- Installation data range- 1997 to 2017
- Test intervals- 2 months
- Failure mode- safety critical
- Failure type- operational failure
- Root cause – all
- Reporting- all

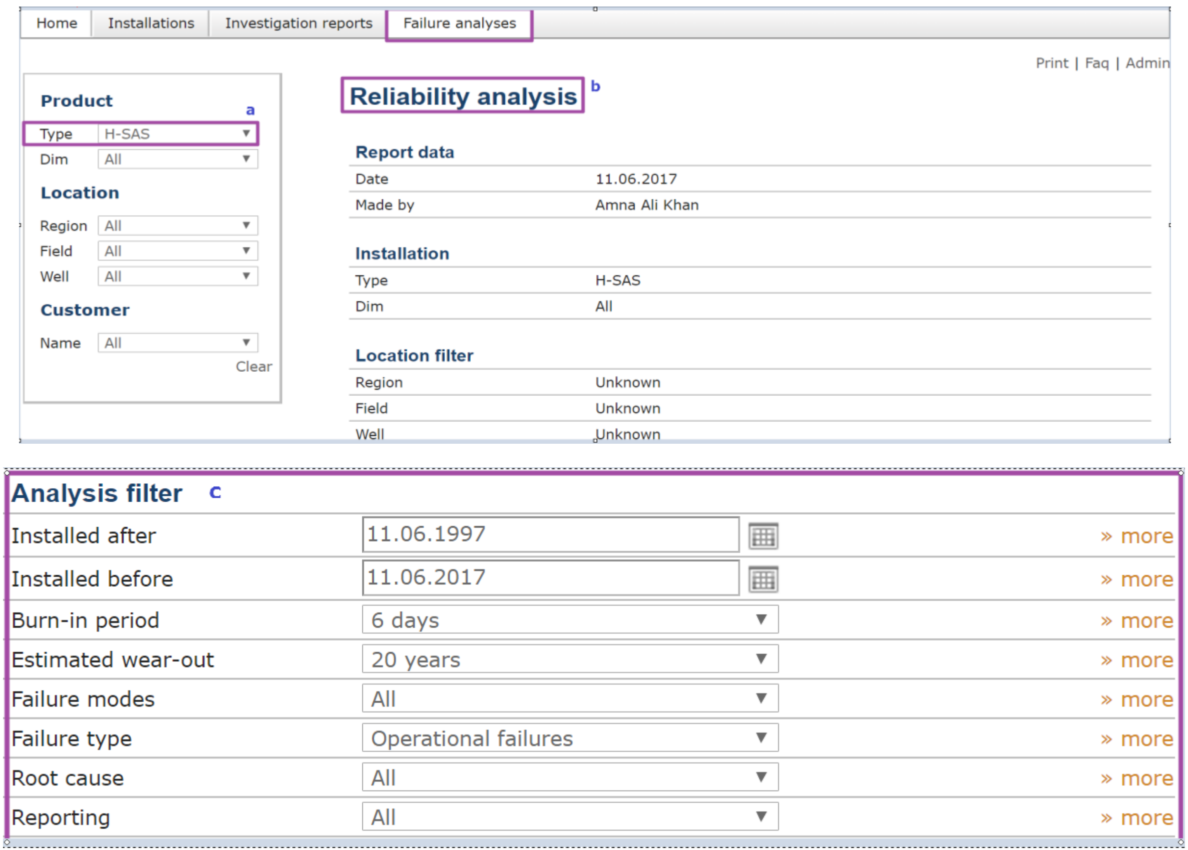


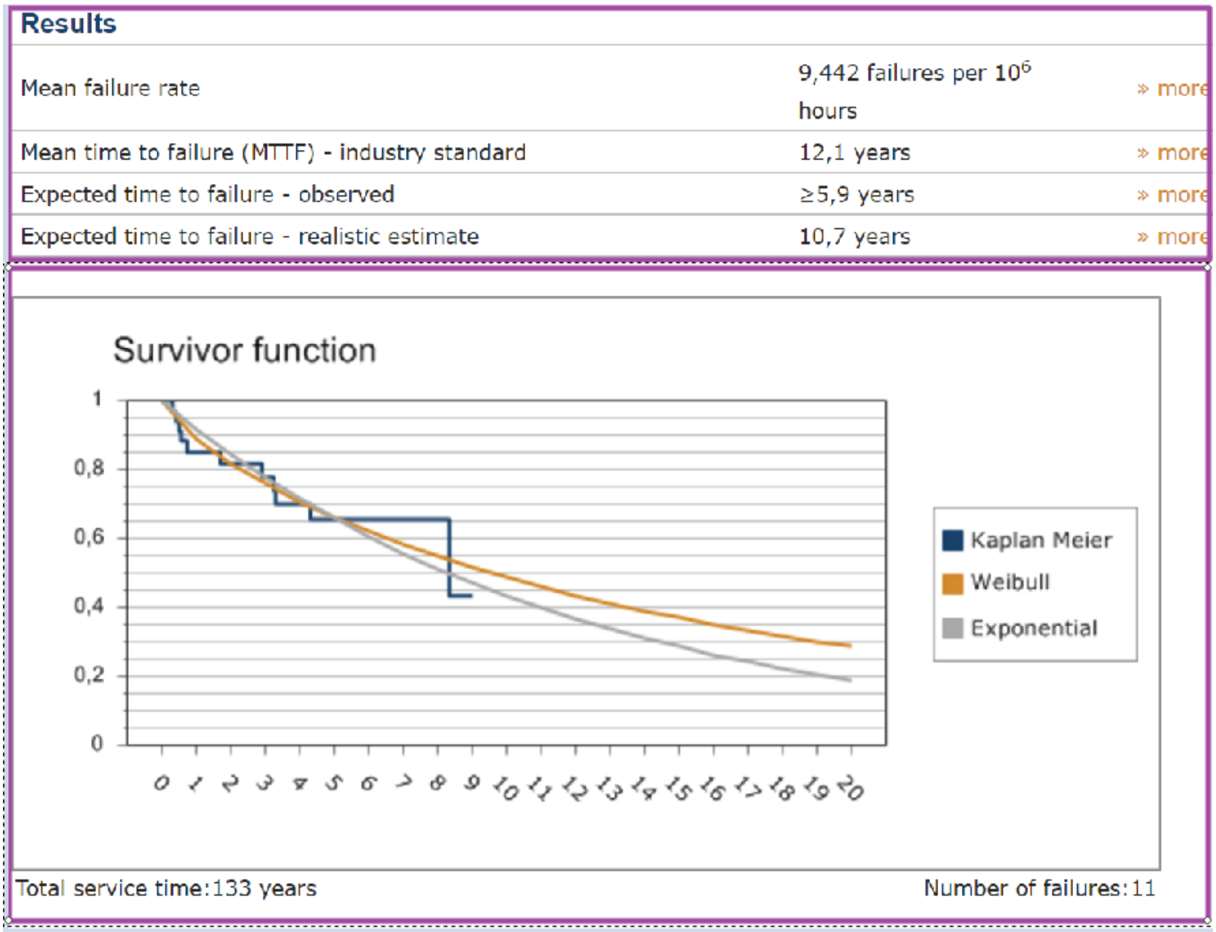
Figure 12 : *Example of values selected in analysis filter*

The reliability results as are shown in figure 13 with following parameters:

- Mean time to failure
- MTTF- industry standard
- Expected time to failure- observed
- Expected time to failure- realistic estimate

Survival function $R(t)$ is plotted in figure 13 with following lifetime distribution models

- Exponential model
- Weibull model
- Kaplan-Meier plot



Results		
Mean failure rate	9,442 failures per 10^6 hours	» more
Mean time to failure (MTTF) - industry standard	12,1 years	» more
Expected time to failure - observed	≥5,9 years	» more
Expected time to failure - realistic estimate	10,7 years	» more

Figure 13 : Reliability parameters displayed in RMS

3.2.3.2. Unavailability analysis

To perform unavailability analysis test interval is required. As explained in Chapter 2, probability of failure on demand (PFD) is dependent on the test time interval. In figure 14, test interval is given as 2 months. PTC RMS includes only safety critical failure mode for unavailability analysis.

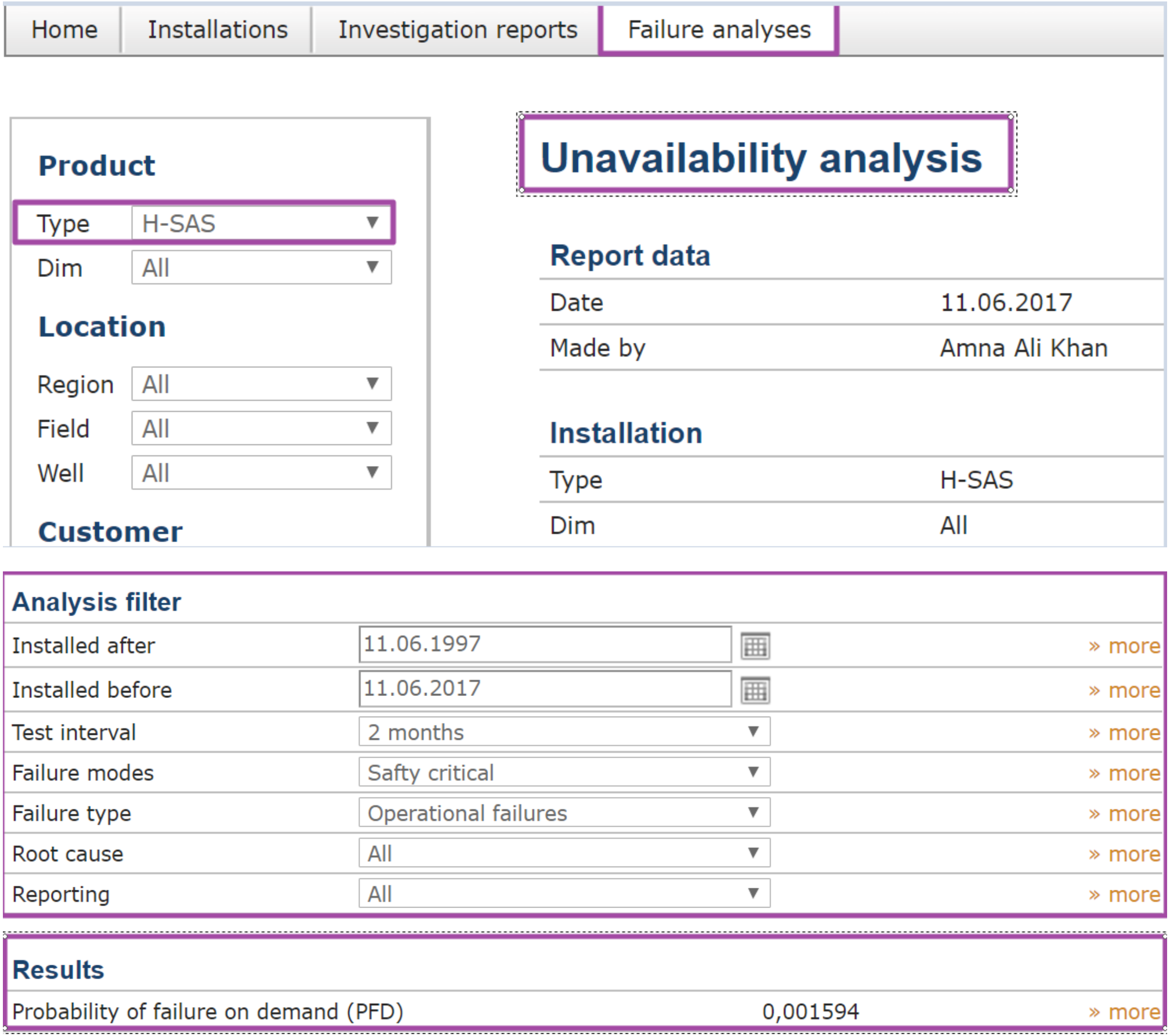


Figure 14 : *PFD calculation with test interval as 2 months*

3.2.3.3. Failure type analysis

In the analysis, it is examined whether failure is occurred during the installation, operational or retrieval phase. For example, for H-SAS installed between 11.06.97- 11.06.2017 there are 11 operational failures and 1 installation. The results are displayed in form of pie chart illustrated in figure 15.

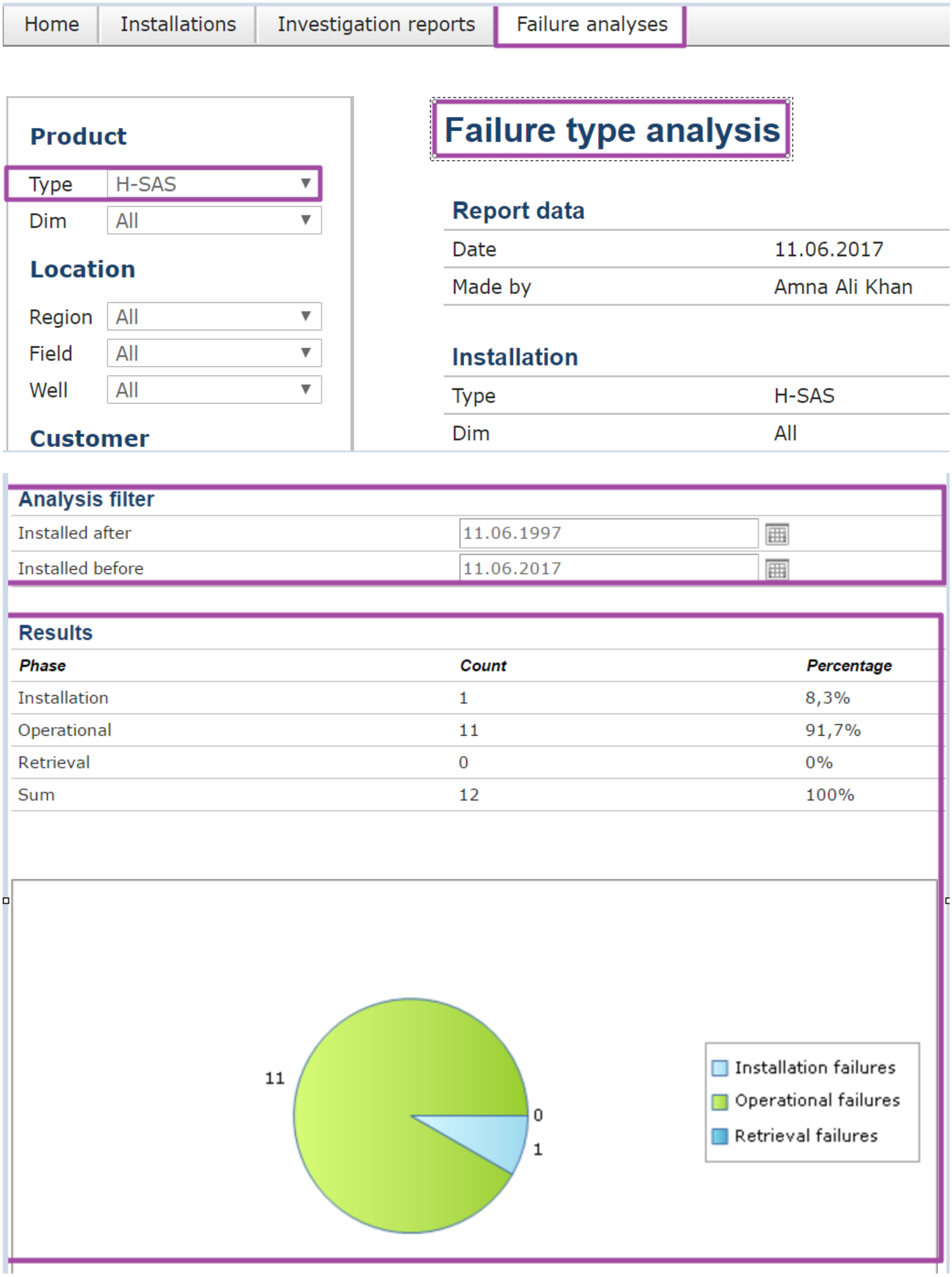


Figure 15 : *Failure type analysis with 11 operational and 1 installation failure*

3.2.3.4.Failure mode analysis

Failure mode analysis tells about the cause of failure for a particular failure type. For the data set in previous section, failure mode analysis result shows one installation failure with failure mode as FPO (Failure prior to Operation) and 11 operational failures with failure mode as LCP (Leakage in Closed Position). This is shown in figure 16 and 17 respectively. The codes for failure mode codes pre-defined in standard such as ISO 14224 and OREDA and embedded in the RMS software.

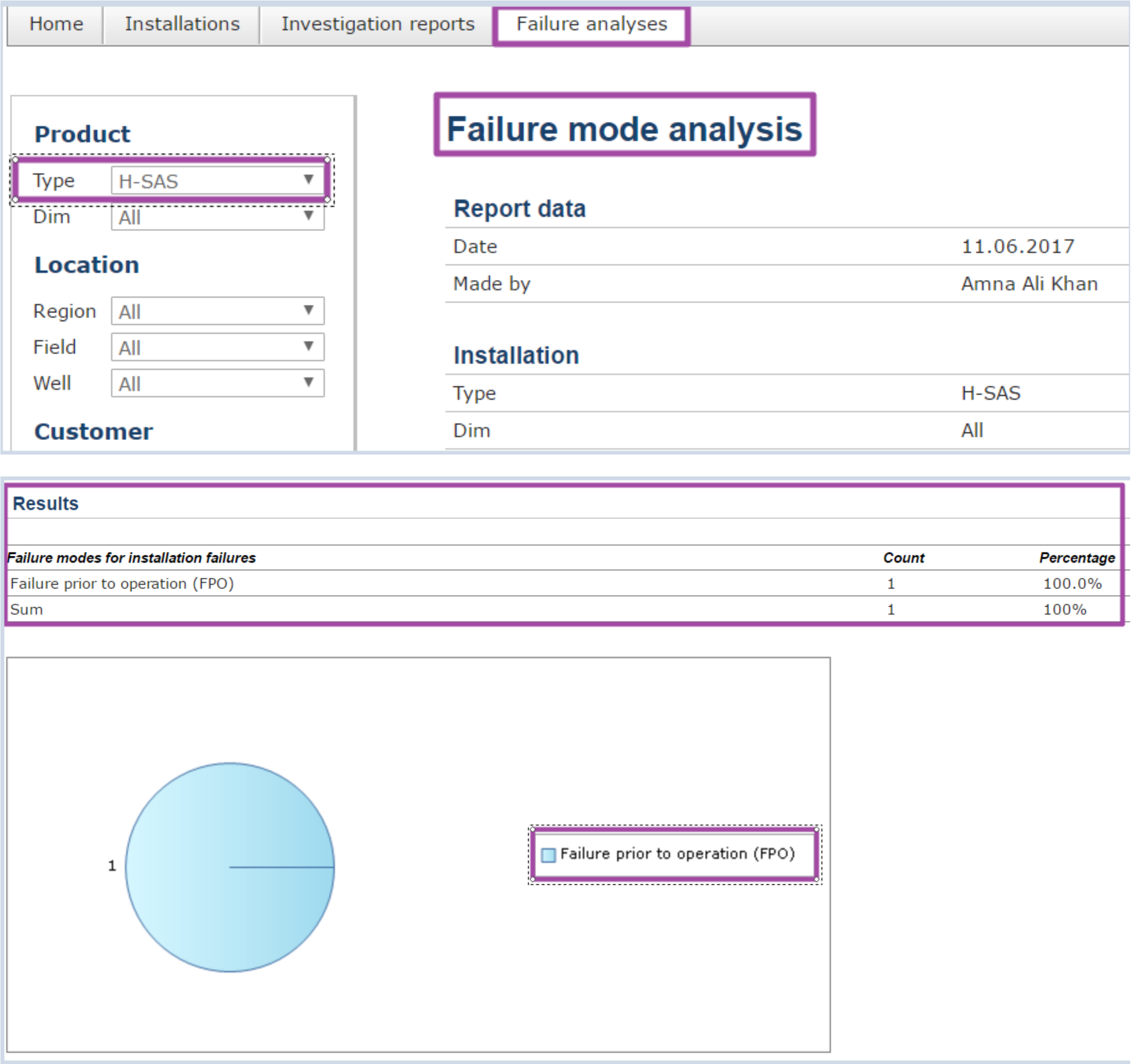


Figure 16 : *One installation failure mode (FPO) for H-SAS*

Failure modes for operational failures	Count	Percentage
Leakage in closed position (LCP)	11	100.0%
Sum	11	100%

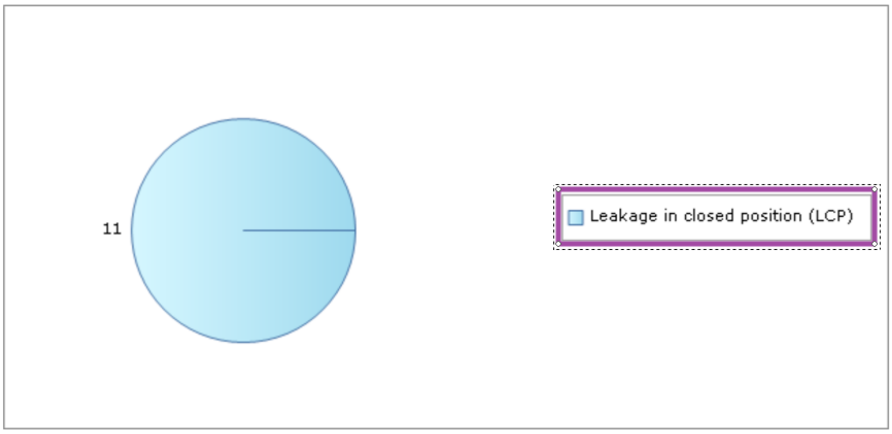


Figure 17 : 11 operational failure mode (LCP) for H-SAS

3.2.3.5. *Failure cause analysis*

Failure cause analysis tells that what causes the component to fail. There can be one or more failure causes for one component. Using same datasets from the previous section, failure cause analysis displays results in form of pie-chart as follows:

- Failure cause for installation failure (figure 18)
  - Human error - 1
- Failure cause for operational failure (figure 19)
  - Component degradation by operational conditions - 4
  - Component deposits by operational conditions – 6
  - Internal cascading failure – 1

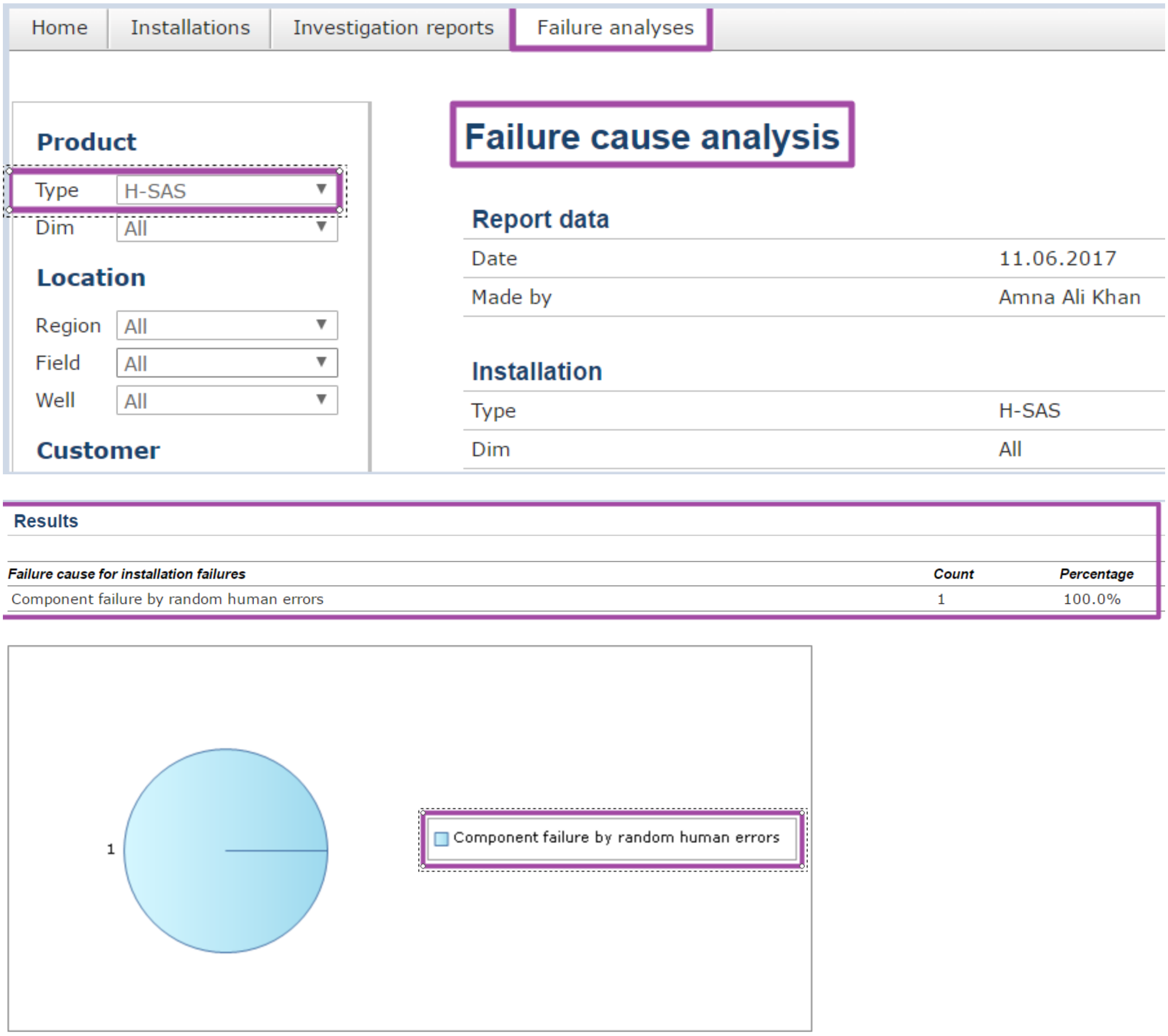


Figure 18 : one failure cause by random human error

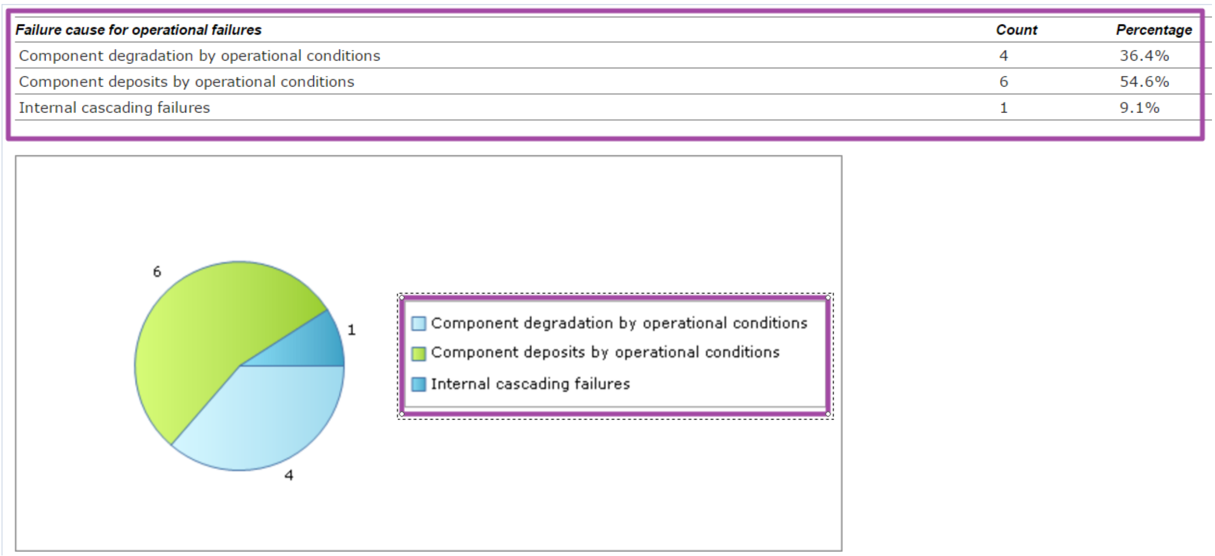


Figure 19 : Failure caused by degradation, deposits or cascading failure

3.2.3.6. Warranty analysis

Warranty analysis verifies that PTC covers the warranty for operational failures of product or not. PTC does not cover warranty for the operational or installation failures.

3.2.3.7. Long-term remedial actions analysis

It is important to mention that what the remedial actions were taken when the failure occurred. Long term remedial actions analysis is done for both installation and operational failures. It can be in form of product change, procedure change or both. Long term remedial actions taken for previous dataset of H-SAS are as follows:

- operational failure (figure 20)
  - no changes – 7
  - procedure changes – 1
  - product and procedure changes – 2
  - product changes – 1
- installation failure (figure 21)
  - procedure changes – 1

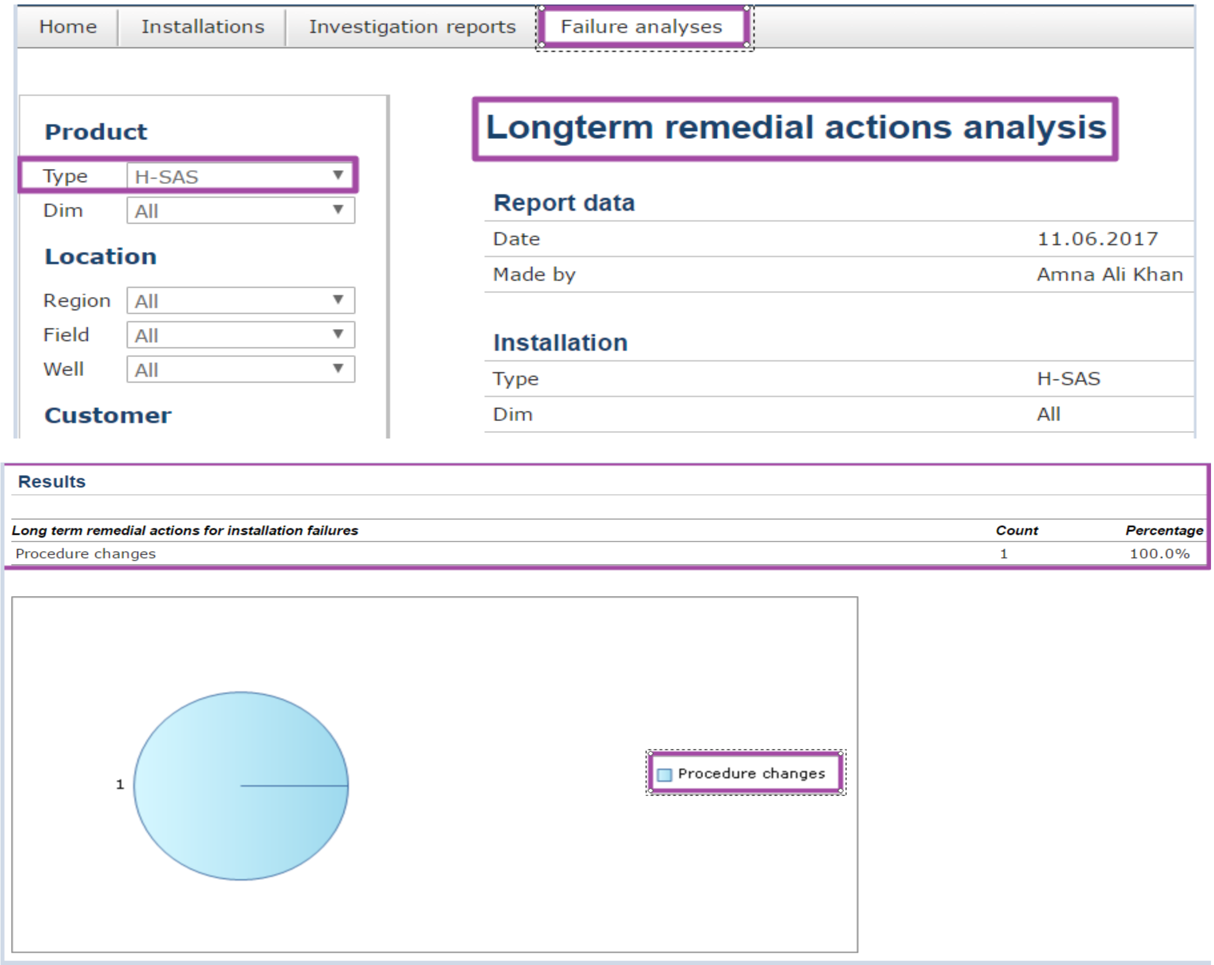


Figure 20 : *One long term remedial action taken for installation failure*

Long term remedial actions for operational failures	Count	Percentage
No changes	7	63.6%
Procedure changes	1	9.1%
Product and procedure changes	2	18.2%
Product changes	1	9.1%

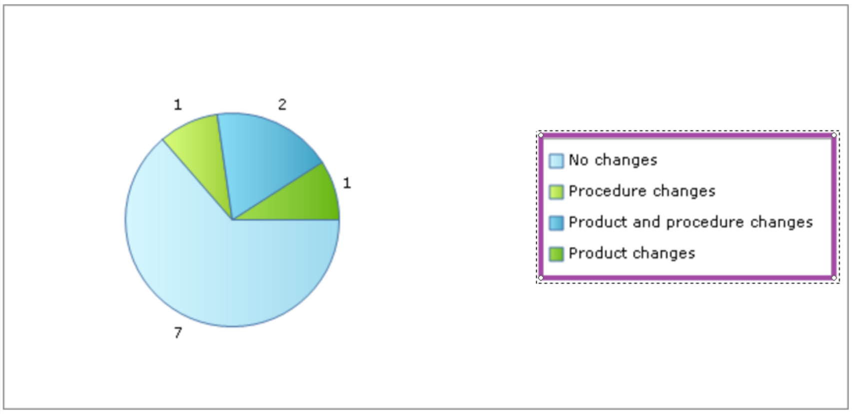


Figure 21 : seven different remedial actions performed for this operational failure

3.3. RMS database structure

The RMS workflow diagram is shown in figure 22. RMS gets the product serial number (SN) from the Production Data Management (PDM) system of PTC. If any event occurs during operation, it is possible to trace the equipment back to the Factory Acceptance Test (FAT) tests, material certificates, component SN, etc. in the PDM system. This is done by searching on the product SN.

The workflow starts with a delivery note referring to the delivered equipment. Equipment installation is registered in RMS. The corresponding installation report is prepared and stored in RMS. However, customer prepares its own installation report after equipment is installed. The default installation report is corrected on the basis of information provided by the customer. When a failure is registered, an investigation report is prepared with the collaboration of PTC workshop mechanics and customer. These investigation reports must be approved by Exprosoft to be included in reliability analysis. (Asbjørn Andersen, n.d)

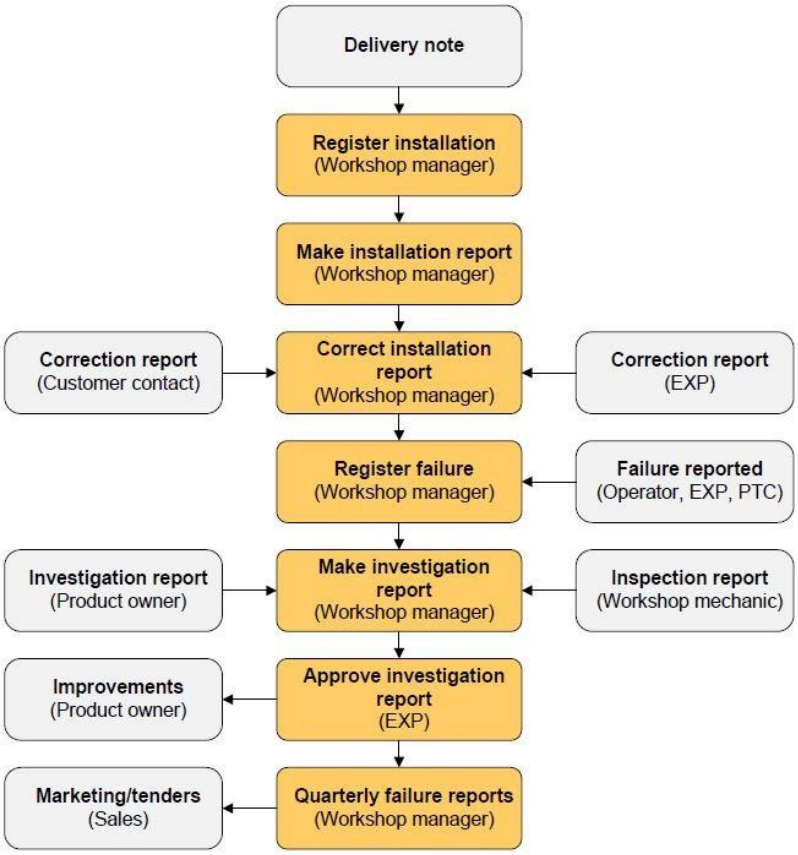


Figure 22 : PTC RMS database work flow (Asbjørn Andersen,n.d)

3.3.1. Failure data bank structure

Following the basic rules of data bank design defined by (Flamm and Luisi, 1992),
PTC RMS introduces a system of three main database files:

- Component Type File

This database file contains information such as component design parameters and specifications, manufacturer, etc. This gives idea about component type number. (Flamm and Luisi, 1992)

- Component File

This database file contains specific component information such as equipment location, serial number, operating parameters, etc. This file serves as component identifier.(Flamm and Luisi, 1992)

- Failure Event File

This database file stores the history related to individual component operations such as failure event, total operating time and/or number of cycles/demands at the time of failure, etc. The general and detailed structure of the RMS failure data bank system is illustrated in figure 23. (Flamm and Luisi, 1992)

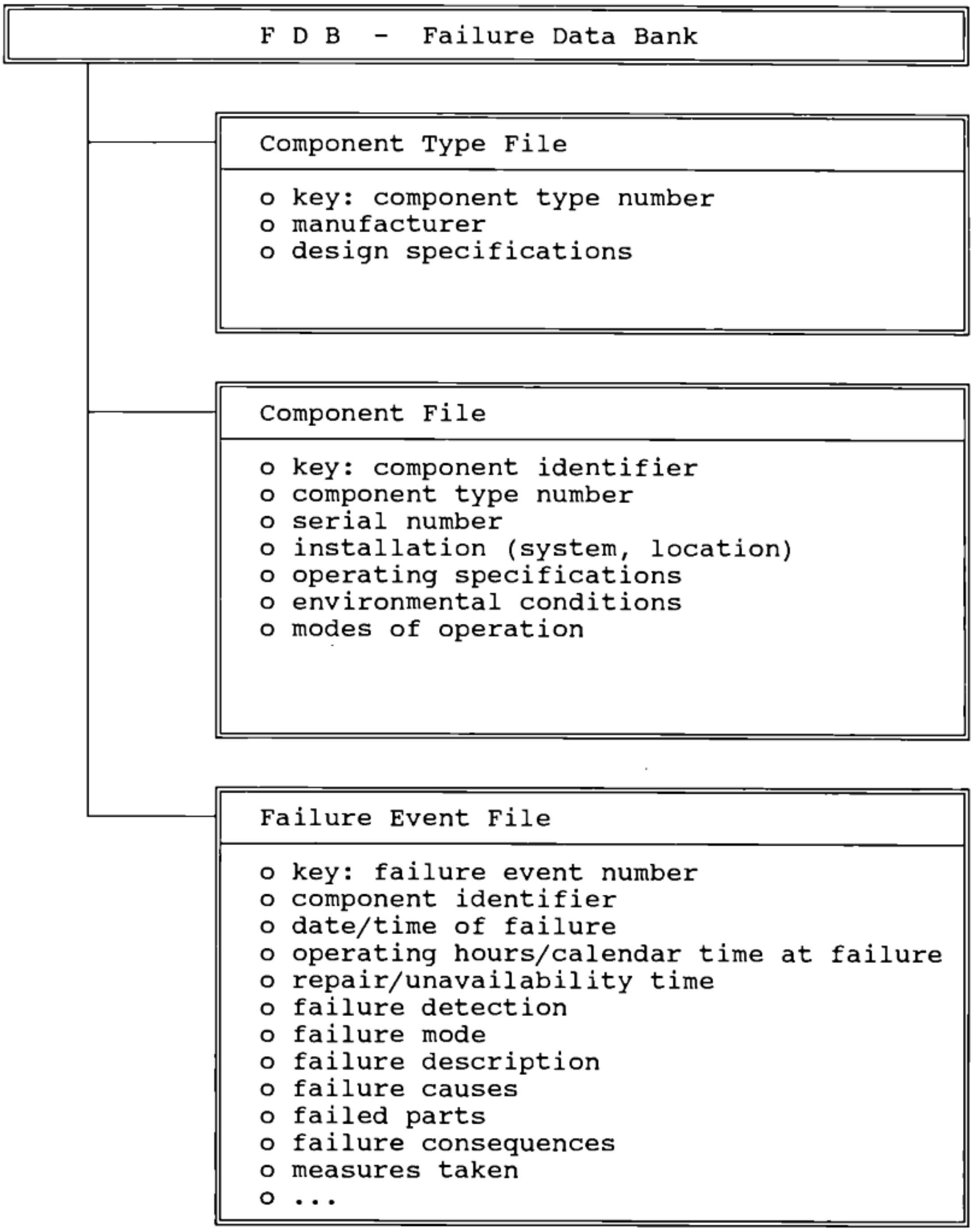


Figure 23 : *RMS failure data bank system (Flamm and Luisi, 1992)*

3.3.2. Taxonomy

Figure 24 shows RMS database taxonomy. In the RMS system, equipment is classified by its type, identification number, and design characteristics. On the basis of these characteristics, numerous data cells with a unique address are created to store failure rate data for specified part of the equipment. The categorizing of the information makes it easier to search and query the database for equipment with similar design and type characteristics.

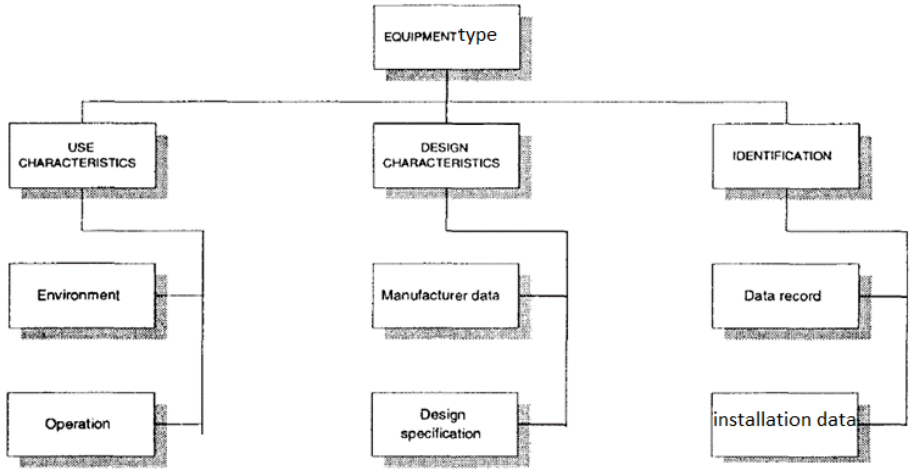


Figure 24 : PTC RMS Taxonomy (ISO14224, 2006)

3.3.3. Data categories

The following sections describe the data categories:

3.3.3.1. Failure data

Unlike OREDA database, RMS does not have any software to fetch data from. So this is done manually through reporting and formal meeting with the client's technical personnel. The main failure event data are:

- Failure record number is assigned to specific equipment along with failure date.
- Failure modes define that how failure occurred.
- Severity class- In RMS you can toggle between only two options of failure mode category, safety critical failure or non-safety critical.
- Failure descriptor has two-level parameter; one describes the failure type (e.g., operational) and other gives more specific cause (e.g. Corrosion, degradation).
- Reporting describes who detected the failure (e.g., by casual observation or by the operator).
- Remedial actions describe that whether suggested corrective procedure cure the failure or item is replaced.

To meet the international standard for collecting and storing failure data, RMS follows format defined by ISO for reporting failure details. Table 1 shows a format of information collected in failure report of RMS system.

Table 1: Failure data format in PTC RMS (ISO14224, 2006)

Category	Data recorded
Identification	Failure record
	Equipment identification/Location
Failure data	Failure date
	Failure mode
	Failure impact on plant safety (e.g. personnel, environment, assets)
	Failure impact on plant operations (e.g. production, drilling, intervention) [b]
	Failure impact on equipment function
	Failure mechanism
	Failure cause
	Subunit failed
	Component/Maintainable item(s) failed
	Detection method
	Operating condition at failure
Remarks	Additional information

3.3.3.2. Remedial action data

Data related to the remedial action taken for operational or installation failure of equipment is collected and stored in PTC RMS as follows:

- No changes
- Procedure changes
- Product changes
- Both procedure changes and product changes

3.3.3.3. Equipment data

In PTC RMS, the reliability data is collected for offshore equipment/component on the basis of their technical, operational and environmental parameters. To meet the objectives of the International Standard, a minimum of data that is collected is displayed in the table 2.

Table 2: *Equipment data collected in PTC RMS*

Data category	Data	RMS example
Use/ location attributes	Installation field code/name	Brae alpha, Eldfisk A
	Owner/customer name	Statoil, shell, ConocoPhillips
	Geographical location	Europe, UK, Brazil
	Well Unit code/name	A-45, B-27, A-11
Equipment attributes	Manufacturer name	PTC
	Equipment type	Shear lift-A, safe lift-C, GLV dummy
	Unique Equipment serial number/identification number	PTC-11770, PTC-10332, PTC-12629
	Design data for each component as applicable	Dim 1.5", 1.0"
Operation (normal use)	Normal operating state	Sent, installed, operating or pulled
	Initial equipment commissioning date	2003.01.01
	Start date of current service	2003.01.01
	Operation time (calculated/measured)	20 years
Additional information	In form of free text as applicable	In section of remarks

3.3.4. Data format

Each failure data recorded, e.g. a failure event is identified by a number of attributes in the database. Each attribute gives a piece of information e.g. failure mode, failure type. According to international standard recommendations, coding of information is used at some places rather than free text. This gives the advantage of ease of data input, reducing the database size, facilitating queries and data analysis. But to prevent the loss of information, an extra remark field is provided to add some additional free text for improved quality of information. Some examples of the coding terms used in RMS are shown in Table 3.

Table 3: *PTC RMS coding example (Andersen, 2012)*

Description	Code
FPO	Failure prior to operation
LCP	leakage in closed position
LAP	Leakage across packer
POP	premature opening
PRL	premature release of packer

3.3.5. Data analysis in RMS

RMS performs both parametric and non-parametric type of data analysis.

3.3.7.1. Non parametric analysis

In non-parametric analysis, it is assumed that $F(t)$ is continuous and increasing as a function of t. In such a situation, complete or censored data set is used to obtain non-parametric estimates of the survivor function$R(t)$. Non-parametric analyses of the data (for all failure modes) are performed, by using the Kaplan-Meier plots such as estimation of survival probability, using Kaplan-Meier's estimator. The Kaplan-Meier estimator serves as a non-parametric maximum likelihood estimator (MLE).This plot is very sensitive to deviations in the early and middle phases of an item's lifetime. (Rausand and Høyland, 2004)

3.3.7.2. Parametric analysis

Fitted curves for the exponential and Weibull distributions are also drawn in the plots. A computer code uses maximum likelihood to perform the fitting of the exponential or Weibull distribution. These computer codes give results as parameters of distribution function and graphical representation on the screen. The results can be exported into a spreadsheet for graphical display. The graphical outputs can be a hazards function like failure rates, distribution histogram, and distribution functions. (Flamm and Luisi, 1992)
In reliability analysis, the most important reliability function is an exponential function which gives a constant failure rate. On the other hand, Weibull distribution provides time dependent failure rates. Weibull distribution involves two parameters, a location parameter and a shape parameter. These parameters allow other distribution functions like normal and lognormal distribution with certain parameters. A Weibull distribution becomes an exponential function when shape parameter is equal to one. There are some special cases where failure are observed/expected after certain 'failure free' time, then this failure free is involved as a third parameter in Weibull distribution. This is the case for components which fail due to planned and predetermined wear. The parameters for these distribution functions are decided in a way that the observed life data are reproduced as close as possible. (Flamm and Luisi, 1992)

3.4. Summary

PTC uses a web-based Reliability management system (RMS) to evaluate the performance and reliability of their equipment. RMS organizes the installation data and failure reports for PTC. RMS categorizes equipment by their design and type characteristics. Each failure data recorded, e.g. a failure event, is identified by a number of attributes in the database. Each attribute gives a piece of information e.g. failure mode, failure type. Reliability parameters such as MTTF, failure rate and PFD are also calculated for particular dataset defined in filters.

Non-parametric analyses of the data (for all failure modes) are performed using the Kaplan-Meier plots i.e. estimation of survival probability, using Kaplan-Meier's estimator. Fitted curves for the exponential and Weibull distributions are also drawn in the plots. A computer code uses maximum likelihood to perform the fitting of the exponential or Weibull distribution. These computer codes gives results as parameters of distribution function and graphical representation. It also presents results of failure cause and remedial actions taken in the form of pie charts.

Reliability management system of PTC is based on collecting field data such as installation time, failure time, pull time, failure modes, then reliability data is made through data analyses Finally, fact-based decisions such Benchmarking, product improvements, system risk analyses, are made on the basis of performed reliability analysis.

Chapter 4

4. ISO 14224 and OREDA databases and the data quality

The International Standard ISO 14224 has been established on the basis of experience gained through the data collection project OREDA (Offshore & Onshore REliability DAta). The OREDA project has been carried out by several major oil and gas companies like Statoil since the early 1980s. During the project, a large population of data has been collected and significant knowledge in reliability data collection is gathered. The data in these standards helps to measure the reliability of the equipment in a systematic way. This chapter summarizes the guidelines defined by ISO for the specification, collection and quality assurance of RM data, assisting the collection of RM data. (ISO14224, 2006)

4.1. ISO 14224

The literature in this section is extracted from the documents of ISO (ISO14224, 2006). This international standard provides the standard data collection practices to support the exchange of information between different parties for example an owner contracture, a manufacturer etc. Any Reliability and Maintenance (RM) data system which is commercially available, should meet the requirement established by this International Standard. The main categories of data that is covered in this standard are equipment data, failure data and maintenance data.

4.1.1. Data collection process

4.1.1.1. Data sources

According to ISO 14224, a Computerized Maintenance Management Information System (CMMIS) is established to serve as a main source of the reliability and maintenance data. The quality of the data in CMMIS is dependent on the way reliability and maintenance (RM) data is recorded in the first place. CMMIS should be established according to ISO 14224 to provide a more safe and consistent basis for transferring RM data to equipment RM databases. Information from other sources such as feedback on data collection, quality assessment (QA) processes, can be transferred across several systems (computers, files) to improve reporting quality.

4.1.1.2. Data collection method

ISO 14224 defines data collection method as follows:

- Available data sources are addressed and relevant data is extracted in raw form. If this information is in a computer database the targeted information is extracted using a computer algorithm or software methods.
- Data from the source(s) is transferred to the reliability data bank with the help of suitable software in desired format or language. However, the software algorithm is effective only if it is robust enough to do a relatively correct conversion. This method is cost-effective only in the cases where there is large amount of data or repetitive data collection of same type. It can also be used to transfer data from one CMMIS to another system for maintenance activities.
- Data-collection methods should be planned and tested before starting main data-collection process since this can affect cost-benefit analysis of data-collection process.

4.1.1.3. Organization and training

Data can be collected either within the company using internal sources or by more specialized personnel. To collect data different, skills from several disciplines are required such as IT, reliability/statistics, maintenance, operation and data collection. The responsible personnel should be aware of the data-collection concept and software for the data-collection process. It would be beneficial if they have some knowledge about technical, operational and maintenance details of the equipment for which data is collected.
To obtain the quality data, responsible person should be properly trained. The data collectors should know the standards and give their appropriate feedback. The feasibility of the adopted data-collection methods should be checked before data collection starts. This will help in accessing if the target can be achieved within a given time and budget.
During the data collections process, some deviations can occur and a system shall be established to deal with these as soon as possible. These deviations can be in form of ambiguous definitions, lack of interpretation rules or inadequate codes etc. A feedback loop should be set by summarizing and evaluating all lesson learned during the data collection process. Thus improvement suggestion related to data definition, maintenance system, and data collection process should be fed back to the relevant personnel.

4.1.2. Timeline issues

4.1.2.1. *Data collection periods*

ISO defines criteria for the time period in which equipment data should be collected.
Data collected for the whole equipment lifetime is not cost effective and may be more ambiguous. Data collected for shorter intervals within a reasonable time frame are cost effective and qualitative.
Data collection starts after equipment's burn in period is completed. This is suitable for those cases where RM data for steady state operation is required. The period length may vary from none to several months. The recorded data during steady state operating periods usually follows constant failure rate.
In some cases, it is important to collect data for burn-in failures. In such cases, data collected for initial burn-in period shall be distinguished from data collected during the steady-state operating period. The data collection period shall be adjusted in accordance to failure rate, and size of population and access to data. The operating time should be estimated on the basis of knowledge from the operating and/or maintenance staff. High priority should be given to estimate the parameter like failure rate where the true failure rate shall be calculated based on actual operations.

4.1.2.2. Operating period

According to this international standard, equipment is considered to be operating or in-service when in idle state i.e. being ready for immediate operation when started. The equipment on cold standby is not considered to be in an operating state. The operating period categories defined by ISO 14224 are given in figure 25.

To get the full picture of down time caused by all maintenance actions, data should be collected for actual preventive maintenance. Data related to Periods when equipment is out of service for extended period for modification is not relevant for RM data collection process.

Total time												
Down time								Up time				
Planned down time					Unplanned down time			Operating time				Non-operating time
Preventive maintenance		Other planned outages			Corrective maintenance		Other unplanned outages					
Prepar-ation and/or delay	Active preventative maintenance (item being worked on)	Reserve [a]	"Cold" stand-by	Modifi-cation [b]	Prepar-ation and/or delay	Active corrective maintenance (item being worked on) [c]	Shutdown, [d] operational problems/ restrictions etc.	Run-down	Ramp-up	Run-ning	"Hot" stand-by	Idle

[a] Means that item is available for operation, but not required for some time. Does not include items considered as "spare parts" or items taken out of service on a more permanent basis.

[b] Modification can change the reliability characteristics of an item and can, therefore, require that the collection of reliability data for the surveillance period be terminated before the modification and be re-started with a new surveillance period after the modification.

[c] Includes fault diagnosis, repair action and testing (as required).

[d] Shutdown of machinery (trip and manual shutdown) is defined in C.1.8.

Figure 25: Operating period categories (ISO14224, 2006)

4.1.2.3. Maintenance times

This international standard defines two main calendar times which are collected during maintenance i-e down time and active repair time. When the equipment is out of service for a repair until it is back to its intended service is recorded as down time. The calendar time during which maintenance work is being performed is active repair time. So, active repair-time shall be smaller than the down-time.

4.1.3. Recommended data for equipment, failures and maintenance

According to ISO, three categories of data should be stored in database

a. equipment data,
b. maintenance data and
c. Failure data.

Following section will describe data categories, data format and database structure according to ISO.

4.1.3.1. Data categories

a. Equipment data

According to ISO, Equipment data provides following information

- equipment identification number,
- its design specifications, and
- Design parameters.

Reader is referred to section 4.1.3.4 for more details regarding equipment data in ISO.

b. Failure data

ISO 14224 categorizes failure data as follows:

- Identification data, e.g. failure record number and related equipment that has failed.
- Failure data for characterizing a failure, e.g. failure date, failed items, failure impact, failure mode, failure cause, failure detection method.

Reader is referred to section 4.4.3.5 for more details of failure data in ISO.

c. Maintenance data

ISO 14224 categorizes maintenance data as follows:

- Identification data, e.g. maintenance record number, related failure and/or equipment record
- Maintenance data, parameters characterizing a maintenance action, e.g. date of maintenance, maintenance category, maintenance activity, impact of maintenance, items maintained
- Maintenance resources, maintenance man-hours per discipline and total, utility equipment/ resources applied
- Maintenance times, active maintenance time, down time.

For all equipment classes, type of failure and maintenance data shall normally be common except where it is essential to collect specific data. Records for corrective-maintenance events and preventive-maintenance are required to preserve equipment complete lifecycle history.

4.1.3.2. Data format

Each failure data recorded, e.g. a failure event shall be identified by a number of attributes in the database; the attributes provide the information such as failure mode, failure type. It is recommended that information should be in coded form rather than free text. This gives the advantage of ease of data input, reducing the database size, facilitating queries and data analysis.
The predefined codes shall be optimized in a long range to give a more precise description; otherwise the input process will slow down and make it difficult for data collector to use it. Predefined coding has disadvantage of loss of some detailed information. To overcome this problem, some additional free text shall be added to the database. For example, in form of some narrative of the how failure event occurred. This will help in checking the quality of information being recorded
In ISO 14224, there is a range of codes given for different equipment types and reliability data. Codes for piping are shown in Table 4 as an example.

Table 4 : Coding example of piping (ISO14224, 2006)

Equipment class — Level 6		Equipment type	
Description	**Code**	**Description**	**Code**
Piping	PI	Carbon steels	CA
		Stainless steels	ST
		High-strength low-alloy steels	LO
		Titanium	TI
		Polymers including fibre-reinforced	PO

4.1.3.3. Database structure

The data collected shall be structured and linked in database such that user can get easy access for updates, queries and analysis. ISO 14224 defines two type of structure for a database.

a. Logical structure

ISO 14224 gives a flow chart for the logical structure of the database. This model gives an application-oriented view of the database.
The structure explains the logical links between the main data categories in database. The failure and maintenance records are linked to the equipment unit (inventory). The preventive maintenance (PM) records are linked to the inventory details. The failures have relative corrective-maintenance records linked to each failure record. Each record may have many attributes for example failure date, failure mode. Figure 26 shows the logical structure of database defined by ISO.

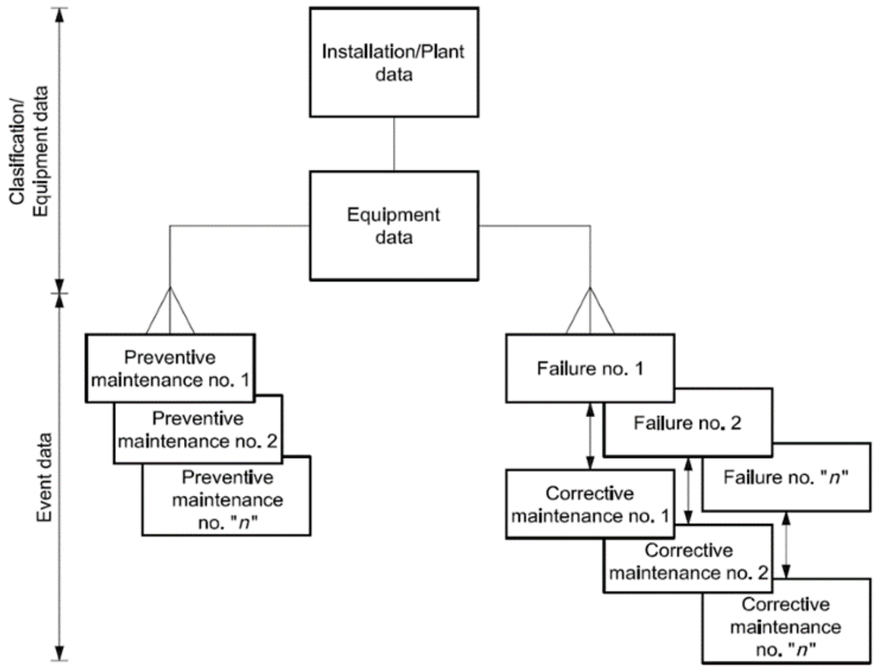


Figure 26 : Logical structure of RM database defined by ISO (ISO14224, 2006)

b. Database architecture

Database architecture defines the design of the database, the way individual data elements are linked and addressed. ISO defines following four model categories which are placed in order of complexity and versatility.

a) "*Hierarchical model: Data fields within records are related by a "family tree" relationship. Each level represents a particular attribute of data.*

b) Network model: This is similar to the hierarchical model; however, each attribute can have more than one parent.

c) Relational model: The model is constructed from tables of data elements, which are called relations. No access path is defined beforehand; all types of manipulation of the data in tabular form are possible.

d) Object model: The software is considered as a collection of objects, each of which has:

i. A structure: The structure is fixed within each object

ii. An interface: While the interface is the visible part that provides the link address between the objects.

Object modelling enables the database design to be very flexible, extendable, reusable and easy to maintain." (ISO14224, 2006)

4.1.3.4. Equipment data

The RM data is collected on the basis of technical, operational and environmental parameters of an equipment. The information about these parameters is necessary to determine if the data is valid for various applications or not. Some of the data can be used for all equipment classes and some is specific for particular equipment class.

Minimum of the data that shall be collected is displayed in the table 5 (to meet the objectives of this International Standard). However, including certain data categories can improve the usability of RM data significantly.

Table 5: Minimum required equipment data defined by ISO (ISO14224, 2006)

Data category	Data
Use/ Location attributes	Industry
	Business category (*)
	Installation category
	Installation code or name (*)
	Owner code or name
	Geographic location
	Plant/Unit category (*)
	Plant/Unit code or name (*)
	Section/System (*)
	Operation category

Data category	Data
Equipment attributes	Equipment class (*)
	Equipment Type (see Annex A) (*)
	Equipment identification/ Location (e.g. tag number) (*)
	Equipment description (nomenclature)
	Unique equipment identification number
	Manufacturer's name (*)
	Manufacturer's model designation
	Design data relevant for each equipment class and subunit/component as applicable, e.g. capacity, power, speed, pressure, redundancy, relevant standard(s)
Operation (normal use)	Normal operating state/Mode (*)
	Initial equipment commissioning date
	Start date of current service (*)
	Surveillance time, h (calculated) (*)
	Operational time, h (measured/calculated)
	Number of demands during the surveillance period as applicable (includes both operational and test activation) (*)
	Operating parameters as relevant for each equipment class; e.g. ambient conditions, operating power
Additional information	Additional information in free text as applicable
	Source of data, e.g. P & ID, data sheet, maintenance system

4.1.3.5 Failure data

It is important to set a uniform definition of failure and a predefined method of classifying failures, when it is required to collect and combine data from different sources (plants and operators) in a common RM database. ISO 14224 defines a common report format for all equipment classes and shall be used for reporting of all failure data. For some equipment classes, e.g. subsea equipment, minor adaptations can be necessary. Data required to meet the criteria of ISO is shown in the table 6.

Table 6 : Minimum required failure data defined by ISO (ISO14224, 2006)

Category	Data to be recorded	Description
Identification	Failure record (*)	Unique failure record identification
	Equipment identification/Location (*)	E.g. tag number
Failure data	Failure date (*)	Date of failure detection (year/month/day)
	Failure mode (*)	Usually at equipment-unit level [a]
	Failure impact on plant safety (e.g. personnel, environment, assets)	Usually zero, partial or total
	Failure impact on plant operations (e.g. production, drilling, intervention)	Usually zero, partial or total
	Failure impact on equipment function (*)	Effect on equipment-unit function (level 6): critical, degraded, or incipient failure [c]
	Failure mechanism	The physical, chemical or other processes which have led to a failure
	Failure cause [d]	The circumstances during design, manufacture or use which have led to a failure
	Subunit failed	Name of subunit that failed
	Component/Maintainable item(s) failed	Name of the failed maintainable item(s)
	Detection method	How the failure was detected
	Operating condition at failure	Running, start-up, testing, idle, standby
Remarks	Additional information	Give more details, if available, on the circumstances leading to the failure: failure of redundant units, failure cause(s) etc.

[a] For some equipment categories such as subsea equipment, it is recommended to also record failure modes on taxonomic levels lower than the equipment-unit level.

[c] For some equipment categories and applications it may be sufficient to record critical and non-critical (degraded + incipient) failures only.

[d] The failure cause and sometimes the failure mechanism are not known when the data are collected, as they commonly require a root cause analysis to be performed. Such analysis shall be performed for failures of high consequence, high repair/down time cost, or failures occurring significantly more frequent than what is considered "normal" for this equipment unit class ("worst actors").

(*) indicates the minimum data that shall be collected.

4.2. OREDA database

This section is extracted from (Sandtrov et al., 1996). OREDA[1] (Offshore REliability DAta) project provided the basis for the development of standards and guidelines for collection and analysis of offshore reliability data. The OREDA concept is used as the basis for developing an ISO-standard on the collection of oil industry reliability data (ISO TC67/WG4). OREDA has developed its own specific software for collection and analysis of data. This project helped to attain a high level of knowledge on data collection process, e.g. specification, procedures, training, cost-effective methods. We are going to discuss further how OREDA concept works on collecting and managing the reliability data. (Rausand and Øien, 1996)

[1] The OREDA (Offshore REliability DAta) project was launched in the early 80's as an initiative from the Norwegian Petroleum Directorate. After several pre-projects with engagement both in Norway and the UK, a main project was initiated (OREDA phase 1). The main objective was to collect reliability data for safety important equipment.

4.2.1 Organization of data

OREDA database consists of three database files:

- An inventory part
- A failure part
- A maintenance part

The inventory part contains the description of equipment such as technical, operating and environmental data. This is stored in the inventory section in the database. The failure part contains all failure events for the equipment during the surveillance period. The failure events are linked to inventory record which is done by cross-reference numbering system maintained by software. (Sandtrov et al., 1996)

The maintenance part gives information about the actual preventive and corrective maintenance being performed. Preventive maintenance is always connected to the Inventory part since it is done before the failure occurs. While corrective maintenance is connected to the failure event records since it is carried out after failure occurs. One failure may be referenced with one or more corrective action, in case if first corrective action does not cure the problem. (Sandtrov et al., 1996)

4.2.2. System hierarchies and boundaries

Usually, reliability data are collected from different systems and platforms. Compatibility of the data is required when it is being merged into a common database. Therefore, the systems must be assigned same level and boundaries for the equipment class. OREDA database adopts the hierarchy shown in figure 27. Each equipment class (e.g., pump) splits into a three-level. Each equipment class has specified hierarchy. To get a consistent failure event description, level of subdivision of an item from the maintenance action point of view is specified. In the figure, the terms Boundary level, Sub-boundary level, etc. are to describe the subdivision of an item from the point of view of maintenance while the terms Equipment unit, Subunit and Maintainable Item describe the hardware unit(s) on each level. The highest level in OREDA is an equipment unit. It can be a pump, a gas turbine, a compressor, etc. Equally important is the boundary definition which specifies what equipment should be considered as part of an equipment class. In OREDA handbook, general guidelines are given to specify the boundary definition and specific boundary diagrams for each equipment class. (Sandtrov et al., 1996)

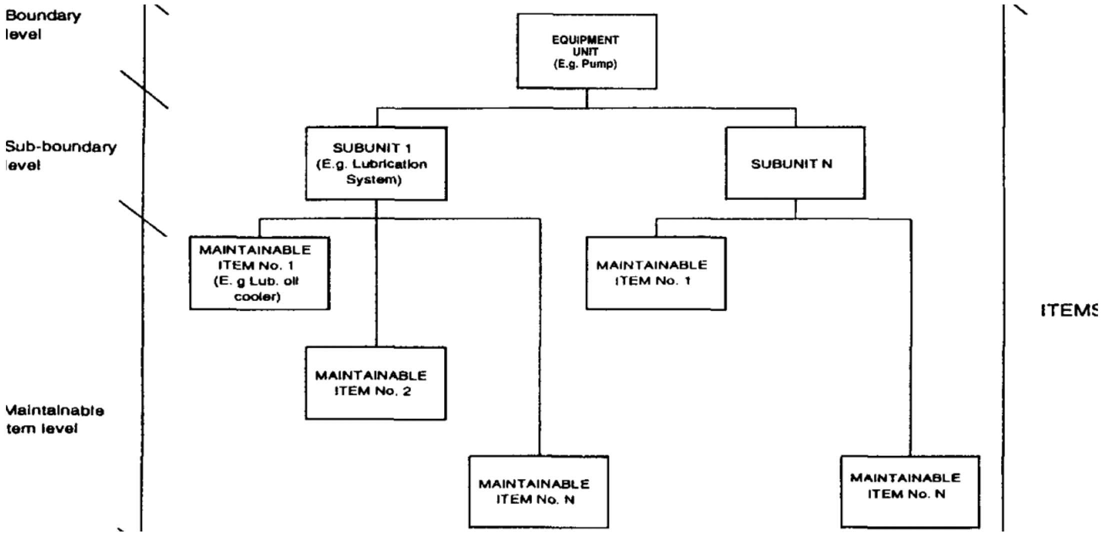


Figure 27: System hierarchies and boundaries defined by OREDA (Sandtrov et al., 1996)

4.2.3. Taxonomy

OREDA organizes the equipment in equipment classes, e.g. pumps, compressors, gas turbines, etc. In an equipment class, each equipment unit is classified by the classification of units. This is to identify the data record, design as shown in figure 29. On the basis of these characteristics, numerous data cells with a unique address are created to store failure rate data for specified piece of process equipment. The categorizing of information makes it easier to search and query the database for equipment with similar characteristics. (Sandtrov et al., 1996)

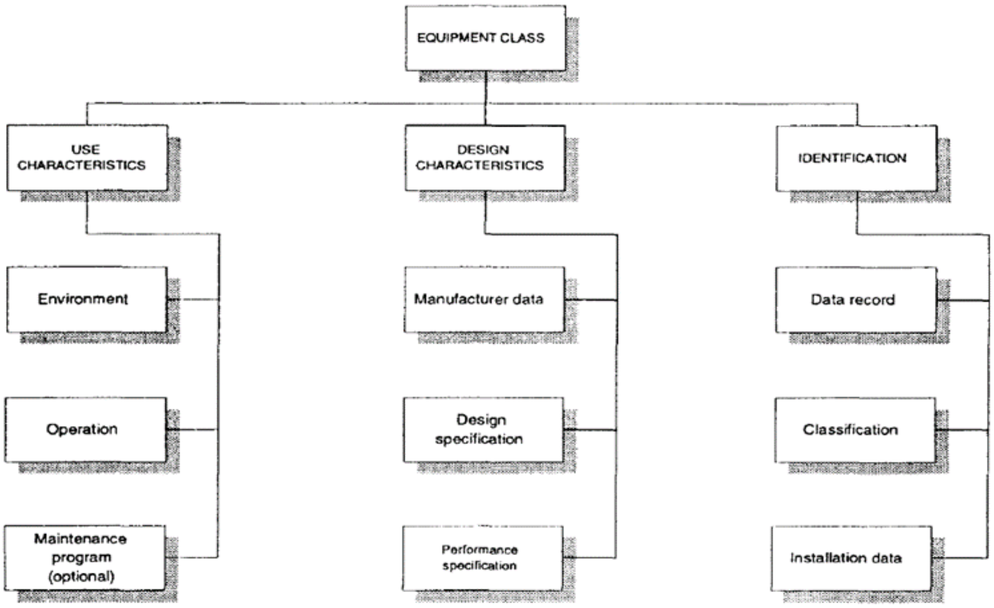


Figure 28: OREDA Taxonomy (Sandtrov et al., 1996)

4.2.4. Data categories

OREDA software uses a list of predefined codes to collect data. This makes the search and analysis of data significantly more suitable than use of free text, but this has the disadvantage of losing some details in the information. To overcome this problem a 'remarks field' is used to add a more details about the event in form of free text. In order to minimize interpretation problems, definition of the codes and selection of code menu should be very considerate. The main failure event data are: (Sandtrov et al., 1996)

1. "Failure modes, which are defined for each equipment class.

2. Severity class, which describes the severity of the failure in three levels, viz. Critical, degraded and Incipient.

3. Failure descriptor defines the observable cause. It is a two-level parameter; upper level describing the failure type (e.g., Material) and lower level the more specific cause (e.g. Corrosion).

4. Observation method describes how the failure was detected (e.g., by casual observation).

5. Failure consequence describes the failure effect on higher level systems (e.g., oil production)."(Sandtrov et al., 1996)

4.2.5. Data Analyses

OREDA software performs three types of data analysis: (Sandtrov et al., 1996)

i. Standard analysis: In the analysis, the failure rates are calculated. This is done for the different failure modes and criticality classes. It is possible to select whether failure rate is calculated based on the calendar time or the operating time. By setting filters on the data, it is possible to carry out this analysis on certain equipment category. Maintenance man-hours (or active repair time) are included in this calculation.

ii. Frequency analysis: By extracting the information from many combinations of data in the database, frequency analysis is performed to get the failure rate for each combination of the values in the selected data field. For example, we may want to calculate the number of failure rates for pumps grouped according to a specified category, and classified on 'failure modes'.

iii. Lifetime distributions: To perform such type of analysis SINTEF has developed many programs which are compatible with the OREDA software. So the data can easily be exported for such analysis. The results can be exported into some spreadsheet for graphical display of the results.

4.3. Quality of RM data recorded in database

The procedure by which data are collected and analyzed highly affects the quality of data stored in database. After significant effort towards improving the quality in data collection and

analysis, several guidelines and standards have been issued. Some of these standards are OREDA and ISO, AIChE 1998, ESReDA. (Rausand and Høyland, 2004)
This section presents different aspects of data quality defined by above standards.

4.3.1. Data quality according to ISO14224

ISO 14224 defines following criteria to obtain high quality data: (ISO14224, 2006)

- Data should be transferred handled and stored accurately as much as possible, regardless of whether it is being done manually or electronically.
- Data should be complete in terms of specifications.
- Data should comply with description of reliability parameters, data types and formats.

Measures for obtaining quality data

ISO 14224 suggests taking following measures before starting data collection process in order to obtain the high quality data. (ISO14224, 2006)

- Data sources should be investigated to make sure that required inventory data is available and operational data is complete.
- Purpose of collecting data must be defined so that relevant data for intended use is collected.
- Data sources should be investigated to make sure that relevant data of sufficient quality is available.
- Classify the installation date, population and operating period(s) for the equipment.
- It is recommended to do a pilot exercise for data collection methods and tools (manual, electronic), for the verification of feasibility of the planned data collection procedures.
- Organize a plan for data collection process e.g. schedules, milestones, sequence and number of equipment units, time periods to be covered, etc.
- Data collection personnel must be trained and motivated.
- Procedures for quality control of data and recording and correcting deviations should be followed for the quality assurance of data collection process.

Evaluation of the data should be done continuously during and after data collection process in order to check consistency, reasonable distributions, and proper codes and correct interpretations. It is important to document the quality control process. Also, when merging individual data bases it is vital that a unique identification should be assigned to each data record. (ISO14224, 2006)
Summary properties of high quality data used in ESReDA[2] is shown in table 7. (Pettersson, 1998)

[2] ESReDA is a European Association established to promote research, application and training in Reliability, Availability, Maintainability and Safety (RAMS). ESReDA was formed from the combined forces of EuReDatA (European Reliability Data Bank Association) and ESReDA (European Safety and Reliability Research and Development Association), two organizations active in the period 1978-1991.

Table 7: Summary of major quality aspects of data (Pettersson, 1998)

Main quality aspect	Quality elements	Explanation
INFORMATION VALUE	Extent	Extent of reliability information contained in the data
	Detail	Level of details available in source data How detailed each type of information is described in the databank
	Access	How easy it is to access the information for use in reliability assessments (information format)
CONSISTENCE	Boundary	Borderline defining systems/items included in the equipment unit collected data on
	Taxonomy	An information structure for defining and storing reliability information.
	Reliability attributes and formats	Attributes that describe the reliability information and format of these attributes
CONFIDENCE	Confidence interval	E.g. 90% confidence interval
	Model uncertainty	Goodness of statistical models
	Populations	Variations between populations
Data collection process	Planning the data collection process	Evaluating data source, population count, access to information, training data collectors etc.
	Quality plan	A documented plan for what actions to take during data collection to ensure proper quality of data

4.3.2. Data quality definition according to OREDA

The OREDA project helped in the collection of large population of high quality data. In OREDA project many companies are involved hence the quality and availability of data differs significantly between the companies. The cases where adequate data sources are not available the data collection has been abandoned for the system. OREDA established comprehensive guideline manual and specific software for data collection. (Sandtrov et al., 1996)

The major quality measures applied in OREDA are: (Sandtrov et al., 1996)

- To obtain maximum quality of information and quality verification during the data collection process a specific Quality Assurance (QA) system is established.
- The data collectors and the project management communicate closely about the procedures, interpretation rules, deviations etc.
- The data collection software has a built in consistency check.

The quality control of the data was carried out at several steps: (Sandtrov et al., 1996)

- Specified self-check routines are performed by the individual data collector person.
- When one platform or system is finished the contractors perform quality check of data.
- The project management performs spot checks and statistical checks on randomly selected data during the data collection process.
- Finally the project management does the verification on the complete database.

Two major challenges have been involved in the quality assurance process: (Sandtrov et al., 1996)

i. Consistency of interpretation rules and quality standards between different data collectors

ii. Handling with changes (plans, definitions, codes etc.) during the data collection project.

These problems are solved with specific control and reporting procedures. Quality control and reporting of deviations are the key points in such procedures. A summary of the most common quality problems experienced in data collection process is shown in table 8.

Table 8: *Common quality problems experienced in data collection process (Sandtrov et al., 1996)*

Quality checks on data Deviation reports		Deviation reports	
Subject	Percent	Subject	Percent
Interpretation of the Guideline / wrong codes	39	Data availability / quality	28
Illegal codes / typographic errors	20	Interpretation of Guidelines (codes, boundaries etc.)	
Missing non-compulsory information	17	Missing codes / new codes	26
Missing compulsory information	10	Revised data collection plan	11
Inconsistency	7	Software errors	4
Questionable information	7	Others	4

4.3.3 Data quality procedure adopted by AICHE 1998[3]

AICHE 1998 defines a procedure adopted for CCPS (Centre for chemical Process Safety) database for ensuring the quality of data through a combination of documents and activities: (CCPS, 1998)

- The data subscriber administrates a quality plan and completes a certification process for quality work process in order to meet the criteria established by the participant committee.
- Data subscriber/data contributor performs internal verification of all data being submitted to the database.
- Database administrator administrates the quality plan and carries out verification of data prior to acceptance into the Database.
    - Table 9 gives an overview of the possible attributes being checked, along with acceptance criteria. The purpose here is to expose as many input errors as possible.
- An independent third party performs audit to verify that work process is fulfilling its objectives.

[3] AICHE 98 is a book developed for the Center for Chemical Process Safety (CCPS). It is designed as a text to be used by operating and maintenance staff, reliability engineers, design engineers, and risk analysts.

Table 9: *check list for data verification (CCPS, 1998)*

Check Item	**Acceptance Criteria**
Check that all compulsory data fields are recorded	100% of required fields completed
Check that surveillance period begins after installation date	Minimum 1 day differential
Check that recorded failures occurred within reporting period	100% of failure data to occur within reporting period (no historical data)

4.4. Defining categorizes of failure modes in database

4.4.1. Failure modes defined by ISO 14224

ISO defines failure mode as "*effect by which a failure is observed on the failed item". (ISO14224, 2006)*. In the hierarchy defined by ISO, failure modes are normally related to equipment class. But for subsea equipment failure modes for lower level equipment are also recorded. ISO categorizes failure mode into three types: (ISO14224, 2006)

i. "desired function is not obtained (e.g. failure to start);

ii. specified function lost or outside accepted operational limits (e.g. spurious stop, high output);

iii. Failure indication is observed but there is no immediate and critical impact on the equipment-unit function [these are typically non-critical failures related to some degradation or incipient fault condition (e.g. initial wear)."

Table 10 shows some failure modes for DHSV (Down Hole Safety Valve) as an example. Type 1, 2, 3 in the table represents the categories defined above. Codes in the table 10 are proposed abbreviation for describing the failure modes.

Table 10 : Well-completion equipment — Failure modes (ISO14224, 2006)

Equipment class [a]	Failure modes			
DHSV	**Description**	**Examples**	**Code [b]**	**Type [c]**
X	Failure to open on demand	Does not open on demand	FTO	1
X	Failure to close on demand	Does not close upon demand signal	FTC	2
X	Leakage in closed position	Leakage through valve exceeding acceptance criteria when closed	LCP	2
X	Well-to-control-line communication	Influx of well fluids into valve control line	WCL	2
X	Control-line-to-well communication	Loss of hydraulic control fluids into the well bore	CLW	3

According to (Rausand and Høyland, 2004), failure modes can be classified into two categories:

i. **Intermediate:** The failure that occurs for short period of time and returns to its full operational standard right after the failure.

ii. **Extended:** The failure that continues until part of the system is repaired or replaced. This can be further divided into two categories:
    a. Complete failure: that causes complete loss of function
    b. Partial failure: that causes loss of function to some extent not complete loss of function.

Both the complete failures and the partial failures may be further classified: (Rausand and Høyland, 2004)

a. Sudden failures: these are unpredicted failures, which could not be predicted by examination or testing.
b. Gradual failures: these failures could be predicted by testing or examination. To access the gradual failure it is important to compare actual device performance with a performance specification and may in some cases be a difficult task.

The extended failures are split into four categories; two of these are given specific names: (Rausand and Høyland, 2004)

a. Catastrophic failures: sudden and complete failure falls in this category.
b. Degraded failure: both partial and gradual defines degraded failure.

The failure classification described above is illustrated in Figure 28.

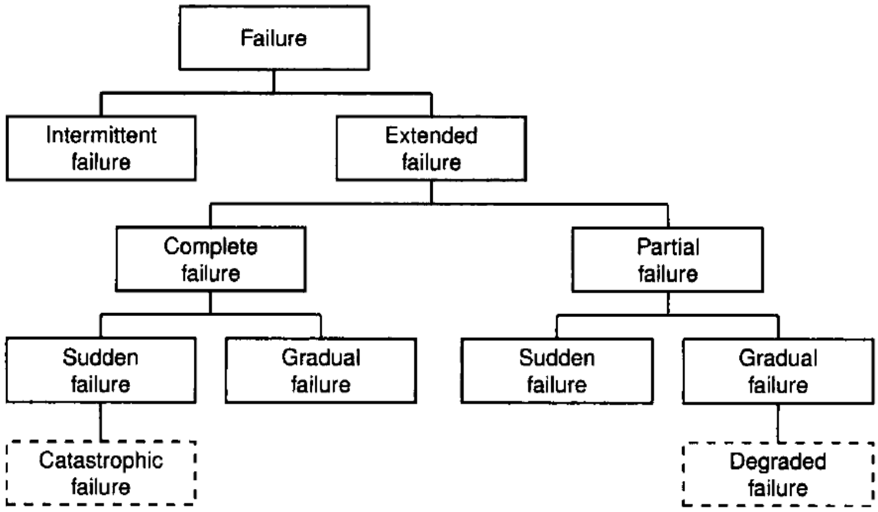


Figure 27 : Failure classification (Rausand and Høyland, 2004)

4.4.2. Failure modes used in OREDA database

OREDA defines failure modes within three categories which are based on the local failure effects on the item, not on the system. (Rausand and Øien, 1996)

i. **Critical failure:** A failure which causes termination of one or more important functions and it happens suddenly. An instant corrective action should be performed in bring the item back to function in a satisfactory way.
ii. **Degraded failure:** A failure which occurs gradually and partially, or both. A failure does not stop the important functions, but effects one or several functions. If not corrective measures are not taken such a failure may develop into a critical failure.
iii. **Incipient failure:** A faultiness condition of a component which can cause a degraded or critical failure to be expected to occur if corrective action is not taken.

An example of the OREDA failure modes of a valve are shown in table 11.

Table 11 : OREDA valve failure mode (Rausand and Øien, 1996)

Failure effect category	Failure modes
Critical	Failed to open
	Failed to close
	Significant internal leakage
	Plugged
	Unknown
Degraded	Improper operation
	Internal leakage
	External leakage
	Unknown
Incipient	Faulty indication
	Unknown
Unknown	Failed

Figure 29 illustrates the relationship between the OREDA and (Rausand and Høyland, 2004) failure mode classification. OREDA critical and degraded failure covers somewhat more than (Rausand and Høyland, 2004) catastrophic failure and degraded failures respectively. In OREDA incipient failure are not considered a failure, only an error. (Rausand and Øien, 1996)

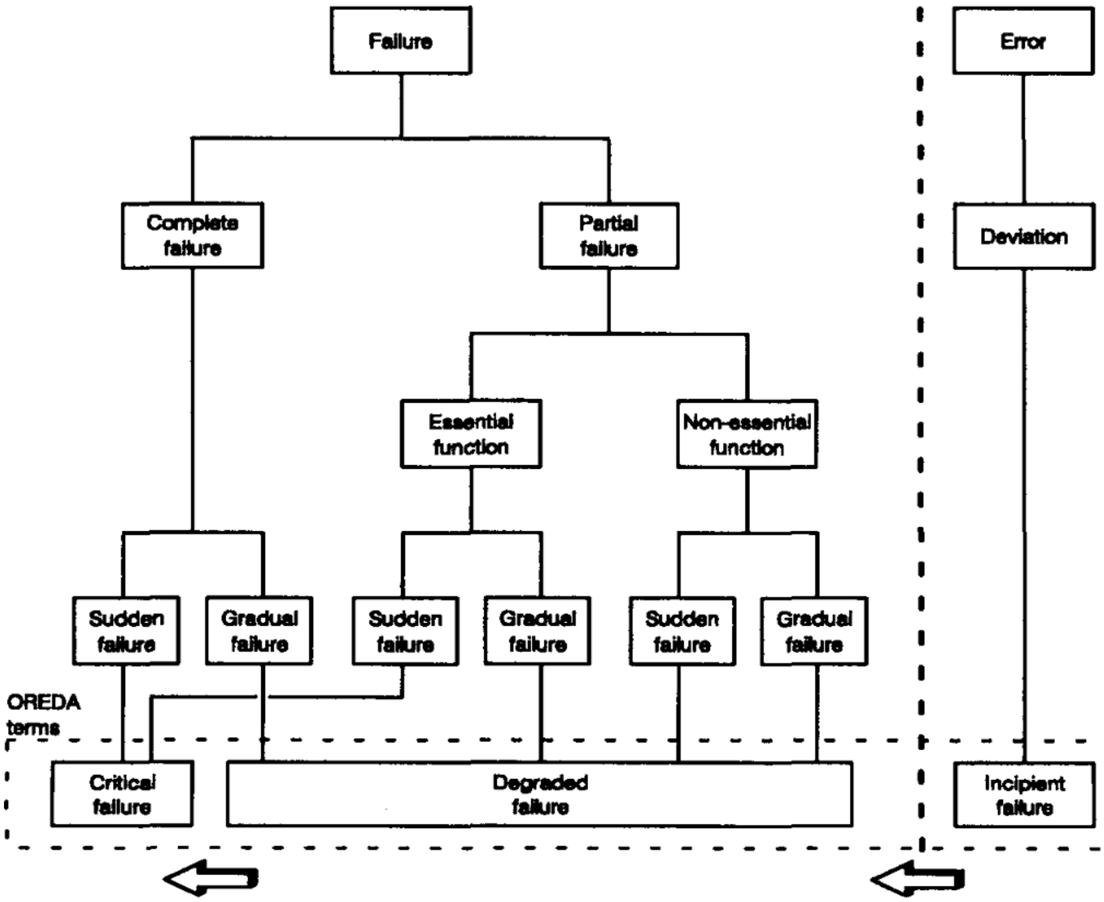


Figure 28 : OREDA failure mode classification (Rausand and Øien, 1996)

The arrow in Figure 29 specifies that an incipient failure may become a degraded failure, and a degraded failure may further proceed to a critical failure, if no corrective action is taken. It is important for data quality that an acceptable limit should be defined to differentiate clearly between incipient failure and a degraded failure and that it is possible to measure the degree of failure exist, to maximum possible level. A problem that is difficult to handle is some equipment are used in different operational settings and hence acceptable limit will be different. (Rausand and Øien, 1996)

4.4.3. Failure mode according to AICHE 1998

(CCPS, 1998) presents following method for defining the failure modes:
Database design uses the concept of inferring failure modes from raw event data, rather than depending on the opinion of a data collector. The analyst develops the structure to collect the intended data from the fields of event data table and then use a fixed algorithm to determine the failure mode. The algorithm is embedded in the software. To program such software, the analyst provides a flow chart or text description of algorithm required to determine the failure mode. To be helpful and more precise the analyst provides the table which shows links between failure modes and events. An example of such table is shown in Table 12.

Table 12 : *An example of table for heat exchangers (CCPS, 1998)*

System Failure Modes	Failure Mode Definition	Relief Valve Failure Logic	
		Input Form	**Criteria**
Fail to open	Fail to open prior to reaching 1.5 times set pressure	Demand	Relief lift = 'NO' or lift ratio equal to or greater than 1.5
		Proof Test	Fail to open if "plugged" or lift ratio equal to or greater than 1.5 or max pressure equal to or greater than 1.5
		Inspection	Discharge piping plugged field = Plugged
Opens above set pressure	Opens between 1.1 and 1.5 times set pressure	Demand	Lift ratio between 1.1 and 1.5
		Proof Test	Lift ratio between 1.1 and 1.5

4.5. Summary

The purpose of ISO AND OREDA standards is to help the user to measure the reliability of the equipment in a systematic way. These standards provide the standard data collection practices to support the exchange of information between different parties for example owner contracture, manufacturer. Any Reliability and Maintenance (RM) data system which is commercially available tries to meet the requirement established by these Standards.

ISO 14224 defines how data sources should be assessed, what methods should be used to collect required data while ensuring its good quality. ISO also defines the requirements for training of personnel responsible for data collection.

ISO has been established as a part of OREDA project. OREDA has their own reliability database developed as result of a research project carried by many organizations. OREDA has its own system hierarchy and boundaries to store data in an organized way. The taxonomy defined by OREDA makes it easier to search and query the database for equipment with similar characteristics. The OREDA software uses a list of predefined codes to collect data. This makes the search and analysis of data significantly more suitable than use of free text. OREDA software can perform three types of data analysis; lifetime distribution, frequency analysis and standard analysis.

Moreover, OREDA and ISO define procedure in order to obtain high quality data. According to these standards a high quality data must have these elements; completeness, consistency and confidence. OREDA performs data quality assessment to ensure high quality data in database. AICHE 98 also has very definitive procedure to ensure data quality in a database.

Finally the failure modes are categorized very carefully in ISO and OREDA database such that they cover every aspect of failure related to equipment, from a small error to a safety critical failure. AISCHE database design uses the concept of inferring failure modes from raw event data rather than depending on the opinion of a data collector. The analyst develops the structure to collect the intended data from the field of event data table and then use a fixed algorithm to determine the failure mode.

Chapter 5

5. Analysis of efficacy of PTC Reliability management system

This chapter is based on the information provided by Petroleum Technology Company (PTC) personnel during the meetings and discussions. The analysis of failure reporting structure of PTC and evaluation of data quality in RMS is performed on the basis of OREDA and international standard ISO 14224.

5.1. Failure reporting in PTC RMS

All the failures that occur during operations, inspections, and testing of the equipment are reported by the PTC customers through a predefined procedure. The procedure involves collecting corrective actions data, maintenance data, time stamps and the operating conditions of the equipment. The field service reports are submitted to PTC in simple, easy-to-use forms, customized in accordance with the relevant equipment details. (Villacourt and Govil, n.d)

5.1.1. Data collection sources

Data collection sources for PTC RMS are consistent with the sources defined by (Flamm and Luisi, 1992), that is;

- Outcomes of the meetings with customer/operators (expert opinion)
- Online production database, inspection database of PTC
- Laboratory testing published information in engineering database (EPDS)
- Event data and field data reports

5.1.2. Data collection methods

The important elements of data collection method in PTC are consistent with the methods discussed by (Flamm and Luisi, 1992), that is;

- Surveys
- Automated tests
- Automated monitoring and reporting

The data collection approach here is field service data. This technique uses the information which is usually gathered from the products in use by the customers. In this technique, the information gathered is influenced by the difference in equipment installation, the environment it is used in, or the operational procedures. However, the approach represents the realistic application of product and hence affects the quality of reliability analysis. This approach is used in feedback process for future revision. Field data collection practices emphasize on characteristics of the field performance of equipment. (Flamm and Luisi, 1992)

The data collection plan at PTC is the following:

a. Available data sources are addressed.

b. The data is collected using internal or external sources. This is done by data collection team responsible for RMS. When considering data sources, a special attention is given to conditions under which the product is transported, stored and used.
c. Relevant data is extracted in raw form. One or more meetings can be arranged as per requirement when the data needs to be collected from external sources (client's on-site operators). Usually, more than one person is involved to provide cross-checking.
d. The data from the source(s) is transferred to the reliability database (RMS). The responsible person collects data and stores all the data in the RMS. The stage at which data is collected usually recorded in form of date and time stamps. When equipment arrived at PTC after failure, the inspection team does the inspection of equipment visually and prepares a report (with predefined format) and adds this report in inspection database. Data collector for RMS can access these reports directly from the database to extract the relevant information required for RMS.

The data collection plan of PTC is quite close to OREDA and ISO 14224 standards. However, these standards recommend to plan and test data-collection methods before starting main data-collection process since this can affect cost-benefit analysis for data collection. (ISO14224, 2006)

Another factor that needs to be considered is that data from the source(s) is transferred to the RMS without any software. The responsible person accesses the failure data from inspection database and feed it to reliability management system of PTC. (ISO14224, 2006)
OREDA database has built-in software to transfer failure data from different databases to a common reliability and maintenance database. OREDA software converts data into desired format for RM database.

If PTC approaches the idea of using software algorithm to extract the desired information from other databases within the company this will benefit in following ways: (ISO14224, 2006)

- It will save the time and cost.
- This way the data transfer from different sources to RMS will be more frequent and will have less error. However, the algorithms should be robust enough to do a proper conversion of data into desired format for RMS.
- The idea can be cost-effective for PTC because PTC databases have large amount of data and repetitive data of similar equipment type.
- The method can also be used for transferring data from one CMMIS to another within the company for maintenance activities.

5.1.3. Data collection process management

During the data collection process an organization should try to combine all the data into a central data logging system. Two types of data collection are presented at occurrence of field failure: (Villacourt and Govil, n.d)

i. *"the user's system that includes equipment utilization and process-related information and*
ii. *Field service reports (FSRs) that include parts replacement information."*

When FSRs are used as the only source of for getting failure data, it is very difficult for the supplier to address the actual problem behind failure. To help with this problem, the client should provide detailed logs to verify problem. The supplier should compare both sources (mentioned above) to find out the actual problem to be resolved. Another suggestion could be that the supplier must be a part of client's data collection system while the product is being installed. (Villacourt and Govil, n.d)

Ideally, when the equipment is being installed all the related information should be logged automatically and then transferred to the supplier's data collection system. This would remove the need for paperwork and the confusions regarding due to duplication of data. (Villacourt and Govil, n.d)

Referring to chapter 4, ISO 14224 defines a criterion for the following aspects of a typical data collection process:

i. Organization and training: Responsible personnel should be properly trained. Data collectors shall know this International Standard and give appropriate feedback. The feasibility of the adopted data-collection methods should be checked to access if the target can be achieved within a given time and budget.

ii. Data collection period: Data collected for initial burn-in period shall be distinguished from data collected during the steady-state operating period. The data collection period shall be adjusted in accordance to failure rate, the size of population, and access to data. Operating time should be estimated on the basis of knowledge from the operating and/or maintenance staff.

iii. Data format: Each failure data recorded shall be identified by a number of attributes in the database. The international standard recommends coding the information but it can slow down the process and make it difficult for data collector to use it. The text details in remarks field can prevent loss of some of the details.

5.1.3.1 PTC data collection process management

Management of data collection process at PTC is done as follows:

- Data collectors in PTC understand the data-collection concept and to some extent, know the technical, operational and maintenance details of the equipment for which data is collected.
- The data collectors are aware of the International Standard. PTC evaluates the appropriateness of various data sources to collect data such as on-site data, environmental data, location, test specification, failure modes, failure mechanisms, time at failure.
- The person responsible for collecting the data for RMS is usually involved in the procedure of inspection of failed equipment. This helps in avoiding the silos of information created with different people involved.
- Field Service Report (FSR) is the only source for getting failure data. Due to this, it is very difficult for PTC to address the actual problem behind the failure.
- Failure data is available to both PTC and the client in a standardized report format. However, the operational data is missing in failure event reports available to PTC.
-

5.1.3.2. Lacks in PTC data collection process management

When the data collection process of PTC is analyzed on the basis of ISO standard, it is observed that the data collection process at PTC has following weaknesses which make procedure bit complicated and requires more effort: (Villacourt and Govil, n.d)

i. As mentioned earlier that RMS is not directly connected to other databases of PTC. This causes the data collection process time consuming because the data collector needs to trace information back to individuals. This causes considerable wastage of productive time. (Kumar, n.d)
ii. PTC cannot act as part of client's data collection system while the product is being installed. Ideally, the information should automatically be transferred to the PTC data collection system. This can minimize paper work and the confusions during the transfer of data.
iii. The information and reports created during the lifecycle of equipment is stored in various databases of PTC. Limited integration of these databases makes it difficult for data collector to work with the information the way they want. The data collectors have to spend a lot of time to search the required information and convert it into an analysis-ready format. This causes the delay in completing activities.
iv. It is very important to train inspection and maintenance personnel to capture information required for an event report, since they are usually the first to identify the problems.
v. The investigation reports in RMS are based on the information from the installation reports. As soon as an equipment is marked as 'failed', the installation report will be transformed into an investigation report, and pulled out of the failure statistics until the report is approved / rejected by a third party (i-e PTC RMS software vender).
vi. The third party is sitting on different location and the staff cannot communicate freely to share critical information. The absence of the necessary infrastructure, tools and procedures to effectively collaborate with reliability experts causes inaccurate results or incomplete analysis. Also in such cases it is difficult to integrate third party into the reliability improvement activities of organization. (Kumar, n.d)
vii. Preventive maintenance can also be optimized if it is properly defined that whether the failure was sudden, evident or hidden and failure modes both with respect to safety and economic expenditure. In RMS it is not always stated that failure was gradual, sudden or aging failure.
viii. During data collection process failure data collected is repair oriented rather than describing failure cause, mode or effect. Generally, failure mode is interpreted by the data collector. How the failure was detected (e.g. by inspection, monitoring, PM, tests, casual observation) is rarely stated.
ix. There is a delay in capturing failure data. It is not done right at the time when the failure occurs. This may cause failure description errors.
x. It's not possible for PTC to capture operational data through the client's tracking system. This causes missing of essential information.
xi. The failure event reports are not connected to the corresponding operational data in the factory tracking system of client.
xii. The PTC and its client systems are not integrated. This decreases the efficiency by increasing the paper work, tracking problems. Also, exchange of the data is done less frequently.

However, in RMS data log files are connected with the failure report to provide software engineers information about events that caused failure. After the data is collected, minimum reliability performance parameters are determined. To address the root cause of equipment failure efficiently and effectively it is important for PTC to get detail failure information event report. This will help the company to determine the state of operation prior and after the failure. (Villacourt and Govil, n.d)

5.2. Evaluation of the quality and the relevance of the RMS database

Databases can be divided into following three classes of quality: (Pettersson, 1998)

i. NO CHOICES: This class of databases has the information organized in a form; we may find failure and repair data for valves, but not information about a subgroup of valves. This class of databases is easy to use but risky to use.

ii. SOME CHOICES: This class of databases uses the estimator for the failure rates as the number of failures divided by the total operating time. OREDA handbook is a good example of this class.

iii. ALL CHOICES: OREDA software database is really a good example of this class. Analyst can select filters for different parameters depending on the equipment class. In this database analyst has a lot of information. He can perform more detailed analyses, using more resources.

According to the author (Pettersson, 1998); with the purpose of getting an overall estimate of system performance, following information must normally be available for a high scored database:

- *"System boundaries must be defined.*
- *Failure modes must be defined and not overlapping*
- *The number of failures and the operating and calendar time must be given*
- *It must be stated if repair time means active repair time"*

Other information that can improve database quality is:
- *"Description of system characteristics, like design parameters*
- *Description of operational conditions*
- *Description of preventive maintenance*
- *Description of environmental conditions"*

If PTC RMS database is compared with the above mentioned elements, it highlights the following main elements; reflecting the scoring level of RMS database.

- System boundaries are not defined in RMS.
- Failure modes categories are limited to safety critical or non-safety critical.
- The number of failures and the operating and calendar time is given.
- Description of equipment characteristics, like design parameters are given to some extent.
- Description of operational conditions is given in RMS.

- Description of preventive maintenance and environmental conditions is missing in database.
- Repair time is not stated in RMS database.

RMS fits in database class of “some choices”, where failure rate is calculated as the number of failures divided by the total operating time.

5.2.1. Analyzing the failure modes used in existing RMS

As we have discussed earlier that properly defined and categorized failure modes are an important aspect of a high-quality database. The failure modes should not overlap, they should be defined for each equipment group and its subgroup categories. Some particular failure modes can help in identifying the need for changes to maintenance periodicities, or the need for additional checks. (Pettersson, 1998)

In chapter 4, failure mode categories have been discussed in details. OREDA uses well-defined failure mode categories; Incipient, intermediate and critical. Incipient failure is considered as an error which if not treated may lead to critical failures. Under each failure mode category, there is a list of failure modes for all equipment. These failure modes are embedded in the algorithm of OREDA reliability database.

5.2.1.1. Failure mode categories used in PTC RMS

This section is concluded from the discussions with PTC personnel. A Safety Analysis Report (SAR) of PTC is also considered here to get more details regarding failure mode classification.

RMS database register failure modes related to installation, operation and retrieval phases. The database categorizes these failure modes into two categories

- Safety critical failure mode
- Non-safety critical failure modes.

The failure modes are determined by a predefined rule set programmed or embedded in the database program. (CCPS, 1998)
If selected option is “non-critical failures” then RMS calculate the failure rate for all non-critical failure modes (for installation, operation or retrieval phases). In case of safety, critical RMS distinguish safety critical failure and present failure rate estimate for only safety critical failure mode.
PTC prepares a SAR (safety analysis reports) on annual basis for their equipment. SAR reports include installation, operational details of particular equipment. In the report, failure rates are calculated for safety-critical failure mode categories in operational phase only. This failure mode category is classified further as; (Andersen, 2012)

- Dangerous detected failures
- Dangerous undetected failures

Dangerous-undetected failure is detected during operational testing and dangerous-detected are detected by automatic self-testing or operator personnel.

In RMS system, the safety criticality option is used for the dominant failure modes according to their criticality measure. Criticality is measured by analyzing failure cause, failure mechanism, realistic MTTF. (Andersen, 2012)

Corrective actions and failure characteristics are also defined to some extent in remarks box for example, whether it was an aging failure, gradual or sudden failure. However, failure characteristic measure is not recorded such as for gradual failures the condition monitoring indicators and for aging failures an aging parameter. (Rausand and Høyland, 2004)

5.2.1.2. Failure rate calculation on basis of failure mode classification

RMS is based on the assumption of constant failure rate as most of the commercially available reliability data sources do. (Rausand and Høyland, 2004)
The total failure rate is calculated as

$$\lambda_{DD} + \lambda_{DU} + \lambda_S = \lambda_{TOTAL}$$

Where,
λ_{DD}= failure rate of dangerous detected failures
λ_{DU}= failure rate of dangerous undetected failures
λ_S= failure rate of safe failures
λ_{TOTAL}= total failure rate

A Gap analysis[4] is performed for failure of particular equipment to prevent inaccuracies and inconsistencies in the component data. For example, Gap analysis on ASV (annular safety valve) addresses the leak rate according to ISO standard 104117 acceptance criteria, if occur during component lifetime.

5.2.1.3. Shortcomings in RMS database

By analyzing failure mode categories and failure rate of PTC RMS on the basis of standards (ISO, OREDA, and AICHE 98), following shortcomings has been observed:

i. **Insufficient failure mode categories**: In RMS number of failure encountered is recorded carefully but it lacks reasonable failure mode classification. The failure mode is most important criteria for defining a failure event. For example, a pump can fail either on demand or during operation (in operation for a certain time). The type of reliability parameters to be calculated from the data depends on the failure mode: the failure on demand is described by a (time independent) failure probability and the failure on operation is described by a failure rate (time dependent). (Flamm and Luisi, 1992). Insufficient categories of failure mode in RMS affect the maintenance activities and results of the reliability analysis.
ii. **Absence of repair time estimation:** RMS system does not offer estimation of the repair times associated to the any failure modes in the system. (Rausand and Høyland, 2004) The repair times (man-hours) and downtimes related to the various equipment failure modes found in OREDA is helpful to determine system unavailability. Each failure

[4] GAP analysis is done to compare the actual performance with desired/expected performance.

mode requires different repair time and the risk during waiting can also be different. Since risk level varies with different phases of restoration time. Therefore it is important to find unavailability for each failure mode. For safety critical failure modes risk level is much high. (Rausand and Høyland, 2004)

iii. **SAR is not connected to RMS:** SAR reports are not linked to RMS. Reliability calculations done in RMS do not give clear picture of failure rates of corresponding failure mode. The analyst has to spend time to find and look back at SAR reports to get detail information about equipment failure rates.

iv. **Cannot calculate failure rates for selected populations of equipment within well-defined boundaries of design and functional parameters:** OREDA participating companies can calculate failure rates for selected populations of within well-defined boundaries of manufacturer, design and functional parameters. The failure rates can be calculated for the different failure modes and individual reports of the failure/repair activities can be reviewed easily. (Flamm and Luisi, 1992)

v. **Only one type of analysis can be performed in RMS:** On the basis of these categories OREDA database offers three types of analysis; standard, frequency and life distribution analysis. OREDA has its own software to perform life distribution analysis and is compatible with SINTEF developed program to perform such analysis. (Sandtrov et al., 1996). In the case of RMS it is only possible to perform life distribution reliability analysis (parametric and non-parametric) but with limitations due to limited failure mode category. By introducing appropriate failure mode and their category in accordance to their criticality level in the RMS database, data variance can be within limits and hence we obtain improve quality of reliability estimation for intended purpose. (Sandtrov et al., 1996)

vi. **Missing operational and environmental data**: RMS system has missing data in field of operational and environmental information. This means analyst has to adopt estimation method to fill missing information. As a result, data may have relatively different values, compared to samples where these data are available. Hence the data collector experiences the less accurate data with respect to operational time, actual number of failures encountered, etc. rather neatly updated maintenance files from an operator.

vii. **Cannot estimate reliability as function of some environmental and operational conditions:** RMS databases do not shows how reliability depends on operational and environmental conditions. In more advanced reliability databases like SINTEF, a detailed and comprehensive failure event database for Surface Controlled Subsurface Safety Valves was established. It was possible to estimate reliability as function of some environmental and operational conditions, to some extent. However, estimation was difficult in many cases due lack of environmental/operational data. (Flamm and Luisi, 1992)

5.2.2. The quality/effectiveness of data in RMS database

As discussed in Chapter 4, a good quality data should have following properties:

- completeness
- unambiguousness
- meaningfulness
- correctness

Another suitable definition of quality data could be "*quality data are data that are fit for use by the data consumer*". Maintaining the quality of data in reliability database is very critical for effective reliability management system. Factors that affect the data quality are: (Lin et al., 2006)

- Poor data management structures
- Untrained data collectors, and non-documented procedure and guidelines for data collection
- Inconsistencies in data collection procedures.
- Lack of focus on weaknesses in the source data
- Users cause the errors to arise by mistakenly adding incorrect or incomplete data. (Abdullah, 2013)
- A poor and inadequately designed database. (Abdullah, 2013)
- *"Data is represented differently in different sources. Moreover, even when data has the same attribute, name or data type." (Abdullah, 2013)*

5.2.2.1. Analyzing PTC RMS data quality

This section is mostly concluded from the meetings and discussions with PTC representatives. Data quality in PTC RMS highly depends on the data collection procedures and plans defined to capture the required data for intended use and feeding it in to the RMS database. Let us have a look at different element that controls the quality of data in RMS;

- **Trained data collectors**: Data collectors for RMS data and other databases of PTC are trained, in terms of operational, installation and equipment specification, to collect relevant data for corresponding databases.
- **Data collection procedure is planned**: People responsible for inspection of failed equipment usually communicate with client through meetings. At the initial stage communication takes place through telephone, videos, email. And afterwards, meeting are arranged to collect data related to failure event. The responsible customer contact (currently 3 or 4 person in PTC) is responsible for populating the information required in the investigation report.
- **Incomplete or missing data:** The data that is accepted in other databases of PTC is only the validated data. However, some data like operational data (pressure, temperature) is not always given by client. It is really hard to get operational data back from the clients, so most of the investigation / inspection reports are based on

assumptions. As mentioned earlier, ISO 14224 defines data quality as data should be complete and correct.

- **Cross-communication between data collector team:** Data collectors need to communicate closely to handle the changes (plans, definitions, codes etc.) during the data collection project. Unavailability of quality data and wrong interpretation of codes and guideline are two major problems in process of data collection according to OREDA data collection project.

When we look at four properties of data defined above, we can say data in PTC RMS is quite close to the elements of meaningfulness, correctness but it lacks the elements of completeness and unambiguousness. Following are some weaknesses in data management system which causes these problems to arise:

- A predefined plan is followed by the data collectors but this plan is left un-revised. This eliminates the improvement chances in data collection procedures and directly effects data quality in RMS database. For this purpose summary of changes to the quality work process shall be provided in form of quality work process reports. This shall be done on annual basis. (Kumar, n.d)
- PTC data collectors are well trained and motivated in terms of equipment knowledge but these data collectors are not reliability experts. So the attributes and data format that describe reliability information are not properly defined. An information structure for defining and storing reliability information is missing.
- Unfortunately, most of the key observations and insights during the communication activities are not always recorded in a structured format. The precious information (raw data) is lost or remains unexplored.
- Due to missing information, data collectors fail to get detailed understanding of equipment operational history and past issues. This adversely affects the quality of data in RMS database.(Kumar, n.d)
- For the data in RMS, a Data Quality Assurance (DQA) plan is missing. As mentioned earlier, there is a team working as a data collector in PTC. To improve the data quality in RMS, a consistency check of interpretation rules and quality standards between different data collectors is required.

5.3. Final remarks on PTC RMS

The design of PTC RMS is ‘hard-wired'. The decisions related to assembling and completing failure modes, data formats, system structures have been taken during the software development. The user of RMS database cannot reconstruct the methods. The same software solution cannot be suitable for all potential users, for all maintenance systems, for all operating environments. (Pettersson, 1998)
RMS has a very confined structure in which equipment categories are not defined according to their corresponding equipment class. The database taxonomy is missing. The design parameters are very limited. Properly defined failure mode classes capture the information about the timing and severity (critical level) of all types of failure modes. In RMS failure modes are defined in two categories safety critical and non-safety critical. But many failure modes which are considered safety critical still need quick attention because they can lead to loss of production if maintenance delay occurs.

PTC data collection sources are limited to manual procedures which need a lot of effort and time. If possible, PTC databases should be integrated to extract the data automatically in an efficient way with less time and effort. PTC should try to get the information from their client's system that includes equipment utilization and process-related information. Operational and environmental data related to investigation report is missing in most cases. This will help to get operational and environmental data from the user tracking system very easily. As a result, improve the quality of data in RMS and maintenance databases. The PTC RMS with improved features and improved data quality could help to redesign the existing equipment with better performance and improved reliability.

Chapter 6

6. Suggestions for improved data collection and decision support

Based on the analysis of PTC RMS in chapter 5, some suggestions are provided here which can help to improve the efficacy and effectiveness of PTC RMS. The suggestions are categorized in to three categories depending on their complexity, in terms of their implementation, and the integration with the existing system of PTC.

6.1. Minor suggestion

Some minor suggestions are as follows:

- Data that is fed into the database of RMS should be assessed in terms of information level, accuracy and access to that obtain data in other databases. For this purpose a data quality assurance should be performed.
- Data-collection methods should be planned and tested before starting main data-collection process. Create a work plan and scheduled deadlines. Decide when and how to collect data. Prepare your clients by informing them about your data collection plan and purpose.
- Responsible personnel shall be aware of the data-collection concept and procedures for the data-collection process. It would be beneficial if they have some knowledge about technical, operational and maintenance details of the equipment for which data is collected.
- To obtain the quality data, the responsible person should be properly trained. Data collectors shall know the ISO 14224 and give appropriate feedback to the data providers.
- The failure data collection should start as soon as collection plan is in place, so that data collected is 'complete' (in terms of information) and less erroneous.

6.2. Moderate suggestions

Following are the moderate suggestions:

- It is a good idea to do automation of data transfer between RMS and other PTC databases. This will save time and effort. This way, the data can be transferred more frequently minimizing the chances of deviations and errors.
- It will be a good step if PTC can directly extract the operational and failure data from their client's database. This would minimize the paperwork and also the errors caused by duplicate data sets. Data collection process will be more time and cost-efficient.
- If failure event reports can be connected to the relevant operational data in the factory tracking system by assigning an identifying number then it will be easy to access data efficiently.
- If the reliability analysis is performed by a third party at a remote location, it is a good idea to arrange meetings with them every more frequently. The purpose of the meetings is to discuss reliability outcomes and critical information.

- It is preferred to have in-house competency for the reliability analysis process because it might be difficult to involve a third party into the reliability improvement activities in the organization all the times.

6.3. Major suggestions

In addition to the minor and moderate suggestions, there are some suggestions which are more complex to integrate in PTC existing systems. The first one is Failure Reporting Analysis and Corrective Action System (FRACAS) and other is Data Mining (DM) process. These techniques require reasonable resources to provide the desired effect. But once implemented with adequate procedures, these techniques can boost organization's business case.

6.3.1. Failure Reporting Analysis and Corrective Action System (FRACAS)

The failure reporting and corrective action system (FRACAS) is a valuable tool used to understand and improve the product reliability. The idea is to create a database with specific factors influenced by a specific test anomaly using a standard set of inputs. In the database, the given input selects specific characteristics of failure events to prioritize the data using Pareto analysis or other ways. (Raheja and Gullo, 2012)

FRACAS is closed loop feedback system for failures, in which both supplier and user work together to collect, record, and analyze failures of particular data sets. The user capture data about the failure using any tool (software or manual) and submit it to the supplier. (Villacourt and Govil, n.d)

A Failure Review Board (FRB) is established at the supplier's end. FRB includes personnel from mix disciplines (design, manufacturing, systems, quality, and reliability engineering) as well as leadership (technical or managerial leads). This is to make sure that a well-rounded discussion is performed for particular failure related issues. (Raheja and Gullo, 2012)

FRB analyzes the failures in terms of time, money, and engineering personnel to identify corrective actions. Ultimately, management is responsible for the decision making based on results from FRACAS. The corrective actions are implemented and verified through follow ups to prevent reoccurrence of failures. A simplified form of this process is represented in Figure 30. (Villacourt and Govil, n.d)

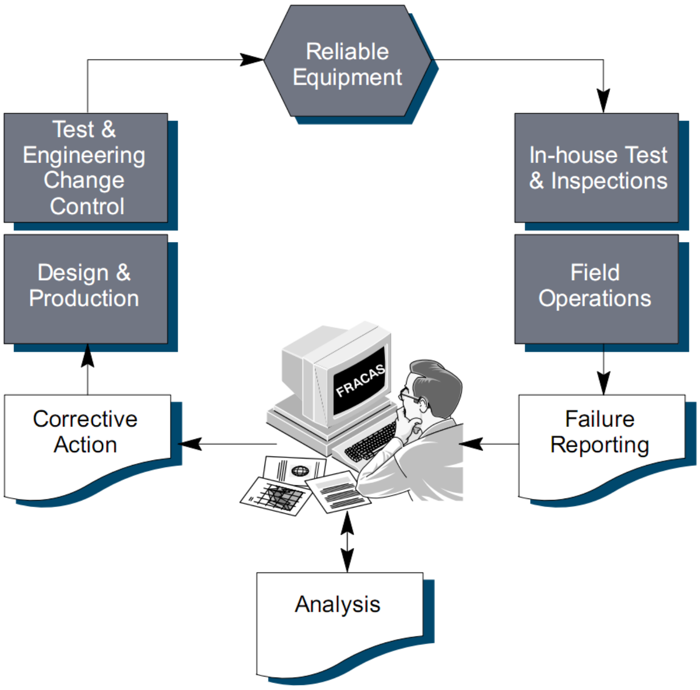


Figure 29 : FRACAS process work flow (Villacourt and Govi, n.d)

Main objectives of FRACAS are providing engineering data for corrective action, assessing record of reliability performance in terms of mean time between failures (MTBF), mean time to repair (MTTR), availability, preventive maintenance, etc. providing patterns for deficiencies, give data for statistical analysis. (Villacourt and Govil, n.d)

6.3.1.1 Main features of FRACAS process

Main features of a successful FRACAS process are: (Villacourt and Govil, n.d)

i. **Failure Reporting**
Failures that occur during inspections and tests are reported through an established procedure. The failure report consists of identification of the failed item, failure symptoms, testing conditions, item operating conditions and failure time. The data in these reports is verified before submitting these reports. The failure reporting process involves data collection process and supervised data logging.

ii. **Failure Analysis**
Failure analysis is the performed to determine the root cause of failure. Root cause analysis is performed for each reported failure. The problem owner, associated FRB member, and reliability coordinator must guarantee that throughout the analysis process database is maintained with the updated relevant information. Corrective actions are also developed in this process. The conclusions made after the root-cause analysis should be documented in a FRACAS system because it is very important to develop proper procedures for tracking the failed parts and reporting the problem analysis outcomes. All reported failures need to be verified by evidences. This verification is tracked within the FRACAS.

iii. Failure Review Board

The FRB performs the following tasks :(Villacourt and Govil n.d)

- Reviewing the failure trends of equipment,
- Helping and managing the failure analysis, and
- It plays an important role in developing and executing corrective actions.

To perform above listed tasks properly, the FRB must have the authority to demand investigations, analyses, and corrective actions by other organizations. The FRB is self-managed team which focuses on improving methods under their control. Many companies widely use advanced method such as the design of experiments as a part of their project plan for problem-solving since it is observed that this method helps their FRBs make unbiased decisions. To assist the FRB in failure analysis, it is required to establish failed parts procurement process. The procurement procedure should be defined clearly including the timeline and responsibilities for all including tasks to give the accurate information to FRB for proper decisions. (Villacourt and Govil, n.d)

iv. Design Modifications and corrective actions

The implementation of planned corrective action should be approved by a client representative, and proper change management should be done. The quality assurance is done through testing and inspection of all redesigned equipment. When corrective actions are implemented then failure report is closed or it may be closed without any corrective action verified by FRB.

6.3.1.2. FRACAS Database Management System (DBMS)

A FRACAS database is for tracking all products offered by a company. Figure 31 shows how problem status is kept updated in FRACAS database.

PROBLEMS RECORD

Reliability Code ATF-STK-PRI-RT-XAX-001

Title/Description LIMIT FLA SENSORS FAIL

System:	ATF	**Initial Status:**	I
Subsystem:	STK	**Fault Category:**	Facilities Elec
Assembly:	PRI	**Error Codes:**	errcode 2
Subassembly:	RT	**Assignee:**	Eric Christie
Sub-subassembly:	XAX		

DATES

Insufficient Info:	11/04/93
Sufficient Info:	/ /
Defined:	/ /
Contained:	/ /
Retired:	/ /
RCS Documentation:	

ROOT CAUSE SOLUTION (RCS)

Original Plan:	/ /
Current Plan:	/ /
Complete:	/ /

Comments: Not enough information at this time. However, supplier is investigating vendor part #po09347-90.

STATISTICS

Current Status:	I	**First Reported:**	11/04/93
Number of Fails:	2	**Last Reported:**	11/11/93
Number of Assists:	0		
Number of Others:	0		
Total Events:	0		
Total Downtime Hours:	2.72		

Figure 30 : Example of failure record of a specific FRACAS database (Villacourt and Govil)

By using FRACAS database management system (DBMS), data can be displayed in different ways. The reports provide a quick graphical representation of equipment performance at any given point. Some of the examples of data representations in FRACAS DBMS are: (Villacourt and Govil, n.d)

- *"The percentage rejection rate on a monthly basis as actual-versus-target rates.*
- *The number of failure modes or problems on a weekly basis.*
- *The number of events being reported weekly by life cycle phase.*
- *A one-page status outline for tracking by the FRB."*

Whichever report is used, it is important to customize it so that it can provide summaries and particular information for both management and engineering personnel. (Villacourt and Govil, n.d)

6.3.1.3. Requirements for an effective FRACAS process

To get effective results from FRACAS process following requirements should be met:

- Failure and maintenance data should be used in a timely and disciplined manner so that corrective actions can be decided and implemented effectively. (Villacourt and Govil, n.d)
- The process can be cost-effective if implemented at early stages of product development as it is easy to provide detail failure data from an early stage and implement required corrective actions. (Schenkelberg, n.d)

- Reliability growth modelling can be used to judge the effectiveness of the FRACAS/FRB process. If the rate of occurrence of failures (ROCOF) is not decreasing, it may require an increase in resources in specified area. Reliability growth modelling can help technical management to judge the process effectiveness. (Raheja and Gullo, 2012)
- Coding of failure cause should be done correctly in the FRACAS database and should be connected with their correct failure-cause categories. (Villacourt and Govil, n.d)

6.3.1.4. How FRACAS can help in failure reporting

FRACAS database may be integrated into companies CMMS. However, small companies may prefer to develop their own FRACAS database but it should be developed in a way that it allows easy entry and retrieval of failure data for analysis. (Keeter, n.d)

To get benefits from FRACAS, the company must work on the developing the close coordination between client and PTC personnel responsible for data collection. (Villacourt and Govil, n.d)

- FRACAS solution gives an advantage that all the information related to equipment failure is in single source and can be accessed from all level of organization. But sizable investment is required to integrate it with existing databases. (Keeter, n.d).
- It is a useful tool for reliability testing as well as good opportunity for reliability improvement during engineering verification, qualification testing, acceptance testing, and field returns activities. When FRB is involved in cause analysis process it helps to gain insight and noticeable improvement over time. (Raheja and Gullo, 2012)
- FRACAS encourages Supplier Company to take part in discovering and addressing key concerns that affect reliability for the item supplied. FRACAS data from FRACAS DBMS can be used effectively to verify failure modes and failure causes in the failure mode effect and criticality analysis (FMECA). (Raheja and Gullo, 2012)
- A well-designed FRACAS methodology provides a platform to sort failure data and when required can be viewed by engineers and managers to get useful pictures of trends and failure drivers. This helps in performing root-cause analysis for occurred failures and to capture the important lessons learned from testing for future design and test programs. (Raheja and Gullo, 2012)
- In a good FRACAS database testing and field experience data available can be useful to update the reliability models thus increase the model accuracy and usefulness. As a result, it improves confidence in the models.(Villacourt and Govil, n.d)

FRACAS is a closed-loop corrective action system. When reliability is assessed using this process it helps to predict possible areas of high failure rate. Review of failure data and analyses recorded in FRACAS database addresses the knowledge of the underlying causes of failures. The fed back information to the design and management helps in addressing the issues. This initiates further analysis and testing providing more feedback. This process continues and gradually improves the product’s reliability. Finally, FRACAS information can help the company in measuring contractual performance to better determine warranty information.

FRACAS process tries to fulfill ISO 9000 requirements which now days is demanded by many clients, to meet ISO 9000 from their suppliers. (Villacourt and Govil, n.d)

6.3.2. Data mining (DM) to improve the effectiveness of the reliability management

The Knowledge discovery in database (KDD) involves various steps where each step is depending on preceding step. In real life applications, extracting useful knowledge is not an easy task. A lot of platforms are available to store and access data. This rapid growth in data size and technology demands to adopt the KDD. The KDD process involves following steps: (Abdullah, 2013)

- Data cleaning
- Data selection
- Data transformation
- Data mining
- Pattern evaluation
- Knowledge representation

The KDD process is generally divided into two phases: Preprocessing phase and Post-processing phase. Data cleaning, data selection and data transforming belongs to phase of pre-processing. Whereas, Data mining, pattern evaluation and knowledge representation belongs to post-processing. (Abdullah, 2013)

This section of thesis is focused on data mining so we are going to discuss data mining step of KDD process here.

6.3.2.1. Data mining introduction

According to (T.Larose, 2014) "*Data mining is an interdisciplinary field bringing together techniques from machine learning, pattern recognition, statistics, databases, and visualization to address the issue of information extraction from large data bases*".

Data mining is an analytical process which is used to look for consistent patterns and /or systematic relationship between attributes and variables. This is performed usually for large sets of data. Basic purpose of data mining is to get data with good quality since with bad quality data the process of discovering pattern, relationship and structures will be affected. (T.Larose, 2014)

6.3.2.2. The relationship between DM and statistical models

It is often thought that process of data mining is same as statistical analysis. However, this is not the case due of many reasons mentioned in table 13.

Table 13 : *A comparison between classical Statistical analysis and data mining (Leventhal, 2010*

	Statistical analysis	**Data mining**
1	Statistical theory is applied on small size sample taken form a population. No. of attributes were small so that variable can be examined individually and transformed according to suited for analysis.	DM is applied on whole database, a large population of data with many variables.
2	Statistical analysis can give erroneous result if applied on large number of samples.	DM provides automated tools to select relevant attributes among large population, hence liable to contain huge number of attributes.
3	Since Statistical analysis is done for small data sets so mostly no facilities are required.	Building and evaluating DM model, it is required that facilities are in place to support large scale model deployment.
4	*"statistical analysis will aim to Identify a model that is statistically significant — that is, outperforms a random prediction — based on a set of significant predictor variables". (Leventhal, 2010)*	*"DM includes diagnostic results to indicate likely business benefits from the model." (Leventhal, 2010)*

6.3.2.3. How DM models are built

A standard process of data mining also known as CRISP-DM (Cross Industry Standard Process-Data Mining) is established in 1996 by a group of companies. This process defines life cycle of data mining in six phases. (Leventhal, 2010)

The process is shown in figure 32.

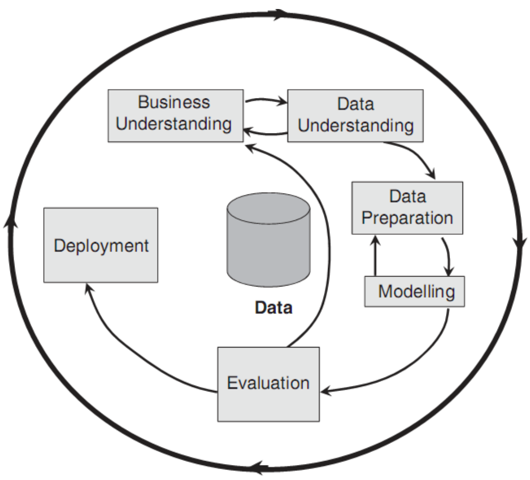


Figure 31 : *Cross Industry Standard Process for data mining (Leventhal, 2010)*

i. Business understanding

The first step in a typical data mining process is to define the objectives of this project. Requirements are defined in terms of business needs. Then from these objectives and business requirement a data mining problem definition is document along with a preliminary plan. (Leventhal, 2010)

ii. Data understanding

After completing data collection process from different databases, different activities are performed for understanding data. In this phase, quality of data is also analyzed to recognize problems with data quality. From this data, interesting subsets are extracted to form hypotheses for hidden knowledge. (Leventhal, 2010)

iii. Data preparation

This phase involves constructing final data sets from raw data. These datasets are added in to the modelling tool. These preparation steps are performed many times. This phase prepares table, record and selected attribute, as well as transformation methods are applied and cleaning of data for modelling tools is done.(Leventhal, 2010)

iv. Modelling

In this phase, modelling techniques which suits best to the objectives, defined in business understanding phase, are selected and applied. The parameters are adjusted to best possible values. Sometimes it is required to return to the data preparation phase because some techniques have particular requirement regarding data category. (Leventhal, 2010)

v. Evaluation

Now a model is built that look to be of high quality from data analysis point of view. It is important to evaluate this model and the steps implemented to build the model, before starting final deployment of the model. This is done to make sure that the achieved model is successfully achieves the business objectives. At the end of this phase, it should be decided that whether the data mining results will be used or not. (Leventhal, 2010)

vi. Deployment

The knowledge gathered during preceding phases needs to be structured and presented in a form which end-client can use. This phase involves either generating a report or implementing a repeatable data mining process, depending on the project and business requirements. The deployment can be done either by the end-client or the data analyst. If this is done by analyst then end-client must be involve in this phase to understand up-front. So that end-client can learn the type of actions which he should carried out to actually make use of built model. (Leventhal, 2010)

6.3.2.4. Data mining techniques

Based on the requirement, single or more than one data mining methodology can be used in order to extract useful information. However, all methodologies contain the following set of main tasks which are performed iteratively. These are described as follows: (Abdullah, 2013)

i. **Pattern summarization**

The first technique in data mining is to adopt pattern summarization method such as the profile-based approach. The problem is even if pattern that lie within specified minimum threshold are removed, total number of patterns remain considerably large. This makes it difficult for the experts for manual examination over patterns. This technique is used to eliminate large number of patterns in data. (Abdullah, 2013)

ii. **Classification**

In this technique set of feature is classified correctly which are related to set classes. The model that emerges from classified set of features in training data can be used to calculate the classes of new data. The accuracy of emerging model is dependent on the accuracy of features. This is supervised data mining task. (Abdullah, 2013)

iii. **Clustering**

In this technique, instances are categorized into number of clusters based on the similarities between them. The instances in same cluster share many features. A common cluster technique is that user specifies the number of required cluster, as K. And based on the ordinary Euclidean distance metric, every instance is allocated to most cluster which appear closest in terms of characteristics. This is an unsupervised technique of data mining. (Abdullah, 2013)

iv. **Association rules mining**

Association rule mining has two phases. The first phase is pattern mining; in which frequent item-set are explored. The second phase is rule generation; in which interesting and useful associations rules in discovered item-set are explored. The association rule helpful in measuring links between item-sets. (Abdullah, 2013)

There are many other different data mining techniques such as frequent pattern mining, rough set theory, and rule generation. Explanations of these techniques may be found in a variety of sources. (Abdullah, 2013)

6.3.2.5.Data mining methods to improve Data quality of a database

Large amount of equipment related data is produced and collected during daily operational activities. These data contains many attributes. When considered simultaneously these attributes helps to understand systems behavior precisely. It is a lot of data from which useful knowledge can be extracted. However it is impractical to manually analyze such huge amount of data for decision making. Data mining provides automated tools to extract valuable knowledge from the huge amount of data existing in database. (Braha, 2002)

Once business objectives and database is defined for data mining process, task of cleaning the data in database is initiated. This stage is most time-consuming but crucial for the success data mining project. Some typical data problems are: (Braha, 2002)

- Duplication: Same data appear multiple times in database.

- Missing Data Fields: It can occur due to many reason for example customer is tired of putting desired information in forms.
- Outliers: (Braha, 2002) defines it as "*an outlier is a data value in field, which is very different from the rest of data values in the same field*". This is because of incorrect recording of outlier fields. It requires an extensive effort to identify such data.

Usually the data owners are unaware of deficiencies in data quality because the system is performing well. Data mining techniques can help to measure, explain, and improve data quality.

6.3.2.5.1. DQM: A DM method to improve data quality for decision making

A data quality mining (DQM) is application of data mining techniques. DQM is used to measure and improve data quality. According to (Hipp et al., 2001), "*the goal of DQM is to detect, quantify, explain, and correct data quality deficiencies in very large databases*."

The main difference between both methods is that goal of data mining process is pattern recognition for finding hidden knowledge and DQM goal is pattern recognition for quality assessment. The aim of QM is to assess data quality using reliable patterns. It is not necessary that these patterns introduce new knowledge. As discussed earlier, KDD involves extracting of knowledge from data in databases. In KDD process, DM task assumes the data is complete, compiled and "cleaned" to start the knowledge discovery phase. QM actually focuses on the data quality evaluation. Figure 41 shows the KDD process dimensions. (Vazquezsoler and Yankelevich, 2001)

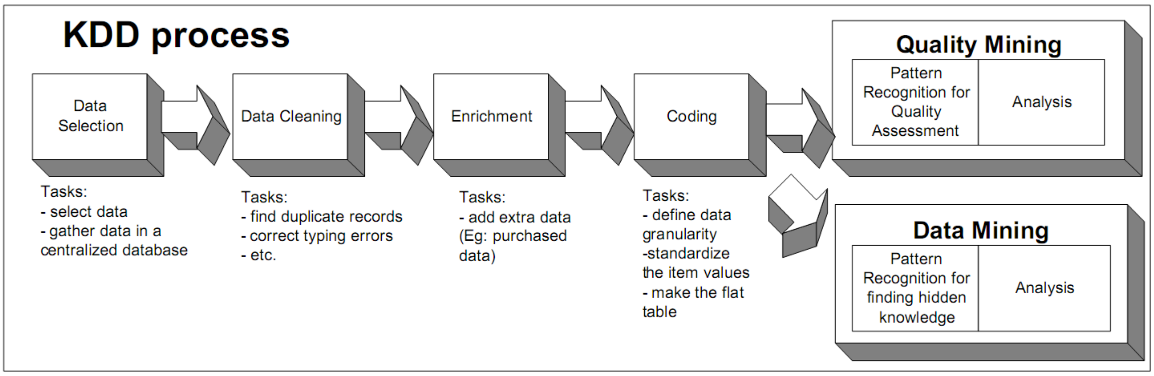


Figure 32 : *A KDD process dimensions with DM and DQM method (Vazquezsoler and Yankelevich, 2001):*

QDM can be used for validation of data before it can be used for decision making. DQM process performs the following tasks to help with data quality problems mentioned above: (Dasu and Berti-Équille, 2009)

a. Outlier Mining

As defined earlier outliers are extreme values that fall outside the defined range for variables or they appear different from remaining data. Identifying outliers is important but it is important to consider that they do not always represent error in data; sometimes they may represent a valid interpretation. So it is not always a good idea to delete outliers without using them in data mining. In some cases they can contribute positively in data quality improvement efforts. (T.Larose, 2014)

Another issue is that, even if an outlier is representing a valid interpretation and is not an error; some statistical methods respond very sensitively towards the outliers. In such scenarios statistical method gives unstable results. (T.Larose, 2014)

According to (T.Larose, 2014), neural networks model is most efficient among all models because they are insensitive to outliers. However, they have very complex structure and lack of clear graphical representation of the results. That is why analysts prefer regression models and decision trees over neural networks. They are to be used only as a last option. (T.Larose, 2014)

Following methods can be used to identify outliers: (T.Larose, 2014)

1. By specifying an acceptable range of values for each variable
2. Using model fitting (such as regression models)
3. Using clustering technique

Reader is referred to (T.Larose, 2014) where these methods are explained with good details. According to (T.Larose, 2014), "*an important observation is that, if a large percentage of the data comes in range of outliers (i.e., more than 5%); this indicates that there is more than one mechanism governing the data at hand. In this case, it is worth investigating developing a separate model for the outliers*".

b. Outlier change Detection

DQM help to detect the change in pattern of outlier data with new coming data stream. **"***Often, an increase or decrease in outliers is the first sign of a distributional shift*." (Dasu and Berti-Équille, 2009)

It may give serious indication towards data quality and simply means that we need to readjust variance by changing detection methods. It is very critical to change detection methods since precise detection of outlier plays an important role in success of DM process. (Dasu and Berti-Équille, 2009)

c. Handling Missing and Duplicate Data

During the process of data collection and transformation from one database to other some error and missing values occurs in data. It is very common practice in DM projects that missing values are skipped from the analysis. In most cases it does not cause any harm to omit missing values from analysis. But as explained by (T.Larose, 2014) that "*the pattern of missing values may in fact be systematic, and simply deleting records with missing values would lead to a biased subset of the data. Further, it seems like a waste to omit the information in all the other fields, just because one field value is missing.*"

Therefore, analyst uses the methods of replacing missing values with a value substituted in accordance to various criteria. Data miner gives the option to choose among following options of replacement values: (T.Larose, 2014)

1. *"Replace the missing value with some constant, specified by the analyst.*
2. *Replace the missing value with the field mean (for numerical variables) or the mode (for categorical variables).*

3. *Replace the missing values with a value generated at random from the variable distribution observed."*

6.3.2.6. Initial steps in selecting DM model

Wide varieties of software are available for DM in marketplace. Software selection depends on the requirements of potential buyers; however no single solution can fulfill all requirements so the buyer need to mix several products that matches their needs. Each product has its own advantages for certain types of applications. DM mining tools should be selected by adopting same procedure as for an IT product. Before making any purchase a buyer should evaluate DM product for their own data. (Leventhal, 2010)

(Leventhal, 2010) defines some guidelines that a buyer should consider before considering any type of DM tool:

a. If a single DM model is required for limited range of variables, for small database, (such as PTC databases), then a 'hand-crafted' modelling solution should be suitable enough, using a DM tool.
b. On the other hand, if multiple DM models are required to be built, using a large set of variables, (as such as a credit card provider) then an automated DM tool is more cost effective. Such models have accuracy of around 90 per cent than hand-crafted models. Automated models also save analyst time by 90 per cent.
c. The cases where incorrect decision can lead to heavy loss, a non-automated DM tool is a good choice because it provides an opportunity to choose algorithms and in-depth analytics functions. This yields the best possible model.
d. When multiple models need to be managed, deployed and monitored then it is important to consider the solution that offers model management functionality.
e. If the objective of DM project is to target direct marketing campaigns, DM tool should be 'marketing friendly', that fits properly with the campaign management system.
f. Finally, it is crucial that the plan for deployment procedure and modelling architecture should be in place — particularly when the data is located in large warehouse. Buyer should prefer DM tool with practical in-database deployment options, such as predictive model markup language (PMML) files or structured query language (SQL) scoring code. Model deployment should be tested for all required model types.

6.3.2.7. Remarks on data mining concept

On the basis of above discussion related to data mining project, some suggestions are discussed as follows:

- **Advanced DM tool**

In order to form a more complete and powerful advanced analytics solution, there are some advanced DM tools which can also be considered during a DM project. Some of them are stated below: (Leventhal, 2010)

- Data visualization: Enormous amount of data is converted and displayed in form of multidimensional pictures and animations. These pictures bring areas of interest in focus and assist in analyzing the complex data.
- Text mining: often data is in form of unstructured texts. These text needs to undergo text mining before feeding them into DM tool.

- **Predictive or descriptive model**

To create a DM model analytical modeling is performed. During this process meaningful relationship between variables are identified and use them to create predictive or descriptive models. Descriptive models is the one which "*gives a better understanding of the data, without any single specific target variable"* and predictive model is the one which *"is constructed to predict a particular outcome or target variable". (Leventhal, 2010)*

Data miners select either one of the model or mix both to create a DM model that suites best to business objectives. (Leventhal, 2010)

- **Risk involved in DM**

Some risks are involved with DM project which can result in failure to deliver expected profits: (Leventhal, 2010)

  - Data must have high quality and consistency to avoid failure of whole DM project.
  - If DM tools users are not well-trained this can result in misleading results through automated modelling tools. Also, particular technical requirements need to apply at modelling stage by trained user.
  - Data pattern being generated without business objectives and without profit-generating applications is costly (in terms of time and money).
  - If model efficiency is not evaluated properly this can cause mistreatment of the findings and zero profit from whole the process.

- **Software packages available**

Some widely used software products for DM are shown in table 14. These software perform almost all the basic tasks discussed in section 6.3.2.3. (Leventhal, 2010)

Table 14 : *Some software packages for data mining (Leventhal, 2010)*

Product	Supplier	Notes
FICO Model Builder	FICO	
IBM Smart Analytics System	IBM	For use with IBM databases
IBM SPSS Modeler	IBM (SPSS)	Formerly SPSS Clementine
KnowledgeSTUDIO	Angoss	
KXEN Analytic Framework	KXEN	Employs structured risk Minimization for model reliability and automation
Oracle Data Mining	Oracle	For use with Oracle databases
Portrait Customer Analytics	Portrait Software	
RapidMiner	Rapid-I	Open source
SAS Enterprise Miner	SAS	
SQL Server Analysis Services	Microsoft	
Teradata Warehouse Miner	Teradata	For use with Teradata databases
TIBCO Spotfire Miner	TIBCO Software	

- **Shelf life of DM model**

The shelf life of a model can be predicted in accordance to the rate of change with time in the relationship between the model characteristics and the behavior. If the characteristics are stable then shelf life of DM model can extend up to many years.

According to (Leventhal, 2010), "*The 'best-practice' way to identify when a model has reached the end of its shelf life is to include a randomly selected control group in all campaigns targeted using the model. This will enable model effectiveness — and hence the return on investment from DM — to be calculated by comparing response rates (or the appropriate metrics) between the target and control groups*."

If a new source becomes available then model should be re-developed. Now days in such a dynamic market, shelf life is shorter hence modelling phase need to be faster and model automation should be the priority. This is the reason that some of the models shown in figure 46 are 'disposable' and 'replaceable'. Model automation is specially required when an organization wants to develop multiple models. (Leventhal, 2010)

6.3.2.8. Conclusions

Data mining is part of Knowledge Discovery in Database (KDD) process. Data mining help to extract interesting patterns from huge population of data in a database. For a large database automated DM tool are employed but for small databases 'hand-crafted' database tools are good enough. Wide varieties of DM software product are available in market. However data mining model should be chosen according to the business requirements of an organization. The well-defined business objective leads to selection of best suitable DM tools and techniques. In order to form a more complete and powerful advanced analytics solution advanced tools such as data visualization and text mining should be part of DM project.

Data must have high quality and consistency to prevent failure of whole DM project. A data mining method, Data Quality Mining (DQM), focuses on the data quality evaluation in KDD process. The aim of DQM is discovering the interesting patterns in data for quality assessment. On the other hand, aim of DM discovering the interesting patterns in data for finding hidden knowledge. "*DQM is the deliberate application of data mining techniques for the purpose of data quality measurement and improvement"*. DQM supports KDD and helps to improve the results of KDD projects. (Vazquezsoler and Yankelevich, 2001)

Potential software buyers should evaluate the shortlisted DM products for their database before making final purchase. "No single product works 'best' in all scenarios and market sectors, and therefore users should be prepared to 'mix and match' between toolsets, ensuring that models may be communicated between them as required". (Leventhal, 2010).

Models should be installed as part of a process through continuous monitoring, evaluation, learning and refinement. This will ensure gain of business value through a DM project.

Chapter 7

7. Discussions

Petroleum Technology Company (PTC) is using the Reliability Management System (RMS) to measure the performance and reliability of their equipment. RMS is not connected to the other management systems in the company such as engineering, maintenance and equipment's quality assurance systems. Currently, the manual procedures such as reporting, meetings and the responsible person (for RMS) to access the other systems used the data collection purpose in RMS. The literature review of ISO 14224 and OREDA was performed to understand the shortcomings in PTC failure reporting procedures and RMS database structural design. In an effort to elucidate weaknesses in the existing reliability management system of PTC, a number of problem areas have been discovered.

The main element of the RMS e.g. data collection sources, methods, and procedures are analyzed on the basis of existing industry standards such as ISO 14224 and OREDA. The elements belong to the procedures for failure reporting in PTC and they play an important role in deciding the quality of data in RMS. Another important element of RMS i.e. 'failure mode category' is also analyzed because the adequate definition of failure modes in RMS affects the quality of reliability analysis results.

The efficacy of RMS is evaluated with the focus on two main aspects:

i. RMS database structure
ii. Data quality in RMS linked with failure reporting procedures in PTC

7.1. RMS database structure

RMS database has been analyzed according to OREDA database. Following are the outcome of the analysis of the database structure:

- A well-defined taxonomy structure is missing in RMS database. In RMS taxonomy structure, equipment is classified by their type (ASV, H-SAS etc.) and one design characteristic i.e. Dim. Types of equipment are not organized in form of equipment classes, e.g., pumps, compressors etc. RMS is lacking equipment classification; in the form of design characteristics (design and performance specifications) and use characteristics (environment, operation, maintenance). Lack of these classifications makes it difficult to search and query the database for equipment data.
- RMS uses the list of failure modes for equipment which is pre-defined by ISO 14224 and OREDA database. Another shortcoming that is observed in RMS database is that failure modes fall into only two categories, that is, critical failure mode and non-critical failure modes. In the case of OREDA database, failure rates and repair time is calculated within three failure mode categories; critical, degraded, incipient. It seems that RMS puts incipient and degraded failure in their category of non-critical failure modes. Incipient failures are considered as errors (deviations) which should be corrected before they become the degraded failure. If these errors are corrected then the equipment doesn't need to be considered failed. Hence such failure rate calculations will give very

different results from those using both incipient and degraded failure modes in one category.

- In RMS database failure rates are calculated for selected population on the basis of equipment type and one design parameter (Dim). OREDA participating companies can calculate failure rates within well-defined boundaries of manufacturer, design and functional parameters equipment.
- Unlike OREDA, RMS system does not offer an estimation of the repair times associated with any failure modes in the system, so it is not possible to determine equipment unavailability. (Rausand and Høyland, 2004) Each failure mode requires different repair time. Therefore it is important to find unavailability for each failure mode. In the case of safety-critical failure modes, it is even more crucial to estimate the repair time and find out the unavailability period of the component.
- RMS database does not show how reliability depends on operational and environmental conditions. In some advanced reliability databases such as SINTEF. It was possible, to some extent, to estimate reliability as a function of some environmental and operational conditions. However, in most practical cases it is very difficult to estimate reliability on the basis of operational and environmental conditions due to lack of the information.

7.2. Data quality in RMS

Data quality in RMS depends on the data sources, data collection procedures and data collection process management within PTC.

RMS is not integrated to other management systems of PTC so a team is assigned to collect the report data from other databases. This makes the process time consuming and increases chances of error due to duplication of data. It is difficult for the responsible person to deal with the deviation (ambiguous definitions, lack of interpretation rules or inadequate codes etc.) during data collection. OREDA database has software to extract data from multiple sources and store it into single reliability and maintenance data. The software has built-in consistency check for the data. Using software for data collection can be cost-effective for PTC since there is repetitive data collection of the same type. PTC can also use it to transfer data from one CMMIS to another for maintenance activities.

The responsible personnel collecting data for RMS data are trained, in terms of operational, installation and equipment specification. The problem arises with the point that RMS is meant for reliability activities and the person who is collecting and storing data in RMS should also have knowledge related to reliability so that relevant data for intended use is collected in best possible format.

During the analysis of data quality in RMS, it is observed that it is difficult for PTC to get operation and environmental data of failed equipment from their clients through the formal meetings. Currently, the company is using Field Service Reports (FSR) and company's other databases as data sources for RMS. The company cannot access client's system that includes equipment utilization and process-related information. This leads to missing environmental and operational data. Thus ambiguities in data occur due to the assumptions being made to fill the empty field in RMS. It has been suggested that it would be good if PTC can download this data directly from client's tracking system. It will increase the efficiency of data collection process. The data collector will not need to make assumptions and completeness improve the quality of data.

It is observed that data from the data sources is collected by the responsible person but the collection method is usually not planned. Review of ISO standards revealed that data-collection methods should be planned and tested before starting the main data-collection process. It is suggested that PTC creates a work plan and scheduled deadlines, decide when and how to collect data and prepare its clients by informing them about your data collection plan and purpose.

PTC data collection procedures lack data quality assurance system. In OREDA database, they have established a data quality assurance system. Quality control checks are performed on the data being collected. Data collectors communicate closely to deal with the deviations occur during data collection process.

The safety analysis reports, for all equipment made by PTC, are prepared by a third party (reliability experts). Two problems arise with this procedure; one is that safety analysis reports are not linked with RMS database so they are not part of reliability analysis perform through RMS. Secondly, there is a lack of communication between PTC and reliability people. So it is difficult to share frequently the critical information. It is good idea if PTC arranges meeting with them more frequently to share important reliability information important for better decision making.

On the basis of the analysis, two major techniques are suggested: Failure Reporting and Corrective Action System (FRACAS) and Data Mining (DM).

7.3 How suggested methods can help with observed problem

FRACAS technique is proposed which can help PTC in improving the failure reporting and corrective actions for better decision making. The failure reporting process involves data collection process and supervised data logging.

FRACAS can serve as a system for PTC to assist in the record, analyze and rectify the cause of equipment failure. Usually, maintenance systems try to fix the failure but FRACAS tries to fix the cause of failure. (Faulconbridge and Ryan, 2002)

Contrary to RMS, a FRACAS database management system will generate failure report to record the failure and failure related data. This report is investigated by the responsible person. The investigators analyze failure by looking into reported data and also look at the other failures with similar characteristics in the database. Bases on this analysis, the investigator generate a corrective action report which states the possible corrective action to fix the failure. The corrective action report is reviewed and approved by failure review board (FRB). The board checks if recommended corrective action is possible to implement (in terms of cost, time and effect). The corrective action is followed to see if it stops recurrence of failure. (Faulconbridge and Ryan, 2002)

FRACAS can benefit PTC as follows:

FRB is involved in cause analysis process; this can help to gain insight and noticeable improvement over time.

- FRACAS can help PTC in discovering and addressing key concerns that affect reliability for the item supplied.

- FRACAS data from FRACAS DBMS can be used effectively to verify failure modes and failure causes in the failure mode effect and criticality analysis (FMECA).
- FRACAS can help the company to organize their failure reports and corrective actions.
- The automated failure reports through FRACAS system will remove the chances of human errors and will prevent silos of information.

Thus, FRACAS could help PTC to collect, organize and analyze its failure and maintenance data more effectively. It will be easier for users to search and look into details of the failure and corrective action reports. But replacing existing RMS with FRACAS can be a challenge for PTC in terms of cost and time. However if PTC works to improve procedures related to failure reporting and data collection according to ISO14224, this may eliminate the data problems in RMS. Implementing data quality assessment procedure like OREDA database can also help to improve the data quality in PTC reliability and maintenance databases

Second suggestion in the thesis i.e. data mining (DM), can help to improve data quality in the database. If PTC would like to continue with existing RMS, the data mining can be a good idea to improve data quality in other databases of PTC along with RMS.

A large amount of equipment related data is produced and collected during daily operational activities. The data contains many attributes. When considered simultaneously these attributes can help to understand systems behavior precisely. It is a lot of data from which useful knowledge can be extracted. Data mining provides automated tools to extract valuable knowledge from the data which exists in the database.

As discussed above, in RMS duplication of data, missing data field and outliers are very common data problems. A special data mining method, data quality mining, can be used to find the erroneous and missing data in the database. Quality mining actually focuses on the data quality evaluation. This technique helps to find and study interesting patterns in the data. Several software systems are available in the market for this purpose. However, the software product needs to be chosen according to company's business objectives. The decision to acquire the data mining software needs to be planned and documented business objective of the company before taking the final decision. The data mining software can be integrated with all systems of PTC. Hence by finding the interesting patterns of different data sets with specific variables can help to find the problem area either within a large database or with the dataset of particular equipment. During data mining, the detected outlier data can sometimes represent a valid interpretation and is not an error. DQM help to detect change in the pattern of outlier data with new coming data stream. Any increase or decrease in outliers can indicate towards a serious problem with data quality. Data visualization: Enormous amount of data is converted and displayed in form of multidimensional pictures and animations. These pictures bring areas of interest in focus and assist in analyzing the complex data. Text mining and data visualization are advanced tools of data mining techniques. Text mining of the data is in form of unstructured texts is done before feeding them into DM tool. So if data mining is carried out on RMS it can highlight the interesting pattern in the database and tells about the quality of data in RMS. DQM can be also be used for purpose of validation of data before it can be used for decision making.

If the company implements the DM model, they need to train their personnel to get intended benefit. DM models should be installed as part of a process through continuous monitoring, evaluation, learning, and refinement. This will ensure gain of business value through a DM project.

Conclusion

The main purpose of the thesis is to analyze the efficacy of existing Reliability Management System (RMS) of Petroleum Technology Company (PTC) and suggest techniques to improve the data for better decision making. The structure of RMS, its features (reliability analysis, equipment data and installation data) and quality of data coming into RMS is analyzed in detail. Failure reporting procedures which involve data collection sources, methods, procedure and data quality is evaluated using the ISO and OREDA standards.

The analysis shows that RMS has a very confined structure in which equipment taxonomy is not well-defined according to corresponding equipment type. Due to limited design parameters and unstructured taxonomy, it requires an effort to search and query the database for equipment data. RMS has limited failure modes categories which are not according to ISO 14224 and OREDA standards. Failure rate calculations are based on the classification of failure modes in RM database, so this affects results of reliability estimation for PTC equipment. PTC requires integration of RMS with its other databases to make the data transfer more efficient and improved data quality. Failure reporting procedures in PTC need revision according to ISO14224. The ISO standard recommends that data collection procedures to be planned and tested. The data quality control plan is missing in the data collection procedures of PTC. Thus, the resulting data quality is not up to the mark. It is recommended that PTC should revise their data collection procedures and implement data quality assurance plan by following the ISO standards.

If possible, PTC should integrate its management systems with RMS to collect and store data. It is also recommended that PTC should have method in place to access equipment utilization and process-related information stored on their clients systems. If PTC can get equipment operational and environmental data from the user tracking system, it could improve the quality of data in RMS and maintenance databases. And it could lead to redesign the existing equipment with better performance and improved reliability.

The suggestion, FRACAS and DM techniques, can help PTC to improve failure reporting structure within the company and improve data quality in RMS along with other PTC computerized management systems.

Future work

The main focus of the thesis has been on the data quality in RMS. Due to limited time, quality of data in other computerized management systems of PTC could not analyzed. Future work could be in-depth assessment of data quality in other databases of PTC. Also, a study of integration challenges of PTC RMS with the other PTC systems as well as with PTC client systems. Analysis of how integration can be performed and what could be the challenges in this process. An analysis of the consistency control within databases as well as data transformation challenges could be an interesting task. The study of creating single platform to store all failure-related data and use that platform to collect data for RMS. Due to limited scope of the thesis, the DM models have not been discussed in details. It seems interesting task to assess and recommend the most suitable DM models to PTC to achieve their business objectives. As the DM technique is not just applicable to RMS, it has a potential to help with data quality in PTC production, inspection, and engineering databases.

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Appendices

Appendix A - List of abbreviation

RMS- Reliability Management System

WI valve- Water Injection Valve

H-SAS- Safety and Automation System

MTTF- Mean Time To Failure

PFD- Probability of Failure on Demand

MTBF- Mean Time Between Failure

MTTR- Mean Time To Repair

FPO- Failure Prior to Operation

LCP- Leakage in Closed Position

SN- Serial Number

FAT - Factory Acceptance Test

MLE- Maximum Likelihood Estimator

PDMS – Production Data Management System

OREDA – Offshore & Onshore Reliability Data

ISO – International Standards Organization

RM data – Reliability and Maintenance data

CCPS – Centre for Chemical Process Safety

ESReDA - European Safety and Reliability Research and Development Association

FRACAS - Failure Reporting Analysis and Corrective Action System

DM – Data Mining

ROCOF - Rate Of Occurrence Of Failures

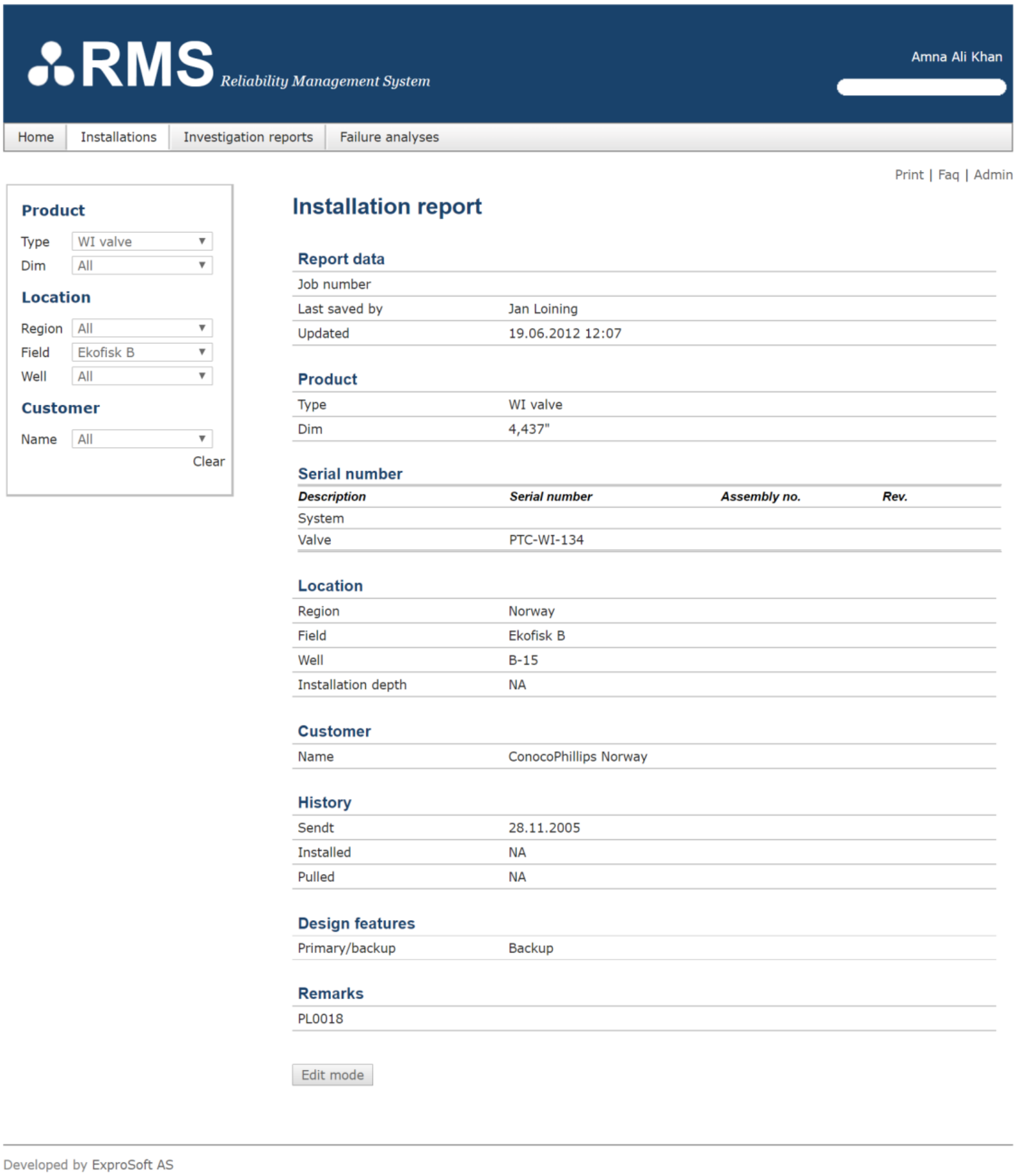
CRISP-DM - Cross Industry Standard Process-Data Mining

PMML - Predictive Model Markup Language (PMML) files

SQL - Structured Query Language

Appendix B – PTC RMS Screen shots

This section includes screenshot of different report from PTC RMS.


RMS Reliability Management System

Amna Ali Khan

Home | Installations | Investigation reports | Failure analyses

Print | Faq | Admin

Product

Type: WI valve

Dim: All

Location

Region: All

Field: Ekofisk B

Well: All

Customer

Name: All

Clear

Installation report

Report data

Job number	
Last saved by	Jan Loining
Updated	19.06.2012 12:07

Product

Type	WI valve
Dim	4,437"

Serial number

Description	Serial number	Assembly no.	Rev.
System			
Valve	PTC-WI-134		

Location

Region	Norway
Field	Ekofisk B
Well	B-15
Installation depth	NA

Customer

Name	ConocoPhillips Norway

History

Sendt	28.11.2005
Installed	NA
Pulled	NA

Design features

Primary/backup	Backup

Remarks

PL0018

Edit mode

Developed by ExproSoft AS

Figure 33: Installation report for WI-Value

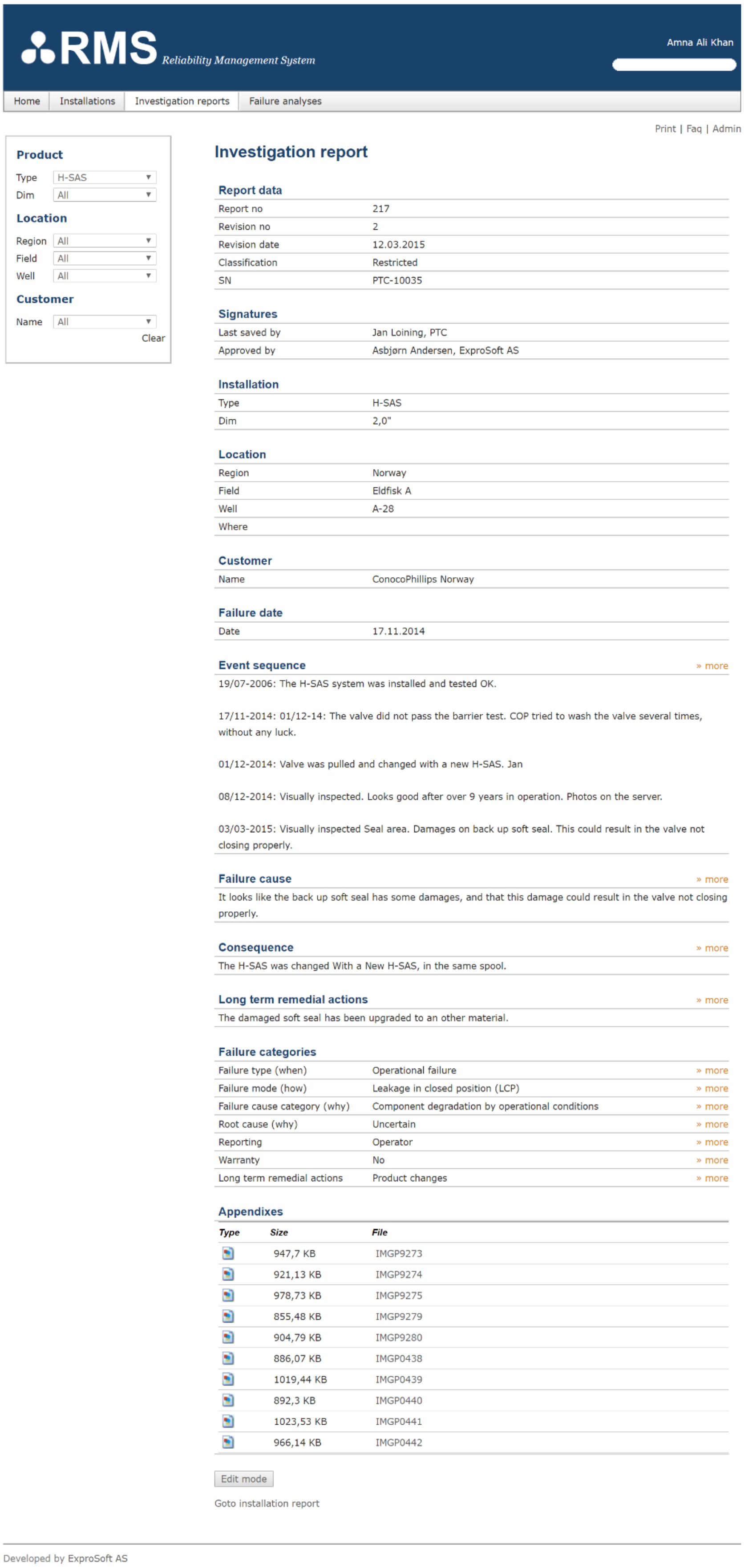
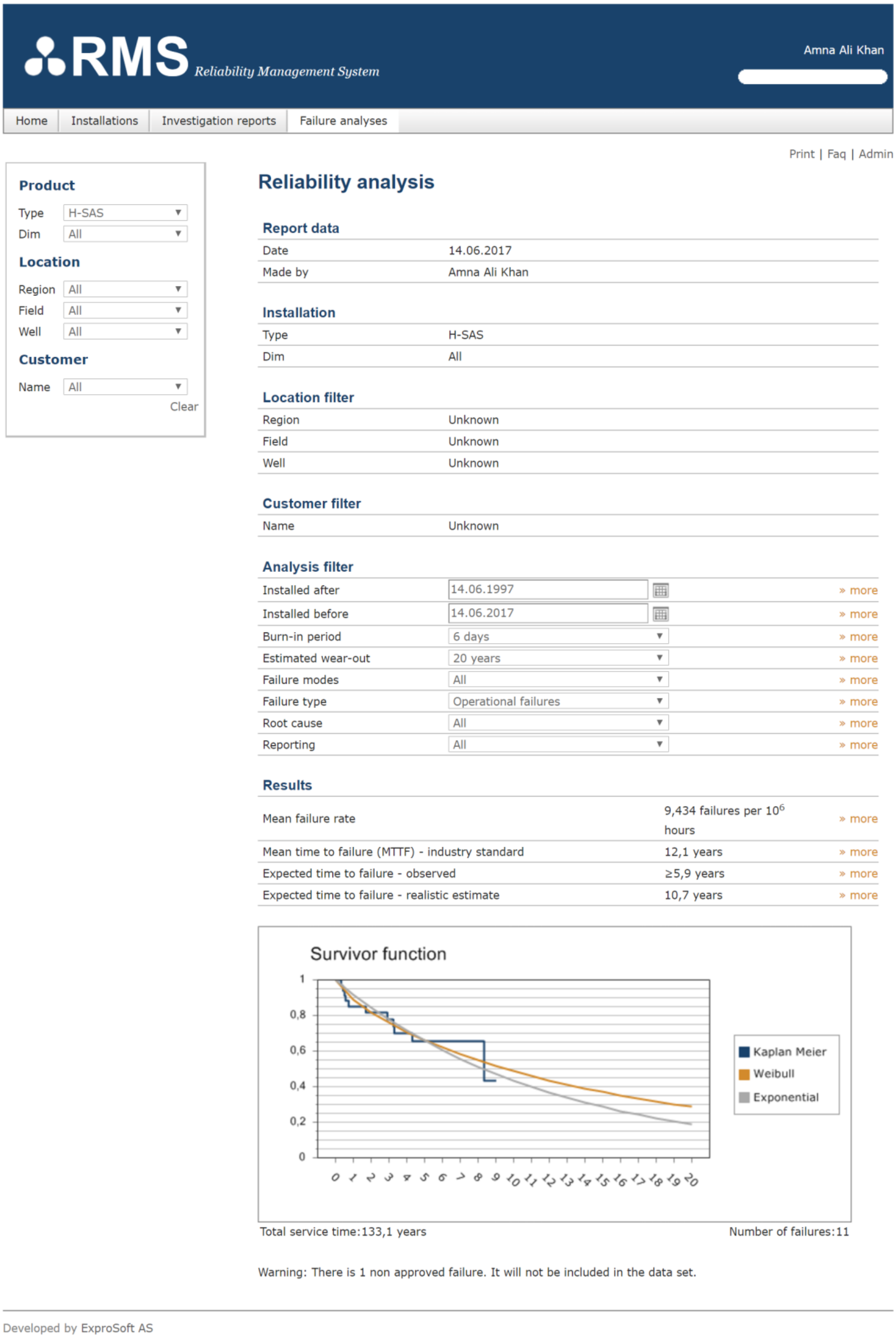


Figure 34 : An investigation report H-SAS equipment


RMS Reliability Management System

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Product

Type: H-SAS
Dim: All

Location

Region: All
Field: All
Well: All

Customer

Name: All

Clear

Reliability analysis

Report data

Date	14.06.2017
Made by	Amna Ali Khan

Installation

Type	H-SAS
Dim	All

Location filter

Region	Unknown
Field	Unknown
Well	Unknown

Customer filter

Name	Unknown

Analysis filter

Installed after	14.06.1997	» more
Installed before	14.06.2017	» more
Burn-in period	6 days	» more
Estimated wear-out	20 years	» more
Failure modes	All	» more
Failure type	Operational failures	» more
Root cause	All	» more
Reporting	All	» more

Results

Mean failure rate	9,434 failures per 10^6 hours	» more
Mean time to failure (MTTF) - industry standard	12,1 years	» more
Expected time to failure - observed	≥5,9 years	» more
Expected time to failure - realistic estimate	10,7 years	» more

Total service time:133,1 years

Number of failures:11

Warning: There is 1 non approved failure. It will not be included in the data set.

Developed by ExproSoft AS

Figure 35: Reliability analysis report of H-SAS equipment

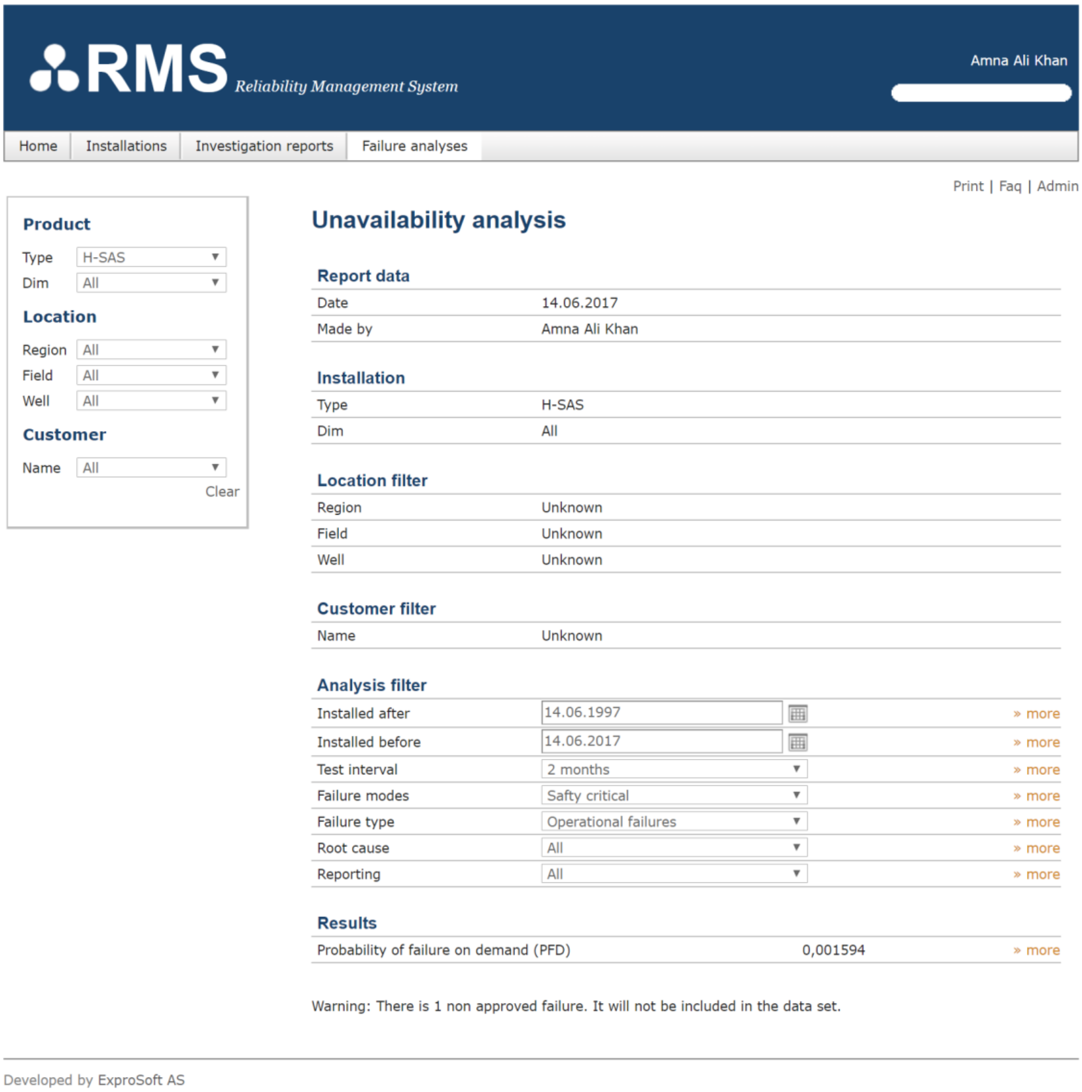

Figure 36: Unavailability report of H-SAS equipment

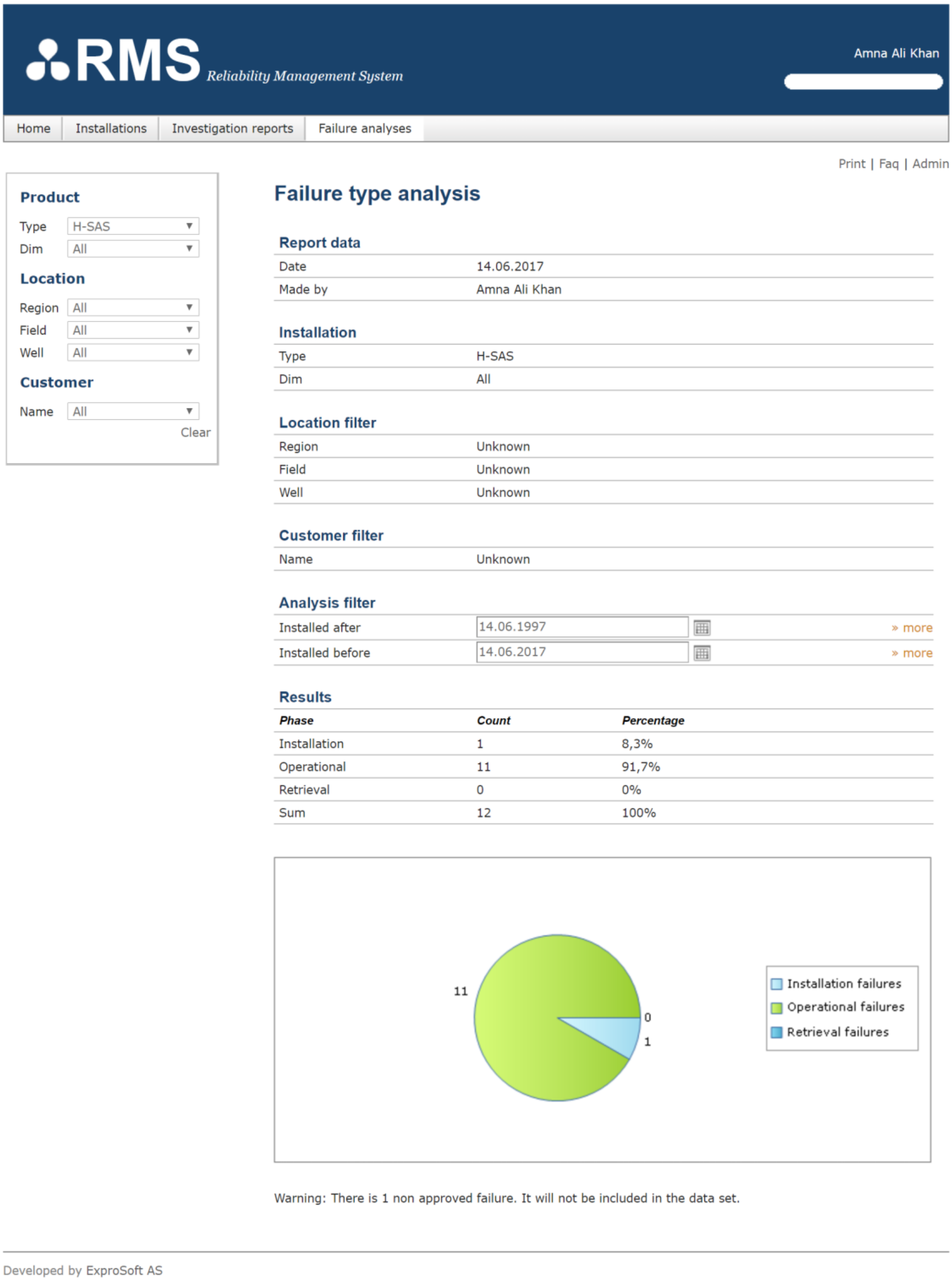

Figure 37 : Failure type report of H-SAS equipment

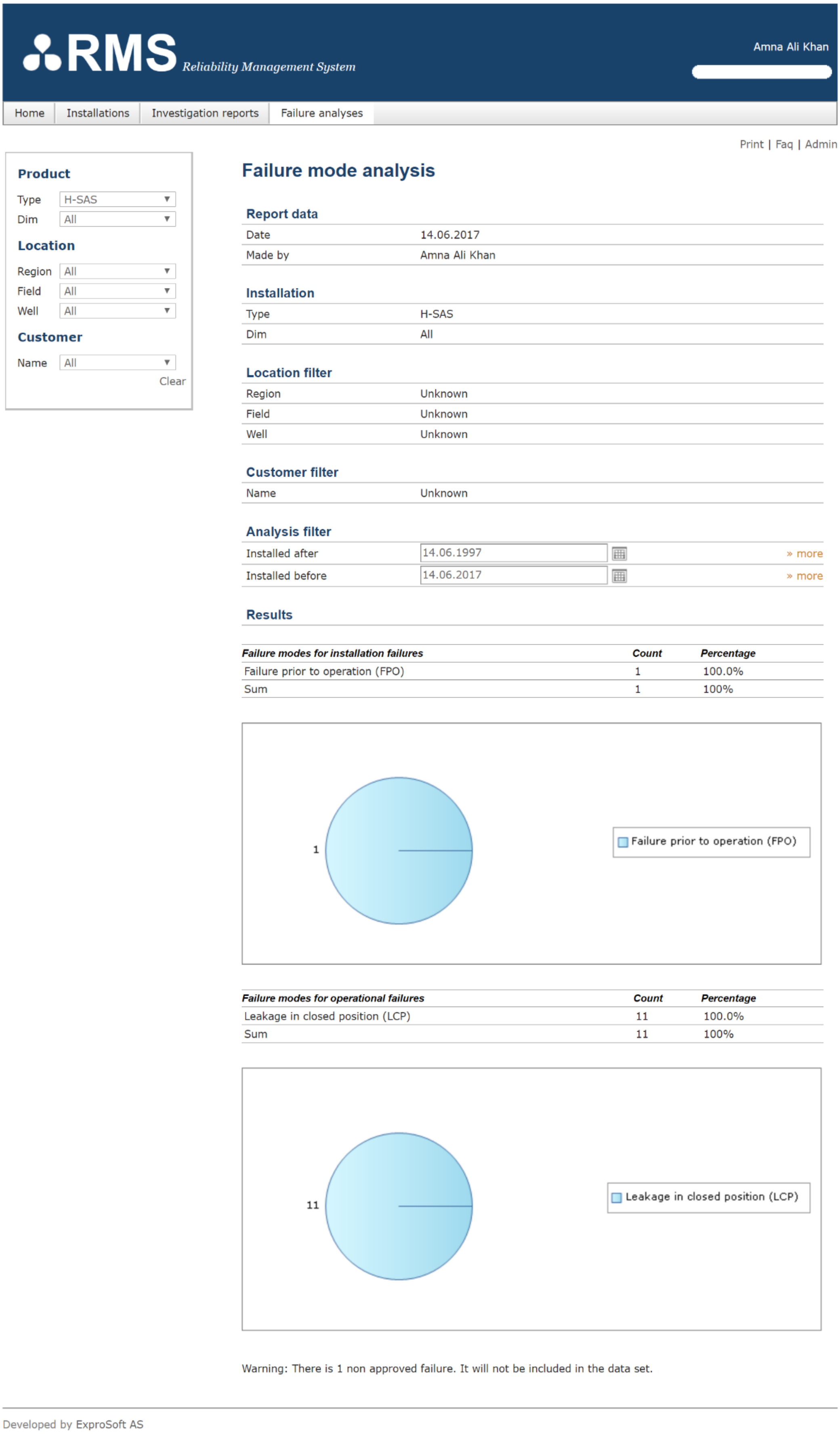

Figure 38 : Failure mode report of H-SAS equipment

RMS Reliability Management System

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Product

Type: H-SAS
Dim: All

Location

Region: All
Field: All
Well: All

Customer

Name: All

Clear

Failure cause analysis

Report data

Date	14.06.2017
Made by	Amna Ali Khan

Installation

Type	H-SAS
Dim	All

Location filter

Region	Unknown
Field	Unknown
Well	Unknown

Customer filter

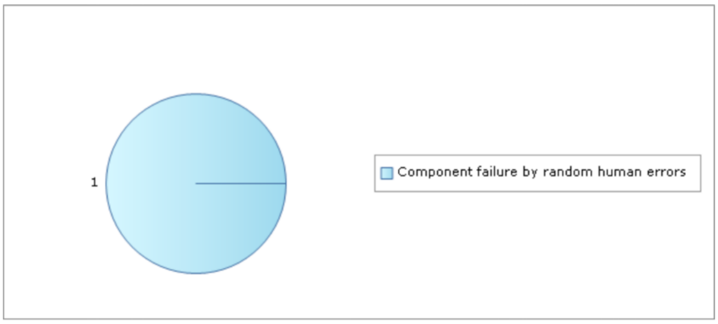
Name	Unknown

Analysis filter

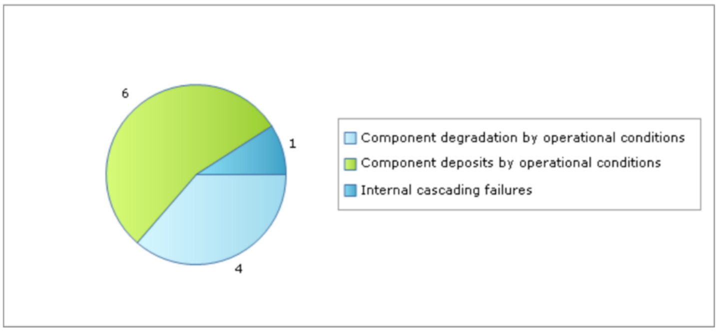
Installed after	14.06.1997	» more
Installed before	14.06.2017	» more

Results

Failure cause for installation failures	*Count*	*Percentage*
Component failure by random human errors	1	100.0%



Failure cause for operational failures	*Count*	*Percentage*
Component degradation by operational conditions	4	36.4%
Component deposits by operational conditions	6	54.6%
Internal cascading failures	1	9.1%



Warning: There is 1 non approved failure. It will not be included in the data set.

Developed by ExproSoft AS

Figure 39: Failure cause report of H-SAS equipment

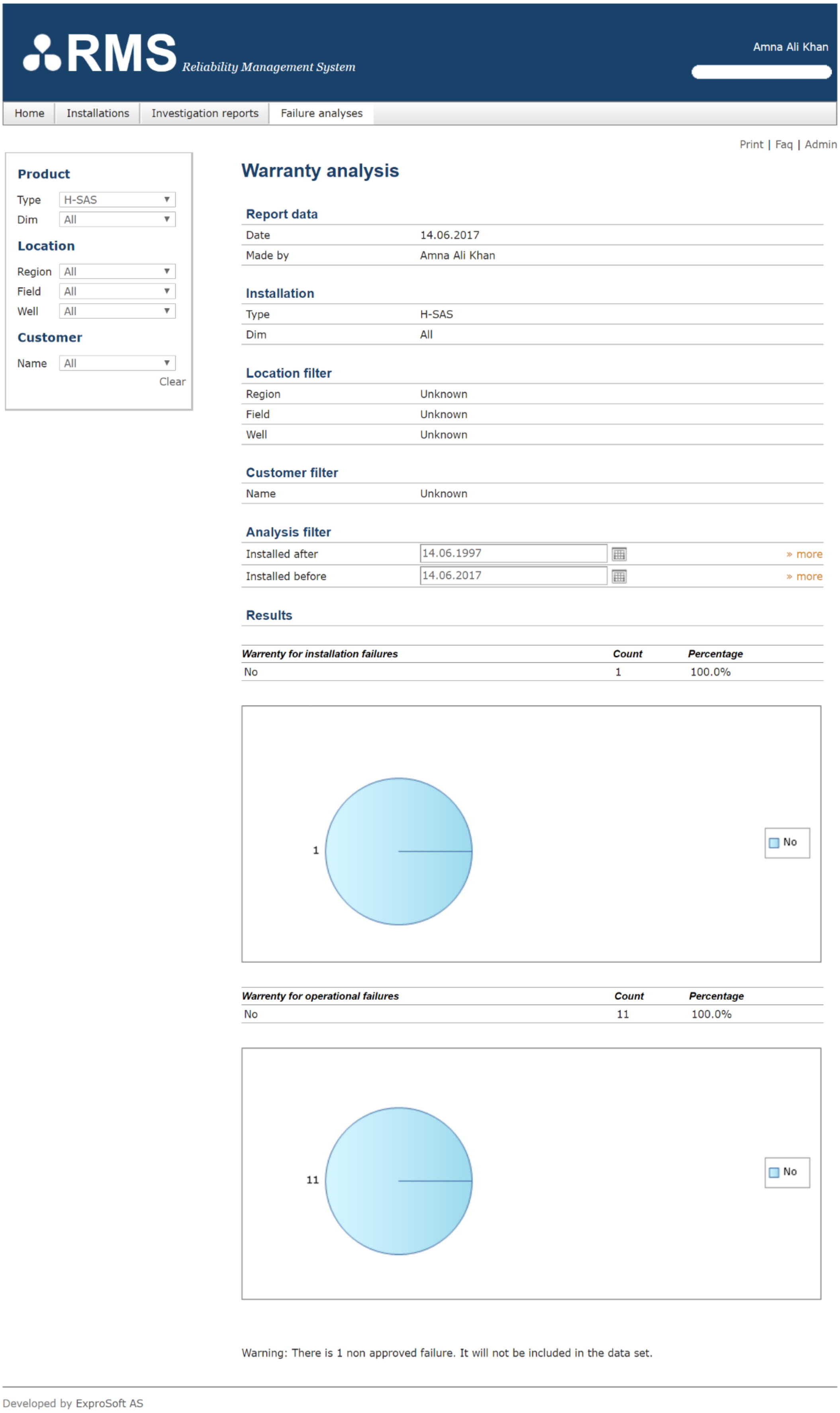
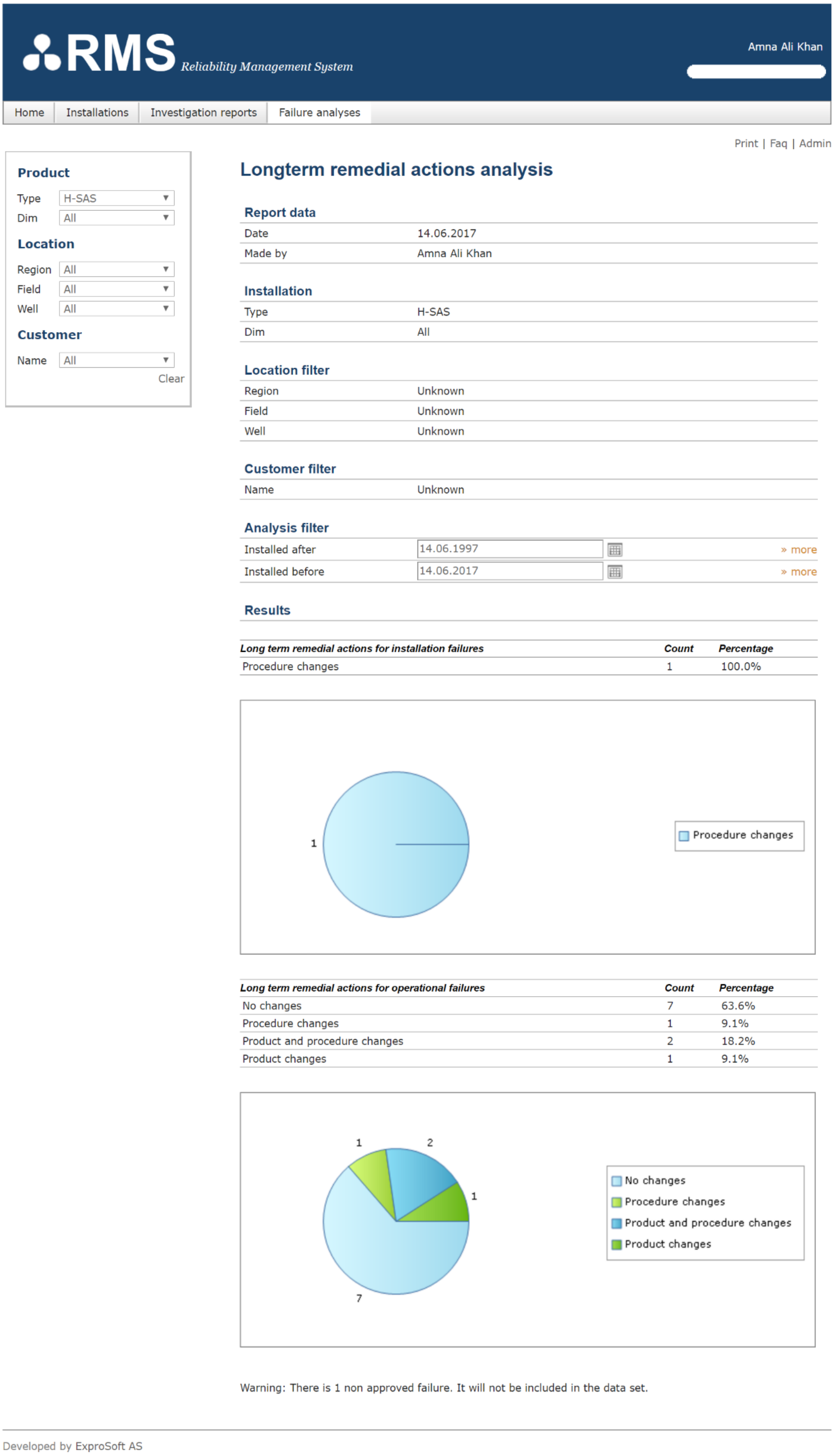


Figure 40 : Warranty analysis report of H-SAS equipment



RMS Reliability Management System

Amna Ali Khan

Home | Installations | Investigation reports | Failure analyses

Print | Faq | Admin

Product

Type: H-SAS

Dim: All

Location

Region: All

Field: All

Well: All

Customer

Name: All

Clear

Longterm remedial actions analysis

Report data

Date	14.06.2017
Made by	Amna Ali Khan

Installation

Type	H-SAS
Dim	All

Location filter

Region	Unknown
Field	Unknown
Well	Unknown

Customer filter

Name	Unknown

Analysis filter

Installed after	14.06.1997	» more
Installed before	14.06.2017	» more

Results

Long term remedial actions for installation failures	*Count*	*Percentage*
Procedure changes	1	100.0%

Long term remedial actions for operational failures	*Count*	*Percentage*
No changes	7	63.6%
Procedure changes	1	9.1%
Product and procedure changes	2	18.2%
Product changes	1	9.1%

Warning: There is 1 non approved failure. It will not be included in the data set.

Developed by ExproSoft AS

Figure 41: Long term remedial action analysis report of H-SAs equipment