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Magnus Geheb Ubostad
15.06.2018

Abstract

As industry 4.0 have gained momentum, a maintenance approach first introduced in the 1960's has been reborn into the age of connectivity. Previously constrained from showing its true potential by limitations in technology, Condition Based Maintenance is finally ready to deliver long promised benefits and be adopted in large scale by industries worldwide. The philosophy behind the maintenance approach is to predict failure before it happens by monitoring the condition of an asset, and by this makes it possible to act in advance. Global technology trends such as Internet of Things, big data and machine learning are some of the main drivers supporting and realizing the vision of Condition Based Maintenance in the fourth industrial revolution that we have just entered. In combination with cheaper and better sensors, processing power and connectivity, Condition Based Maintenance sets out to be one of the corner stones in enabling intelligent and smart maintenance.

While the onshore industry has realized the benefits and have been exploring how to reap the fruits of Condition Based Maintenance in relation to industry 4.0 for a longer period, the maritime industry has been slow to adopt it. If this is due to limitations present at sea, organizational resistance, lack of suitable technological solutions, or just being an industry traditionally known for being conservative enforcing the saying "why change a winning team", can be up for debate. What is clear on the other hand is that shifting from a time-based preventive maintenance strategy to a strategy towards predictive Condition Based Maintenance has the potential to significantly improve reliability, safety and maintenance efficiency while reducing downtime and unpredicted failures in a cost-effective manner. In an industry that has a high cost pressure and have experienced decreasing profit margins lately, it seems like the time have come to address how Condition Based Maintenance can contribute to the maritime industry and its evolution into a new era.

This have resulted in the following research question to answer in this thesis:

- *With a technological outlook in mind and considering limitations at sea, how can a retrofit predictive maintenance system be developed and implemented onboard a container vessel, and what potential impact will it have on OPEX?*

This thesis is part of a project initiated by Klaveness Ship Management with the purpose of exploring how changes in different areas of their organization can contribute to reach a goal of 30% reduction in OPEX. The thesis is meant to support the justification of moving from a not very well defined time-based preventive maintenance strategy to a Condition Based Maintenance strategy for their fleet. The thesis is considered a case study of the Main Sea Water Pumps which is a part of the cooling system onboard a series of 3 container vessels. Standards is used as the basis in the process of development and implementation of a predictive maintenance system for the pumps. The condition monitoring technique presented in the case is vibration monitoring. Historical data on maintenance activities is used to assess current maintenance regime to create a maintenance base-line and identify corrective maintenance, as well as doing an assessment of what potential impact it will have on OPEX. Limitations special for the maritime industry is addressed in the process, as well as considerations to be done in terms of technology outlook.

The applied research method has the characteristics of being exploratory research. It has a practical orientation and the approach is highly qualitative. A main reason for this is lack of enough relevant data with good enough quality. Since a specific research question is to be answered, the research approach is inductive in nature.

It was expected that implementing vibration monitoring on the pumps as a part of a predictive maintenance system would significantly contribute in supporting Condition Based Maintenance as a solution in reaching the project goal of 30% reduction in OPEX. The thesis confirms this expectation with a reduction in manhours used on maintenance of the pumps by an average of 32% across all three ships. In terms of development and implementation of a predictive maintenance system, it concludes that the lack of connectivity while at sea requires a different high-level system design than an onshore application, and that it is important to have a holistic approach that supports interoperability and use of standards.

Key words: Condition based maintenance, Predictive Maintenance, Condition Monitoring, Diagnostics, Prognostics, Maritime Transport Sector, Standards, Industry 4.0

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List of abbreviations

CBM	Condition-Based Maintenance
DOM	Design-out maintenance
FBM	Failure-based maintenance
FMEA	Failure modes and effects analysis
FMECA	Failure mode effect and criticality analysis
ISO	International Organization for Standardization
KSM	Klaveness Ship Management
MTTF	Mean time to failure
MTTR	Mean time to repair
MSP	Main Sea Water Pump
NGO	Non-governmental Organization
OBM	Opportunity-based maintenance
OPEX	Operational Expenditures
PdM	Predictive Maintenance
PHM	Predictive health monitoring
PM	Preventive Maintenance
TBM	Time-based maintenance
TEU	Twenty-foot equivalent unit (volume of a 20-foot ISO-standard container)
UBM	Used-based maintenance

1 Introduction

1.1 Problem Background

As industry 4.0 have gained momentum, a maintenance approach first introduced in the 1960's has been reborn into the age of connectivity. Previously constrained from showing its true potential by limitations in technology, Condition Based Maintenance is finally ready to deliver long promised benefits and be adopted in large scale by industries worldwide. The philosophy behind the maintenance approach is to predict failure before it happens by monitoring the condition of an asset, and by this makes it possible to act in advance. Global technology trends such as Internet of Things, big data and machine learning are some of the main drivers supporting and realizing the vision of Condition Based Maintenance in the fourth industrial revolution that we have just entered. In combination with cheaper and better sensors, processing power and connectivity, Condition Based Maintenance sets out to be one of the corner stones in enabling intelligent and smart maintenance.

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1.2 Problem Formulation

This thesis is part of a project initiated by Klaveness Ship Management with the purpose of exploring how changes in different areas of their organization can contribute to reach a goal of 30% reduction in OPEX. The thesis is meant to support the justification of moving from a not very well defined time-based preventive maintenance strategy to a Condition Based Maintenance strategy for their fleet. The thesis is considered a case study of the Main Sea

Water Pumps which is a part of the cooling system onboard a series of 3 container vessels. Standards is used as the basis in the process of development and implementation of a predictive maintenance system for the pumps. The condition monitoring technique presented in the case is vibration monitoring. Historical data on maintenance activities is used to assess current maintenance regime to create a maintenance base-line and identify corrective maintenance, as well as doing an assessment of what potential impact it will have on OPEX. Limitations special for the maritime industry is addressed in the process, as well as considerations to be done in terms of technology outlook.

1.3 Research Question

- *With a technological outlook in mind and considering limitations at sea, how can a retrofit predictive maintenance system be developed and implemented onboard a container vessel, and what potential impact will it have on OPEX?*

1.4 Methodology

The applied research method has the characteristics of being exploratory research. It has a practical orientation and the approach is highly qualitative. A main reason for this is lack of enough relevant data with good enough quality. Since a specific research question is to be answered, the research approach is inductive in nature. The thesis is to be considered a case-study.

1.5 Delimitations

Cost of Standards have resulted in that I have not been able to access all relevant standard and not able to access the latest edition of standards. High degree of qualitative analysis. Data provided by the company was not sufficient to perform a detailed cost benefit analysis. The data provided was lackful and not optimal for an analysis like this.

2 Theory and background

2.1 The Maritime Industry

Historically the maritime industry has played a significant role in shaping our society. It has connected people together, moved borders, been a source of enormous resources and worked as a catalysator for global commercial trade. It has been an industry that traditionally characterized by secrecy and being closed, and an industry that many people have a connection or relation to, but still don’t know nothing about. According to Review of Maritime Transport 2017 made by United Nations Conference on Trade and Development (UNCTAD, 2017) 80% of global trade volume and 70% of global trade value is carried out by sea and handled at ports worldwide. This shows that maritime transport is the backbone of international trade and global economy and play a significant role in all our lives.

2.1.1 International Seaborne Trade/The shipping Industry/Maritime Transport sector

Being a global industry, the maritime transport sector follows global trends and is reflecting the state of the world economy. The sector has faced economic downturn since the financial crisis in 2008/2009 and continued to remain under pressure in 2016 due to continued weak global demand and high uncertainty caused by factors such as trade policy and low commodity and oil prices according to UNCTAD (2017). This has caused the capacity in the market to increase faster than the demand and resulted in downwards pressure on freight rates and lowered profitability in most segments of the shipping market. Even though the annual growth of world fleet has declined since 2011, the capacity in 2016 continued to increase faster than demand due to one of the reasons being larger newbuilds with higher capacity. Despite of this, the tide might seem to be slightly turning. In Maritime Outlook Report published by Norwegian Shipowners Association (2018) the shipowner’s expectations for operating result have improved significantly from 2016 to 2018, with expectations for improved profitability for short sea and deep sea shipping being the highest of the segments in 2018 compared to 2017, as showed in figure Figure 1.

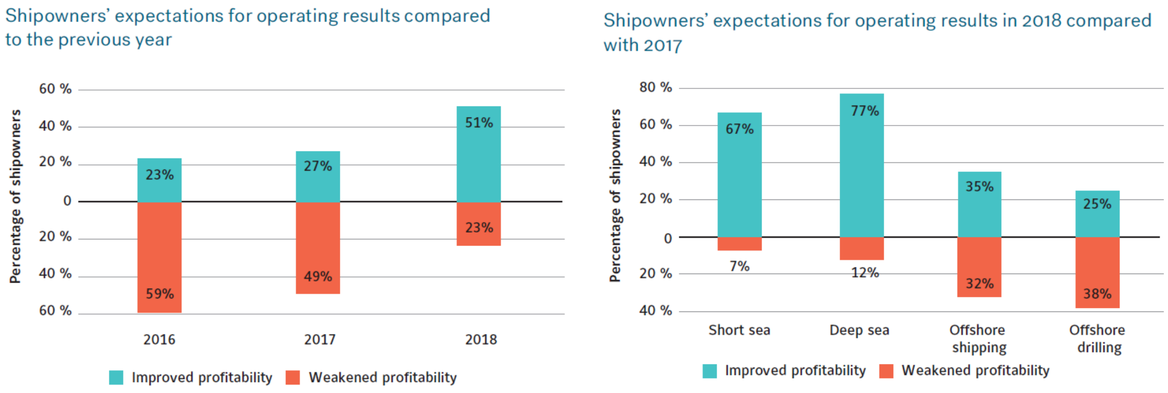


Figure 1: Shipowners' expectation for profitability (Norwegian Shipowners Association, 2018)

The vessels in the maritime transport sector is by UNCTAD (2017) divided into the groupings presented in Table 1.

Table 1: Vessel groupings (UNCTAD, 2017)

Oil tankers	Oil tankers
Bulk carriers	Bulk carriers, combination carriers
General cargo ships	Multi-purpose and project vessels, roll-on/roll-off cargo, general cargo
Container ships	Fully cellular container ships
Other ships	Liquefied petroleum gas carriers, liquefied natural gas carriers, parcel (chemical) tankers, spesialized tankers, reefers, offshore supply, tugs, dredgers, cruise, ferries, other non-cargo

Container ships, which is the subject of this thesis, have some general distinctions to be aware of in terms of size, capacity, operating segment, and capabilities. Container ship size categories has historically been named after whether the container ship was able to pass the Panamax canal or not.

Ships with a size that made it possible to sail through the canal was placed in the category with the original name of Panamax, while ships that were too big to pass were called Post-Panamax. In June 2016 however, the Panamax canal got a new third set of locks which allowed larger ships to pass, which kind of retired the Post-Panamax category to the history books and created a new container ship category called Neo-Panamax. Ships that are still to large to enter the expanded Panama Canal is called Ultra Large Container Vessel (ULCV) and vessels smaller than Panamax are called Feeders. In terms of capacity container ships is usually measured in TEU, which is short for twenty-foot equivalent units and equal to a 20-foot ISO-standard container. A simple overview is given in Table 2.

Table 2: Container vessel category and capacity

	Ultra Large Container Vessel (ULCV)	**Neo-Panamax**	**Post-Panamax**	**Panamax**	**Feeder**
Capacity (TEU)	14 501 and higher	10 001-14 500	5 101-10 000	3 001-5 100	Up to 3 000

Figure 2: Geared Vessel, MV Balsa (Fleetmon.com, 2015)

Another distinction is whether the container vessel is geared or gearless. A geared container ship is equipped with ship-to-shore container-handling equipment such as a crane (Figure 2), while gearless container ships is dependent on land-based equipment to offload cargo when at port. Gearless vessels is the most common type and geared vessels is usually container ships in the Feeder category with a capacity between 1000-3000 TEU according to (UNCTAD, 2017), which also highlights that only 4.1% of global newbuild TEU capacity delivered in 2016 was geared.

Two other terms used in the maritime transport sector that is determining operating segment is Deep Sea shipping and Short Sea shipping. Deep Sea shipping is transportation of goods for longer distances, often crossing an ocean to another continent, and is usually done by larger ships such as Panamax and larger due to economics of scale. Deep sea markets are highly competitive and dependent on the situation of the world economy. Short Sea shipping, also called Coastal shipping, is transportation of goods for shorter distances often within a country or region such as the Nordic or Scandinavia. Vessels used for Short Sea is usually smaller in size, typical in the Feeder category. The market for Short Sea is not as dependent on the global economy as Deep Sea is, but more exposed to economic situation and geopolitic situation in the region it operates. While this distinction between operating segments is established, it is important to emphasize that it is only describing what segment a vessel is operating in and that small ships might be Deep Sea and large ships might be Short Sea.

The maritime industry is one of Norway's largest industries. Norwegian Shipowners Association (2018) states that it employs 90.000 people in Norway and generates value of NOK 140 billion annually. Further on it explains that the Norwegian-controlled foreign-going fleet consist of 1771 ships as of 2017, valued at approximately 48 billion USD. This makes Norway rank number 5 in the world in terms of value of the merchant fleet, just below USA with a value of approximately 50 billion USD as showed in Figure 3.

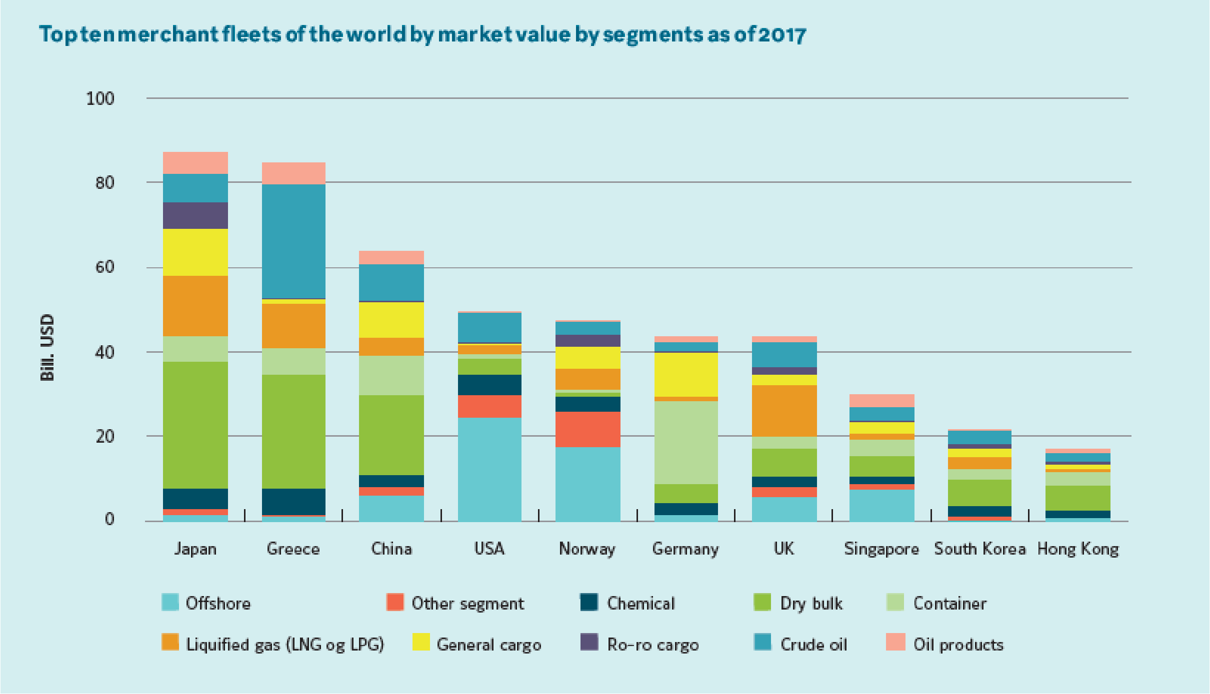


Figure 3: Top 10 merchant fleets of the world by market value as of 2017 (Norwegian Shipowners Association, 2018)

2.2 Maintenance

2.2.1 Definitions

The literature and industry are not consistent in the terminology used in maintenance. Confusion about whether something is a maintenance policy or maintenance task, what to consider as a preventive maintenance task or scheduled maintenance, and disagreement about whether to call it a concept, philosophy or strategy is typical examples of inconsistency in the terminology. This may be caused by many factors, such as rapid technological development and the fact that maintenance is such a dynamic and young management discipline, or be a result of what degree of simplicity and practical orientation is required. Arguments of almost philosophical character is often used when trying to describe maintenance terms.

As illustrated in Figure 4, Pintelon and Parodi-Herz (2008) divides precautionary maintenance actions into preventive, predictive, proactive and passive in nature, while corrective maintenance is described as a reactive action. Mobley (2002) only uses Run-to failure (corrective), Preventive and Predictive without any further categorization, which also seems to be in line with how ISO17359 (2011) does it. Wireman (2008) explains it a bit differently, where he sees Basic Preventive, Proactive, Predictive, Condition-based and Reliability Engineering as tools and methods for a successful Preventive Maintenance Program. This interpretation of Preventive Maintenance differs from Mobley (2002) and Pintelon and Parodi-Herz (2008) which are describing Preventive Maintenance as either Time-based maintenance (TBM) or Use-based maintenance (UBM), which means that maintenance is scheduled based on preset time intervals or when a machine has been running for a certain number of hours.

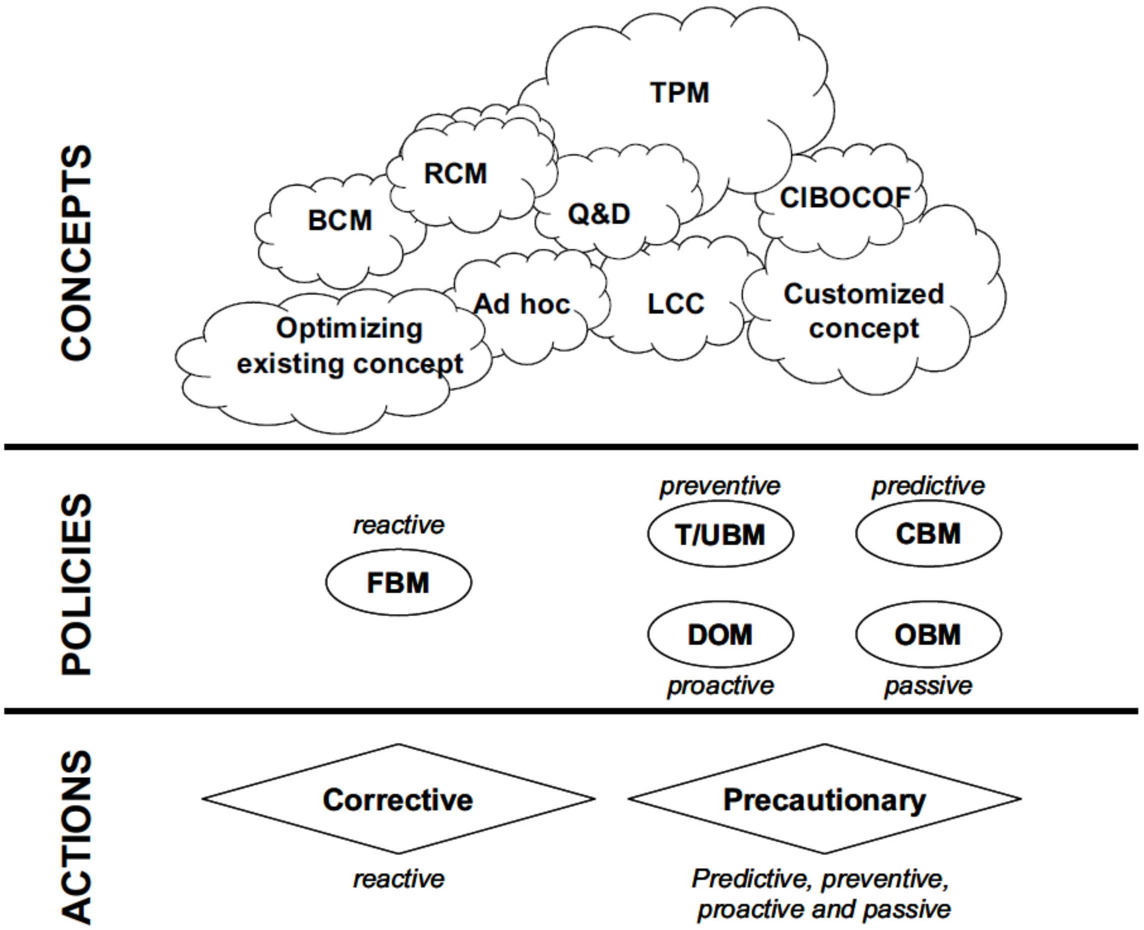
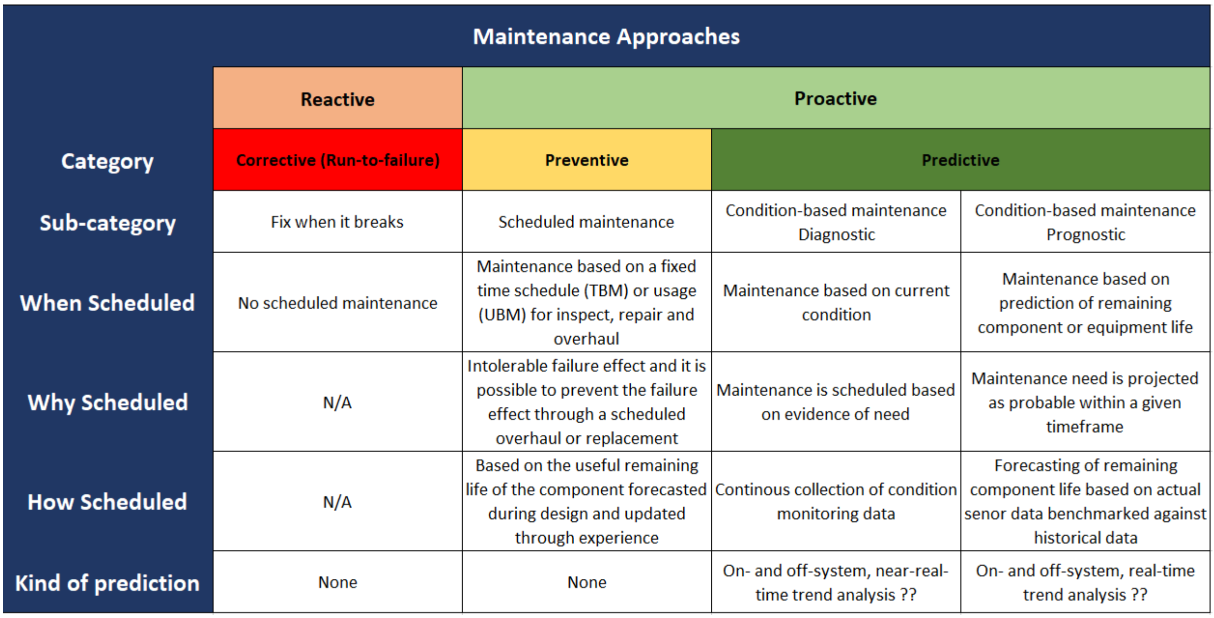


Figure 4: Actions, policies and actions in Maintenance (Pintelon and Parodi-Herz, 2008)

A very practical and logical interpretation of maintenance, that seems to be in line with Pintelon and Parodi-Herz (2008) and Mobley (2002), is presented by US Department of Defence (2008) (DoD) in their Guidebook on Condition-Based Maintenance Plus. This is a guidebook on how to successfully develop, implement and execute DoD’s own version of CBM, which is called CBM+, and is describing management actions necessary to integrate the technologies in order to increase reliability, availability, operational effectiveness, and maintenance efficiency. As it is shown in Figure 5 US Department of Defence (2008) have divided their Maintenance approach into 2 types, which is Reactive and Proactive. Corrective maintenance (run-to-failure) is the only one that is Reactive, while both Preventive maintenance and Predictive maintenance is considered Proactive approaches. Predictive maintenance is equivalent to condition-based maintenance but is further on divided into diagnostic and prognostic analysis.



Maintenance Approaches				
	Reactive	Proactive		
Category	Corrective (Run-to-failure)	Preventive	Predictive	
Sub-category	Fix when it breaks	Scheduled maintenance	Condition-based maintenance Diagnostic	Condition-based maintenance Prognostic
When Scheduled	No scheduled maintenance	Maintenance based on a fixed time schedule (TBM) or usage (UBM) for inspect, repair and overhaul	Maintenance based on current condition	Maintenance based on prediction of remaining component or equipment life
Why Scheduled	N/A	Intolerable failure effect and it is possible to prevent the failure effect through a scheduled overhaul or replacement	Maintenance is scheduled based on evidence of need	Maintenance need is projected as probable within a given timeframe
How Scheduled	N/A	Based on the useful remaining life of the component forecasted during design and updated through experience	Continous collection of condition monitoring data	Forecasting of remaining component life based on actual senor data benchmarked against historical data
Kind of prediction	None	None	On- and off-system, near-real-time trend analysis ??	On- and off-system, real-time trend analysis ??

Figure 5: Maintenance Approaches. Based on (US Department of Defence, 2008). Also in APPENDIX XX!!.

Two types of maintenance approaches are not included in Figure 5, and that is Design-out of maintenance (DOM) and Opportunity-based maintenance (OBM). DOM is considered proactive and involves minimizing and optimizing maintenance in the design-phase. OBM is considered a Passive approach which involves performing maintenance when the best opportunity to do so occurs. This can be during low-season of a production facility, when a vessel is in port, or exploiting downtime due to other major maintenance actions such as an overhaul.

This thesis will use the terminology and definitions presented in Figure 5. Corrective, Preventive and Predictive maintenance is further explained in this section. DOM and OBM will not be explained any further but may be included later in the thesis if relevant.

2.2.2 Corrective maintenance

US Department of Defence (2008) explains in their guidebook that corrective maintenance is performed for items that are selected to run-to-failure or those that fail in an unplanned or unscheduled manner. In other words maintenance is performed after the failure has occurred, and is either a planned approach or a result of an unpredicted failure. Pintelon and Parodi-Herz (2008) supports this statement and explains that it is a reactive action based on the policy of Failure-based Maintenance (FBM).

A case where planned corrective maintenance is a good approach, Pintelon and Parodi-Herz (2008) uses an example of a lightbulb. In this case the lightbulb is not replaced until it is broken because the consequences and repair cost are considered low. The cost of implementing condition monitoring on the lightbulb or regularly replace it before it fails would by far exceed the cost of loosing the lightbulbs function. This is a consideration of the risk factors probability, cost and consequence.

In most cases however, corrective maintenance is unplanned as a result of an unpredicted failure. Mobley (2002) explains that corrective maintenance is the most expensive method of maintenance management, and that an analysis of maintenance costs indicates that that a repair performed in reactive corrective maintenance mode will cost about three times as much as the same repair made within a scheduled or preventive mode. Some of the major expenses with a corrective maintenance approach is high spare part inventory cost, high overtime labour cost, high machine downtime, and low production availability. In addition, a true corrective maintenance approach need to be ready for all possible failures at all times. Compared to a planned preventive maintenance approach, it also has higher repair time and associated cost of manhours.

2.2.3 Preventive maintenance

Describing preventive maintenance in one sentence is difficult, as there are many definitions. Pintelon and Parodi-Herz (2008) give it a try by saying that the fundamental ideas behind preventive and predictive maintenance aim at diminishing the failure probability of the physical asset and/or to anticipate, or avoid if possible, the consequences if a failure occurs. This essential means that we want to be upfront of the failure, before it happens, and try to reduce the probability of the failure happening. The way Preventive maintenance is trying to achieve this is by scheduling maintenance based on pre-determined time intervals (TBM) or equipment-operating time (UBM). These intervals are based on average historical failure rates, engineering estimates and/or predetermined time cycles.

Typical examples of preventive maintenance tasks are lubrication, yearly bearing replacement and change of filters. The difference between the actual implementation of Preventive Maintenance programs may be significant according to Mobley (2002). While some have a very limited extent of only lubrication and minor adjustments, other programs may include scheduling repairs, lubrication, major adjustments and complete rebuilds or overhauls for all critical equipment. What they have in common is that they are all based on time or usage.

2.2.4 Predictive maintenance

US Department of Defence (2008) defines predictive maintenance as follows:

“Predictive maintenance can be categorized as either diagnostic or prognostic. Diagnostic identifies an impending failure, while prognostics add the capability to forecast the remaining equipment life. Knowing the remaining life is an obvious benefit to enable optimum mission and maintenance planning”

Predictive maintenance is also described in Figure 5 and Figure 6.

2.2.5 Comparison of Maintenance Approaches

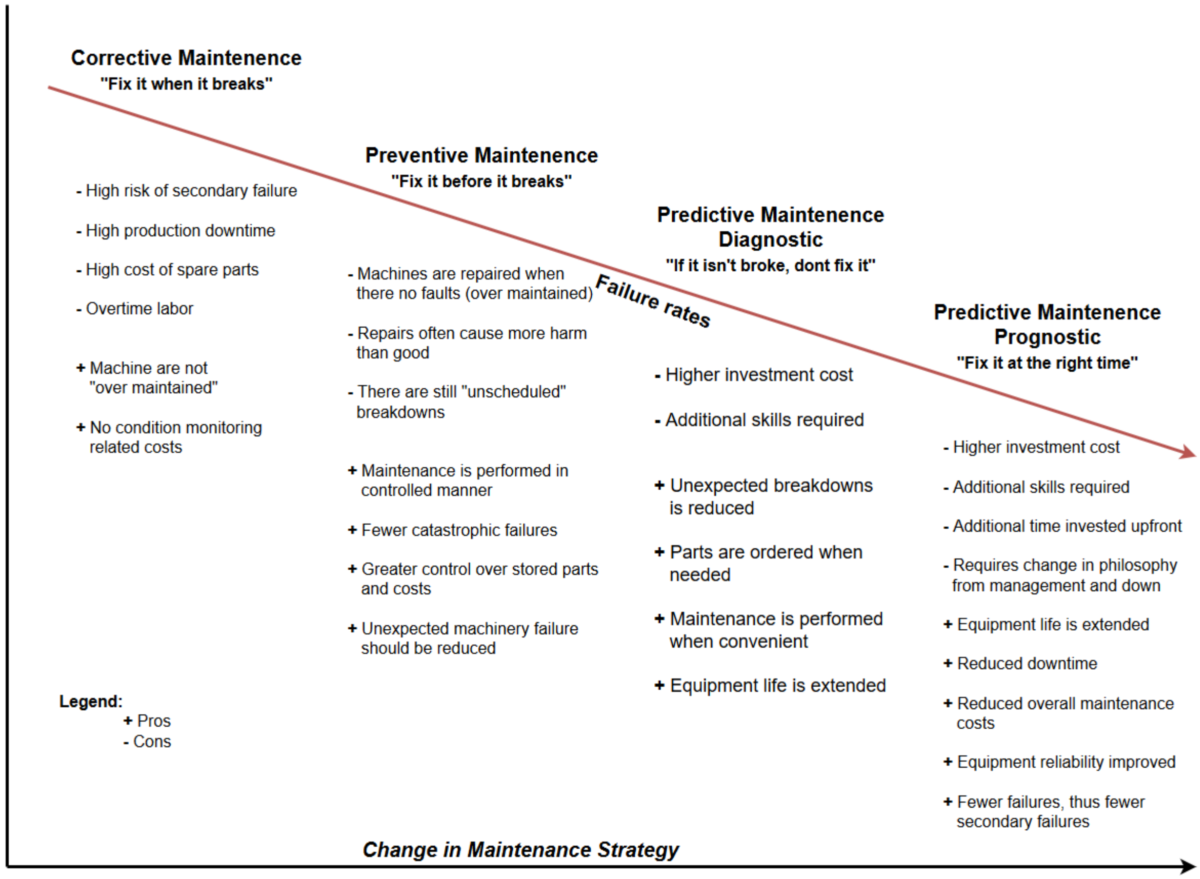


Figure 6: Evolution of Maintenance Strategy. Based on US Department of Defence (2008)

There is no answer in what the best maintenance strategy is. It is often a combination of several approaches based on an assessment of the system and it environments.

2.3 Condition based Maintenance

As previously described the terminology and definitions regarding maintenance are inconsistent, and Condition Based Maintenance (CBM) is no exception of this. Predictive Maintenance, Predictive Health Monitoring, Condition Monitoring and Proactive maintenance are all terms used to refer to what is essentially CBM. Fortunately, what they all have in common even though the exact wording may be different, is that they all agree that the fundamental concept of CBM is to only perform maintenance when there is an evidence of need. This evidence is gathered through monitoring the condition of an asset over a period of time to detect changes in the parameter that is monitored. This is called condition monitoring (CM). In this age of digitalization, it is easy to presume that CBM is a relatively new concept that is a result of Industry 4.0, cheaper and smaller sensors, higher processing power and increased connectivity, but this is not the case. Even though all of those factors have worked as catalysators to bring CBM back into the light and gain momentum as ever before, the fundamentals of CBM was introduced when the first jumbo-jet arrived in the 1960's.

Sondalini (2018a) and explains that with the introduction of the first Boeing jumbo jet in the 1960's there were raised questions about the current maintenance practice which was based on the traditional "bath-tub" curve at that time with the assumption that the older equipment gets the more likely it is to fail. Investigations of past aircraft maintenance history identified 6 patterns of failure, of which only 3 of them was related to age, representing only 11% of total failures. The other 89% of failures showed no relation to the age or time used. The conclusion of this was that most failures is a random event and unpredictable, and that the basis of maintenance need to be based on other parameters than age. And so it started, the work to identify the best suitable parameters to monitor and detect change that can indicate a change in the condition of the asset. Only by doing this they could identify the need for maintenance.

As a result of this discovery, Sondalini (2018b) explains that the aviation industry made major changes to its maintenance practices and that the results were dramatic. Previously 20.000 hours flying time equaled to 2.000.000 manhours of maintenance, but with this new approach it went down to 66.000 manhours per 20.000 hours, which is a staggering 30:1 reduction in maintenance manhours. Similar effects was also shown in improvement in safety, effectively reliability. Sondalini (2018b) highlights that much of this improvement is a result of design improvements and technological development, but that condition-based maintenance techniques provides a considerable amount of information to assist in this development. As the idea behind CBM has been utilized by several industries since it was conceived, it has gained a high degree of validity, and CBM is one of the principal foundations of Reliability Centered Maintenance (RCM).

A justification of investing in a CBM strategy is illustrated in Figure 7.

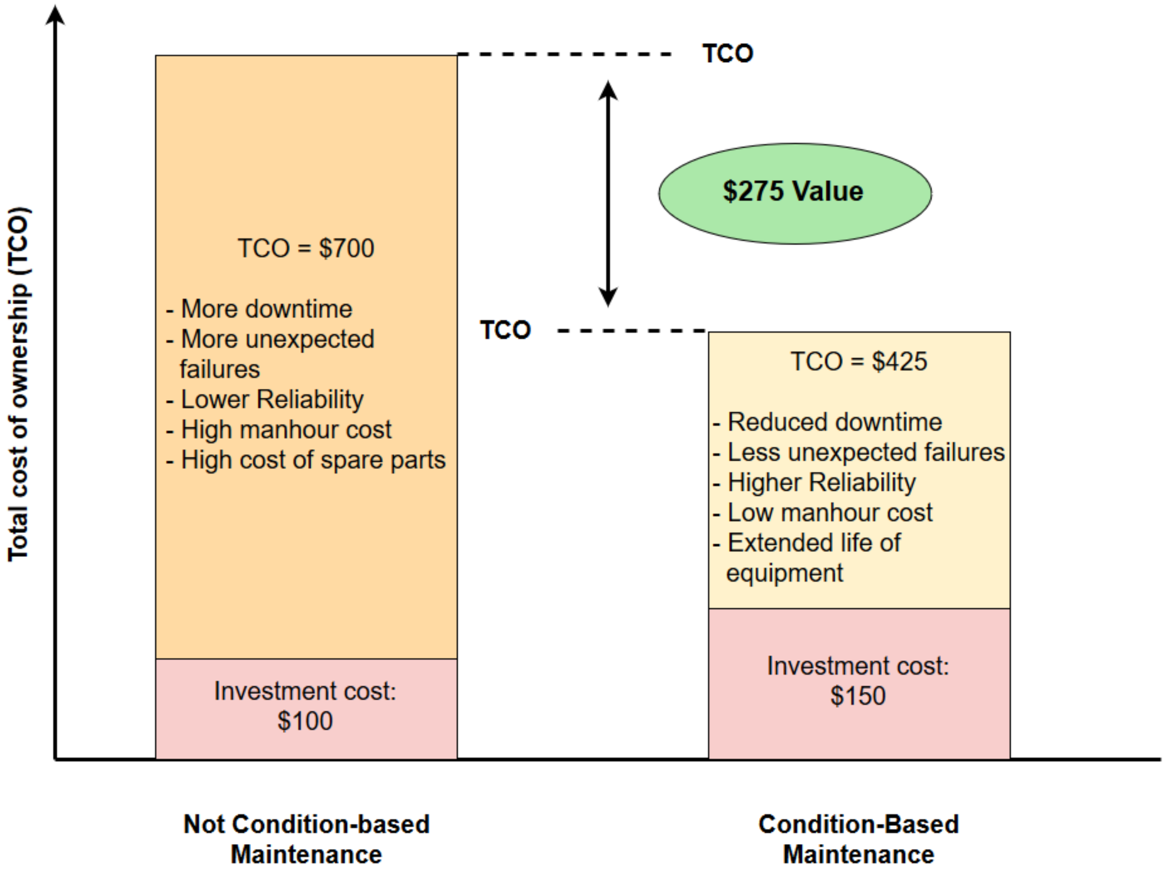


Figure 7: Justification of investing in CBM

2.3.1 Using Standards, ISO17359 & ISO13374

Using standards is the same as agreeing to a way of doing something. It represents, an often global, consensus in the latest development in a subject of that particular standard. A standard can be published in several ways including technical specifications, rules, definitions or guidelines, and can be enforced by a legal entity or be a voluntarily implementation. There is an agreement that complying with standards in most cases deliver benefits that outweigh the cost and effort of implementation. A recent study by Menon Economics (2018) confirms this with 73% of the companies stating that they consider the benefits to exceed the cost of standards, while 18% consider the benefit to be equal to the cost. Interoperability is an important benefit of applying standards, as well as increasing effectiveness and efficiency of any repeated interaction, and ensuring quality and safety. Using industry standards in expressing information and processes minimizes the need for adoption to different environments and applications, ultimately reallocating resources to be distributed to other important parts of a supply chain.

International Organization for Standardization (ISO) is an independent non-governmental organization (NGO) based in Geneva that develops and issues standards for product, services and systems primarily within technology and manufacturing. The organization have a membership of 161national standards bodies that brings together experts to share knowledge and develop voluntary consensus-based market relevant International Standards that support innovation and provide solutions to global challenges (International Organization for Standardization (ISO), 2018)

To assist in identifying core areas in the value chain of a company where standards may contribute significantly, ISO have developed something called Standards Impact Map (APPENDIX X). This is a generic check list containing typical activities relating to business functions that make up the company’s value chain. An extraction of the Production/Operations function on this map is shown in Table 1. The entire table may be relevant for a thesis like this, but the most fitting part of the table is marked with green. It shows that standards exist and can be applied to activities related to production/operation to enhance performance.

Table 3: Extraction from ISO Standards Impact Map (ISO, 2013)

Function	Activities	Impacts	Description
Production/ Operations	All activities	Better internal information transfer	Using standardized documents and specifications makes passing on internal information about products and services more efficient
		Better training of personnel	Productions/operations staff can be trained better because relevant specifications are standardized, for both products and services.
		More efficient processing	Due to the reduced number of types of non-standardized products, Production/operations can become more efficient.
	Processing	More efficient assembly	Assembly processes are more efficient due to the modular product architecture
		Better quality of equipment and supplies	Higher quality of equipment and supplies based on standards reduces the failure rate and related correction costs.
	Quality assurance	Better quality management	Quality management based on standards can be implemented more effectively
	HSE (health, safety and environment)	Reduced disadvantages from regulations	Influence in standard-setting process helps to reduce disadvantages from regulations

		Better health/safety/environmental compliance	HSE management based on standards can be implemented more effectively

There are several standards related to condition monitoring and techniques for doing this. I have identified two standards that will be used as a basis in this thesis:

ISO 17359:2011 Condition monitoring and diagnostics of machines – General guidelines

ISO 13374-1:2003 Condition monitoring and diagnostics of machines – Data processing, communication and presentation – General guidelines

2.3.1.1 ISO 17359:2011

ISO17359 (2011) is the parent document of a group of standards which cover the field of condition monitoring and diagnostics. The standard explains that it presents an overview of a generic procedure recommended when implementing a condition monitoring programme and provides further detail on the key steps to be followed. It introduces the concept of directing condition monitoring towards root cause failure modes and describes the generic approach to setting alarm criteria, carrying out diagnosis and prognosis, which are developed further in other International Standards. An overview of these other standards that further explains aspects regarding techniques, diagnosis & prognosis, data management, training and applications in condition monitoring can be found in APPENDIX X.

In general, ISO17359 works as a guide to the steps to be considered when implementing a condition monitoring programme, with an emphasis on directing activities towards identifying and avoiding root cause failure modes. As shown in Figure 8: Condition monitoring procedure flowchart (ISO17359, 2011) the standard proposes 8 main steps to be followed, and it is those steps that will be used as basis in the case presented in this thesis. To not violate copyright protection of the ISO17359:2011, no further direct explanation of the 8 steps provided by the standard will be given in this thesis, as it eventually will become available to the public.

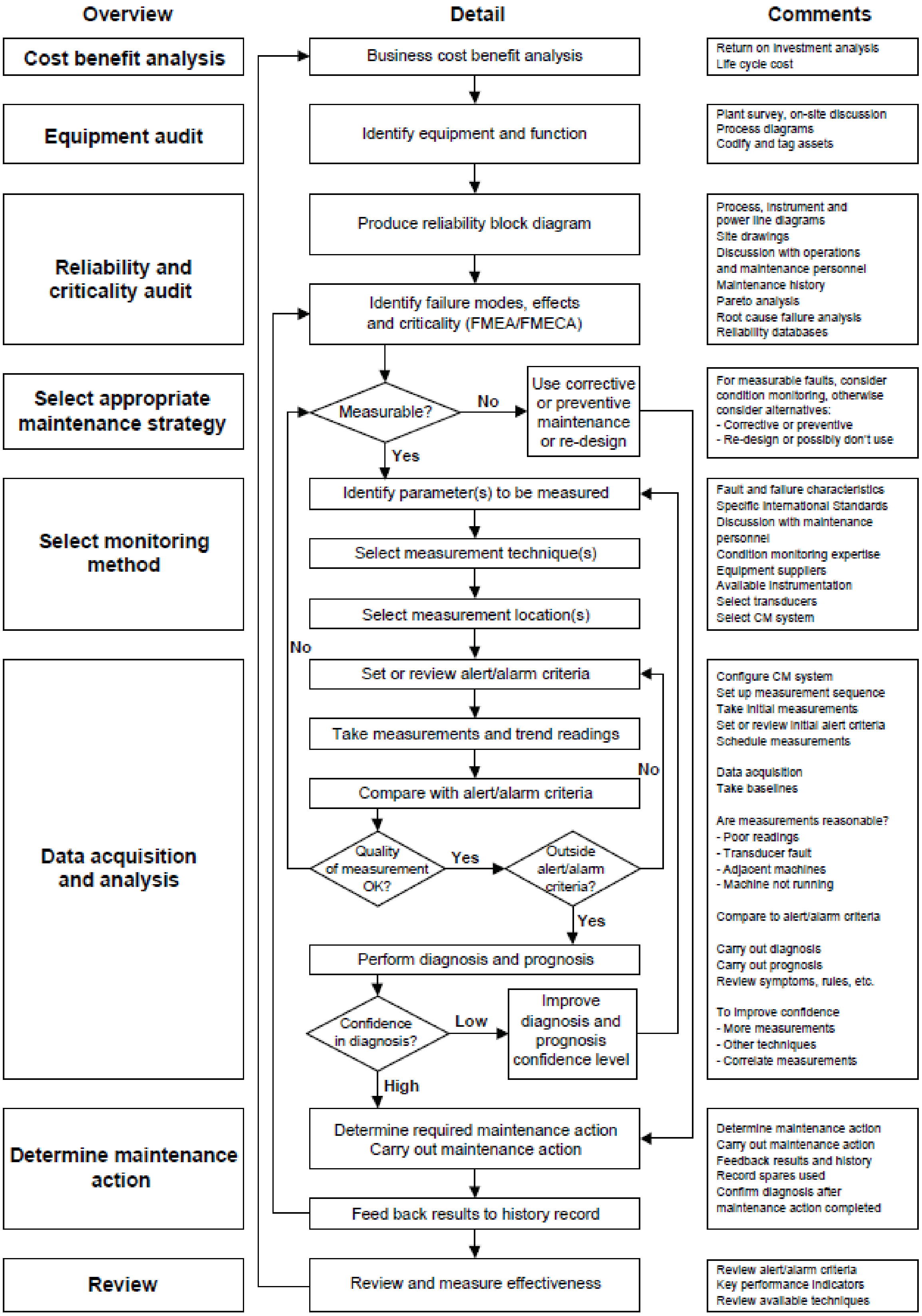


Figure 8: Condition monitoring procedure flowchart (ISO17359, 2011)

2.3.1.2 ISO 13374-1:2003

ISO 13374-1:2003 is the first document in a series of 4 that covers data processing, communication and presentation in condition monitoring and diagnostic. According to the standard it provides the basic requirements for open software specifications which will allow machine condition monitoring data and information to be processed, communicated and displayed by various software packages without platform-specific or hardware-specific protocols. This means that it covers the challenge of interoperability between elements in a condition monitoring system. It is difficult to integrate systems and provide a unified view of the condition machinery to users, due to the fact that different condition monitoring systems and equipment from various suppliers does not easily exchange data or operate in a plug-and-play manner without extensive integration effort.

The steps shown in Figure 9 that is presented in ISO13374-1 (2003) represents how data is managed from the initial acquisition of raw sensor data based on specific configuration according to CM technique, to the final diagnostics or prognostics results that is used for advisory and recommended actions. These steps will in this thesis be used as basis in explaining how data and information is managed. To not violate copyright protection of the ISO13374-1:2003, no further direct explanation of the steps provided by the standard will be given in this thesis, as it eventually will become available to the public.

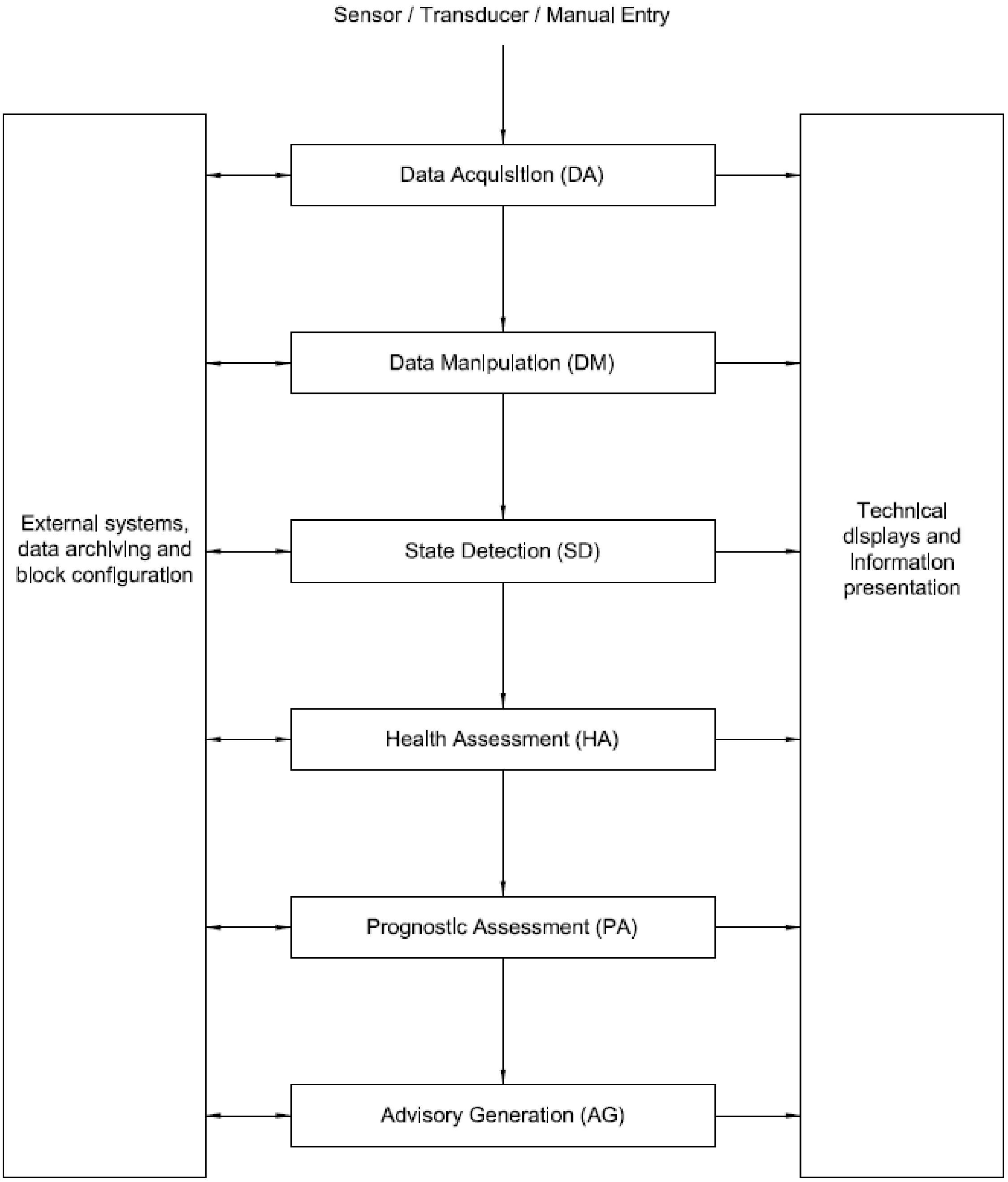


Figure 9: Data-processing and information-flow blocks (ISO13374-1, 2003)

The relationship between ISO17359 and ISO13374-1 is illustrated in Figure 10. It shows that ISO13374-1 is located within the layers of Data Acquisition & Analysis and Determine Maintenance Action of ISO17359. An additional layer that relates to transfer of data is added to ISO13374-1 in this thesis as this complies to technology trends such as IoT and Industry 4.0.

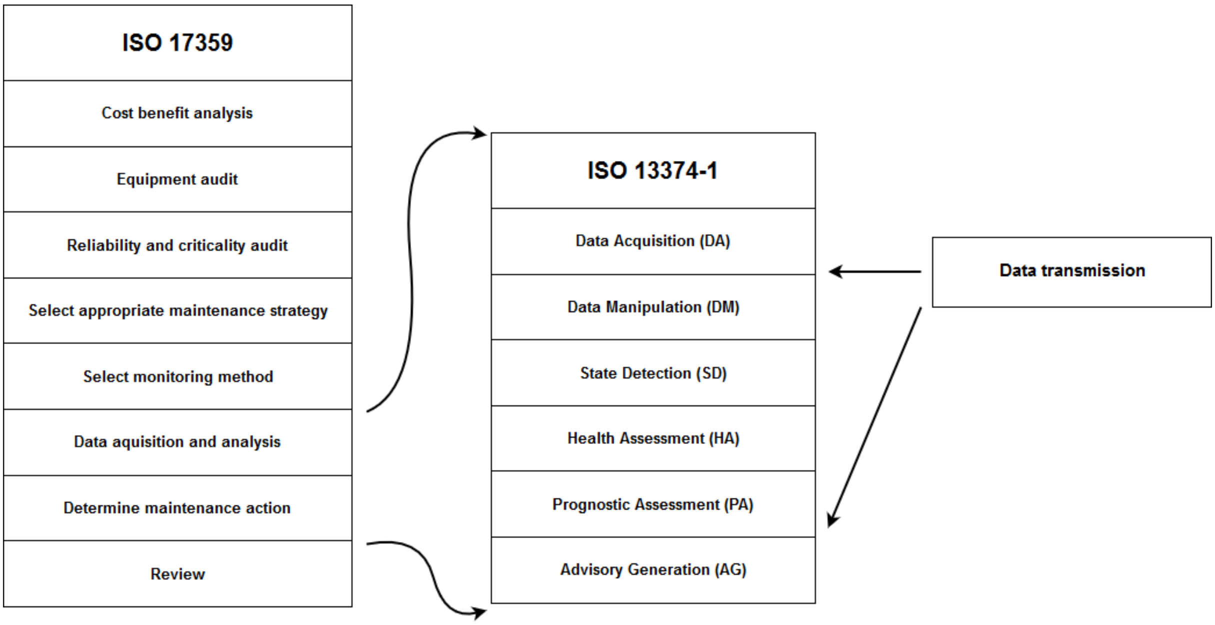


Figure 10: Relationship between ISO standards

3 Analysis of Development, Implementation and Potential Impact on OPEX.

ISO17359 can be used as a practical guide to follow when actually implementing a Condition Monitoring system, or it can be used to generate a theoretical assessment. In this case it is used as the latter in the for of a study on development and implementation of a retrofit predictive maintenance system onboard a container vessel.

It is important to clarify that the steps do not match the actual initial approach and starting point of this thesis. Some of the steps were excessive and already determined and assessed outside the framework of the standards. Nonetheless the thesis will go through every step as they are presented in the standard and give an explanation on what should be considered if the standards are to be followed step by step.

The standards is in many ways meant to be followed to asses implementation on a large scale, not on a component or subsystem, as is the case in this thesis.

Limitations: Connectivity. Lack of data. Quality of data. Ability to identify root-causes.

3.1 Cost benefit analysis

The purpose of starting with a cost benefit analysis is to establish initial Key Performance Indicators (KPI) or other types of benchmarks that can be used to measure effectiveness of a condition monitoring program. This might include life-cycle cost, cost of lost production, consequential damage or other types of measurable indicators. It is supposed to give an initial assessment if the project is feasible or not to support the decision to move forward to the next step. The approach explained in ISO17359 is based on an assessment of a large system such as a production facility or a processing plant, and not as much a component or subsystem as is the case in this thesis. EXPLAN THAT ASSESSMENT OF BOTH PUMPS IS DONE TOGETHER, NOT AS SINGLE COMPONENETS.

When starting the work on this thesis and using ISO 17359 as the basis, some assumptions and decisions were already in place. The purpose of an in-dept initial cost benefit was not present as it was already decided that condition-based maintenance was one of the solutions to explore in the project, with the assumption that it would contribute positively to the goal of the project.

3.1.1 Benchmark

The benchmark for comparison in this thesis is going to be an estimation of manhours related to the maintenance activities registered in historical data provided by KSM. The data is originating from two Main Sea Water Pumps (MSP) located onboard 3 container sister vessels in their fleet. Time-span for the data used in the thesis is from January 2014 to March 2818, which equals to 4 years and 3 months. The data is in some cases not consistent across the three ships and is not registered in an optimal way that supports an analysis and study like this. Differences in planned maintenance intervals and planned maintenance tasks exists. In the data it seems like unplanned Corrective Maintenance (CM) have been registered in planned maintenance category, making it harder to differentiate the two and identify which category is the correct. In addition, CM is not documented well enough to identify failure root-cause, an in some cases it is hard to even know what component the failure is related to. Despite of this, in the best possible extent and effort in interpretation, a maintenance base-line have been created based on the available data.

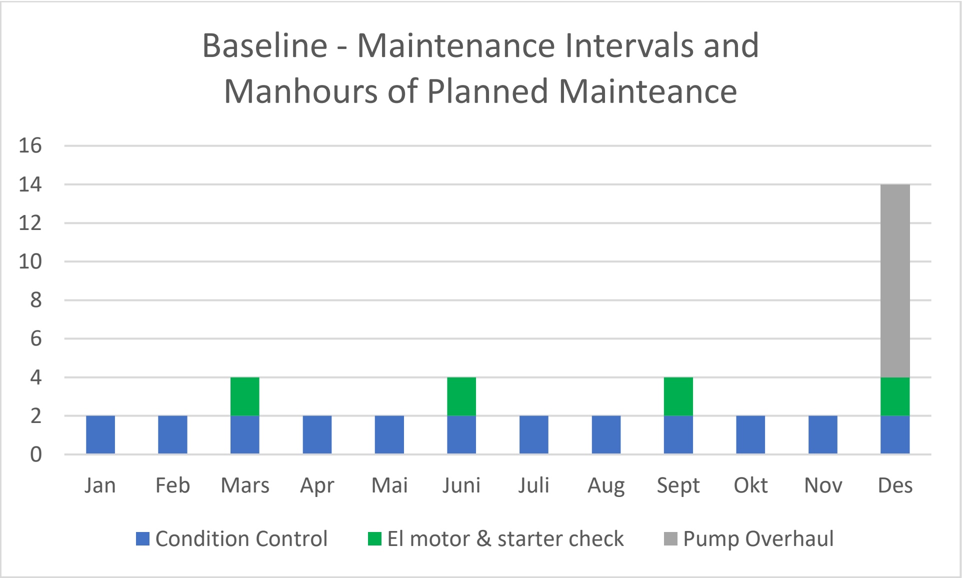


Figure 11: Base-line - Maintenance Intervals and Manhours of Planned Maintenance

Figure 11 illustrates the current maintenance intervals and connected manhours to each of the planned regular maintenance jobs during one year. The figure has been made by analysing historical maintenance data from all 3 vessels supported by information from job-cards used by vessel crew in operation. Each maintenance job is further explained in Table 4. Two maintenance jobs, continuous machinery survey and electrical motor overhaul, has been left out of the study because of 60 months interval between each time.

Table 4: Description of Planned Maintenance Jobs

Condition Control	**El.motor & Starter check**	**Pump overhaul:**
Interval: 1 month **Responsible:** Engine (Mechanical) **Est. Time:** 1 manhour **Tasks:** - Visual inspection & cleaning - Function test - Test emergency stop and auto start of standby pump - Greasing - Check for leakage - Check for noise - Check for vibration - (Check pressure)	**Interval:** 3 months **Responsible:** Electric **Est. Time:** 1 manhour **Tasks:** - Visual Inspection & cleaning o Electrical Motor o Wirings & connections o Starter control panel - Function test - Megger test (Resistance, insulation) - Greasing of electrical motor - Tighten electrical connections	**Interval:** 12 months **Responsible:** Engine (Mechanical) **Est. Time:** 5 manhours **Tasks:** - Visual inspection - Function test - Check for leakage - Check for noise - Check for vibration - Check pressure delivery - Check temperature - Replace ball bearings - Change wear parts

The base-line presented in Figure 11 represents how a perfect situation would look like, without any unpredictable failures. Unfortunately, the world is never perfect. When distributing the planned maintenance over the period covered by the historical data, and inserting identified CM for each vessel, the real situation for MV Balao, MV Balsa and MV Ballenita looks quite far off from being ideal, as presented respectively in Figure 12, Figure 13 and Figure 14.

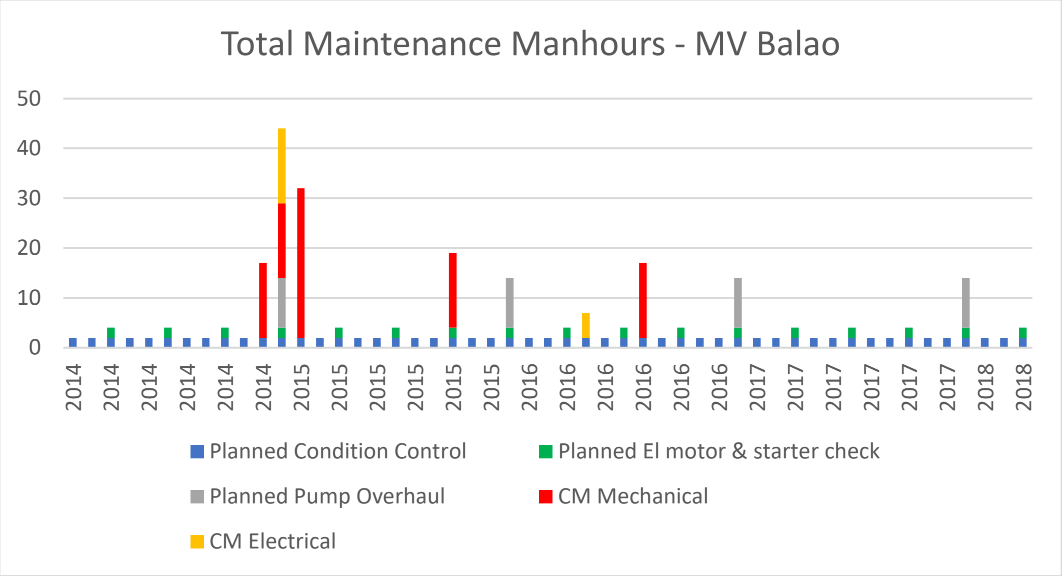


Figure 12: Total Maintenance Manhours - MV Balao

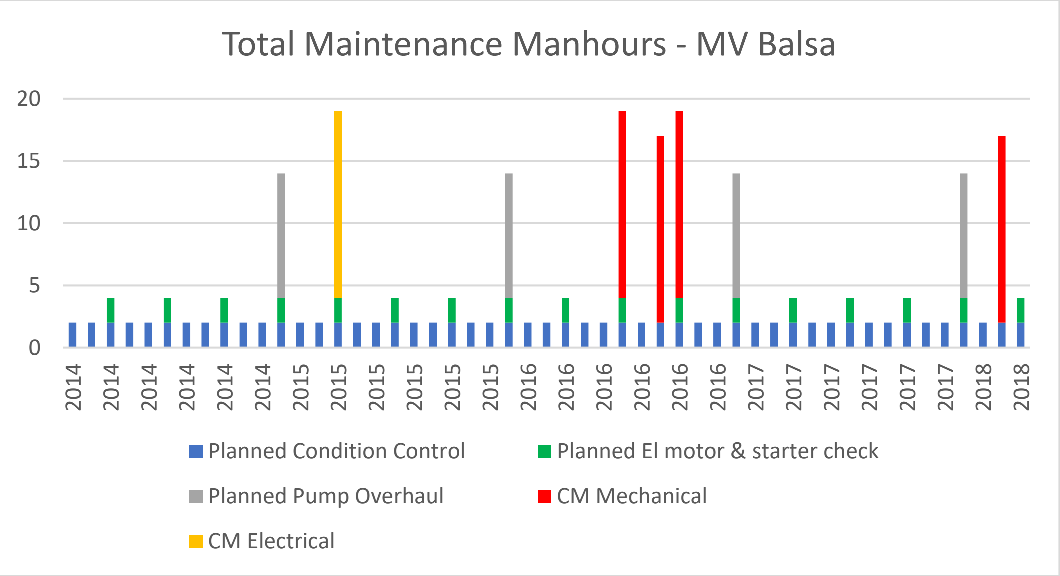


Figure 13: Total Maintenance Manhours - MV Balsa

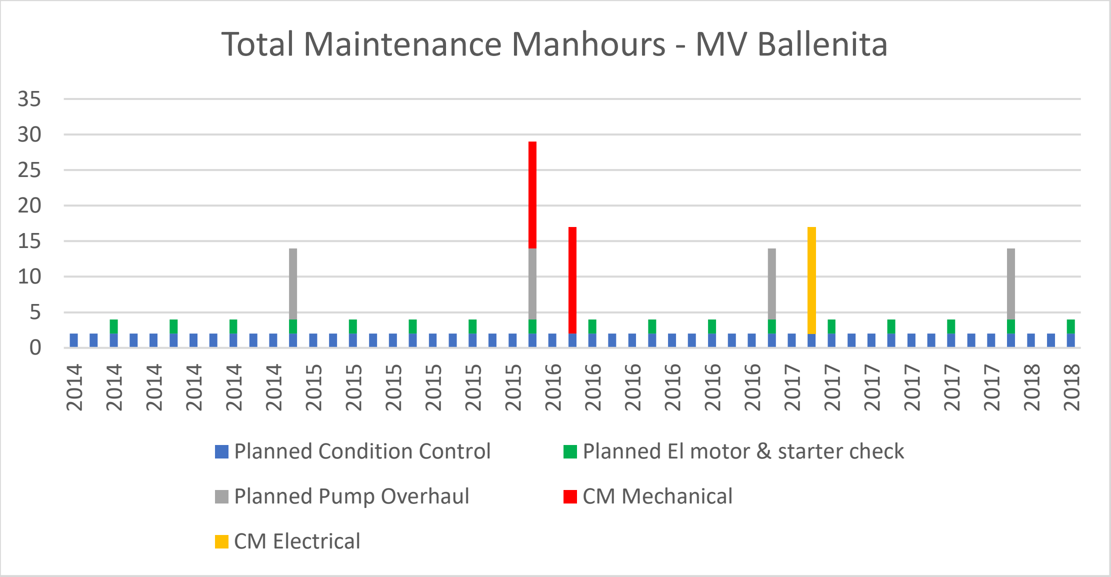


Figure 14: Total Maintenance Manhours - MV Ballenita

The figures show that unpredicted failures resulting in CM contributes to a significant increase in total number of maintenance manhours on each ship. Table 5 shows that on average for all three ships, maintenance manhours is increased by 46 %, with MV Balao at the top with 71%.

Table 5: Increase in Maintenance Manhours Caused by CM

	Total manhours Planned Maintenance	**Total Manhours Corrective Maintenance**	**Total Manhours Maintenance**	**Increase %**
MV Balao	176	125	301	71,02
MV Balsa	176	75	251	42,61
MV Ballenita	176	45	221	25,57
All three vessels	528	245	773	46,40

3.1.2 Justification of estimates

The manhours of each maintenance activity is estimated the following way:

Condition control =	1 manhour per pump
El.Motor & Starter Check =	1 manhour per pump
Pump overhaul =	5 manhours per pump

Electrical CM = 15 manhours per pump

Mechanical CM = 15 manhours per pump

CM avoided as a result of CBM is estimated to have the same amount of work as a pump overhaul.

Due to lack of estimates on manhours required for each planned maintenance job from KSM and lack of historical registered manhours spent on CM, the maintenance jobs have been estimated in a purely qualitative manner based on remarks in historical maintenance data about what each job consist of.

Manhours related to corrective maintenance is based on estimates presented by Mobley (2002), where he presents a study that shows that maintenance performed in a corrective manner is on average three times more costly than maintenance performed in a preventive manner. One can argue that preventive maintenance is not the same as predictive maintenance, but maintenance planned on evidence of need is still planned maintenance, and therefore preventive in nature.

Corrective maintenance has been divided into two categories; Mechanical CM and Electrical CM. Electrical CM is illustrated in the figures but is not considered applicable for vibration monitoring in this thesis, even though it might be. Mechanical CM and Electrical CM will be given a weight three times as much as Planned Pump Overhaul, with the exception if it is clearly stated in the historical data that it is a minor CM task. This is based on the assumption that CM would require a similar or more extensive amount of work than a Pump overhaul, multiplied with a factor of three as stated above. Interpretation of information from historical maintenance data implies that most, if not all, of the mechanical failures could have been detected in advance by vibration monitoring. Based on this the assumption is made that all mechanical CM registered could have been avoided before it reached failure by implementing vibration monitoring. For more information on mechanical CM and failures, go to chapter 3.3.

Using ISO17359 in a practical real-world application would use the result of an in-depth cost benefit analysis as a go or no-go to continue with the process of implementation. However, in a theoretical study like this thesis it is not

3.2 Equipment Audit

Implementation of condition monitoring on a large scale such as a plant, ship, or production facility requires an identification of all relevant processes, equipment and their functionality. Relevant power supplies control systems and existing monitoring systems should also be identified. This is done to get an overview of possible improvement areas to consider. Creating a systems-of-systems (SoS), as the example in **FIGURE XX** shows, may be a result of such an audit audit. This will show the hierarchy and relationship of systems, sub.-systems and components. In addition to this, mapping the functionality and purpose of each element, in addition to its operating environment and conditions, will create a solid base for further analysis. Plant survey, on-site discussions, process diagrams and tagging assets are common methods to achieve a satisfying overview.

In the case covered by this thesis the component to assess was not found by doing a complete equipment audit of the entire ship as a top-down approach, but was identified through discussions with representatives from KSM based on some pre-set requirements and characteristics that is inherent in sub-systems or components with large potential. This approach is described in the next chapter on Reliability and Criticality audit.

The component that was identified and selected was the Main Sea Water Pumps (MSP). MSP is part of the fluid cooling system onboard the ship and is responsible for pumping sea water from outside of the ship to central coolers located onboard the ship. The central coolers function is to exchange heat from the closed loop of fresh water onboard, used to cool the main engine and other systems, with cold sea water delivered by the pumps in an open loop that ends back into the ocean. This cooling sub-system that delivers sea water consist of 2 MSP and one standby pump with lower capacity for contingency purposes.

All three pumps are manufactured by a company named Allweiler GmbH, which is a part of a group called Circor and is Germanys oldest pump manufacturer. MSP is vertical mounted single stage centrifugal pumps powered by a 186 kW electrical motor delivered by Svend Høyer AS. Pump operating specificatioans is presented in table 6.

Table 6: Pump operating specifications

Pump operating specifications	
Capacity	1200 m^3/hr
Pressure	32 mlc
Specific gravity	1025 kg/m^3
Speed	1776 rpm – 1/min
Abs. Power	143 kW

Figure 15: Vertical Centrifugal Pump (Allweiler, 2018)

3.3 Reliability and Criticality audit

A reliability and criticality audit of the systems and equipment mapped in chapter 4.2 is done in order to create a prioritized list of what to include in the condition monitoring program. This includes creating a simple high-level reliability block diagram, a criticality assessment of all machines to

Common to use RCM as method in identifying and ranking whether a machine should be maintained in a corrective, preventive or predictive manner.

3.3.1 Selection of component/sub-system

The selection of MSP to focus on for this study was done after discussion with representatives from Torvald Klaveness. In the process of identifying the best sub-system or component to do a case on, some characteristics and requirements to consider were set:

- The sub-system/component should be a continuous rotating machinery
- Cost of sub-system/component downtime
- Failure rates, mean time to repair (MTTR)
- Redundancy
- Consequential or secondary damage
- Replacement cost of the sub-system/component
- Cost of maintenance (manhours)
- Life-cycle costs
- Safety and environmental impact

Several components were discussed and proposed. Because of low availability of relevant data to support many of the above-mentioned characteristics and requirements, the decision was done in a highly qualitative manner and largely based on knowledge and experience. First option was the fuel separator, which is a component that purifies fuel before it reaches combustion. This is a component that is rotating as long as the engine is receiving fuel. It is a critical component that in case of failure may cause complete engine failure at worst. This is however a situation that happens very rare. Combined with that it is not a very expensive component that have a high repair or replacement cost attached to it, nor requires a lot of manhours to maintain or repair, the fuel separator was discarded for this thesis.

Another option was the bow-thrusters of the ship, which is mainly used for navigation of the vessel when in narrow seas, in port and for dynamic positioning. The bow-thrusters were considered a much more complex system to do a study on, with a lot more disturbance from its surrounding environments. The thrusters are considered critical for successful operation of the vessel. The fact that the bow-thrusters is only used a fraction of the time that the ship is operational and not considered a continuous rotating machinery, it was discarded for this thesis. In hindsight, after conversation with a representative from SKF, the bow-thrusters might have been a suitable selection for the thesis.

The third option was the main sea water pumps (MSP) which main function is to provide sea water to the central coolers. Without cooling, the engine and other systems can not be operational, and is therefore considered critical for the operation of the vessel. The pumps are located on a series of 3 container sister vessels build in 2013. They are continuously running as long as the engine is operational. Two of the main determining factors for selecting MSP was that Torvald Klaveness had approximately 5 years of data on operation and maintenance activities, and that they have had a fair amount of trouble with the pumps. Condition monitoring of pumps is also a well-established area of engineering and science with a lot of available information about.

3.3.2 Reliability Block Diagram

The MSP is part of the cooling system onboard the ship. A simple high-level reliability block diagram of the sea water cooling system is presented in Figure 16 and it shows that the pumps have a parallel reliability effect. This means that for the sea water not to reach one of the central coolers, all three pumps need to be defect. In other words, only one of the pumps needs to be functional in order for the system to be functional and supply sea water to the central coolers. This is to be considered a highly reliable system with a high degree of redundancy and low probability of complete system failure. However, if both MSP fails, the ship would probably sail with reduced power due to lower capacity of the stand-by pump.

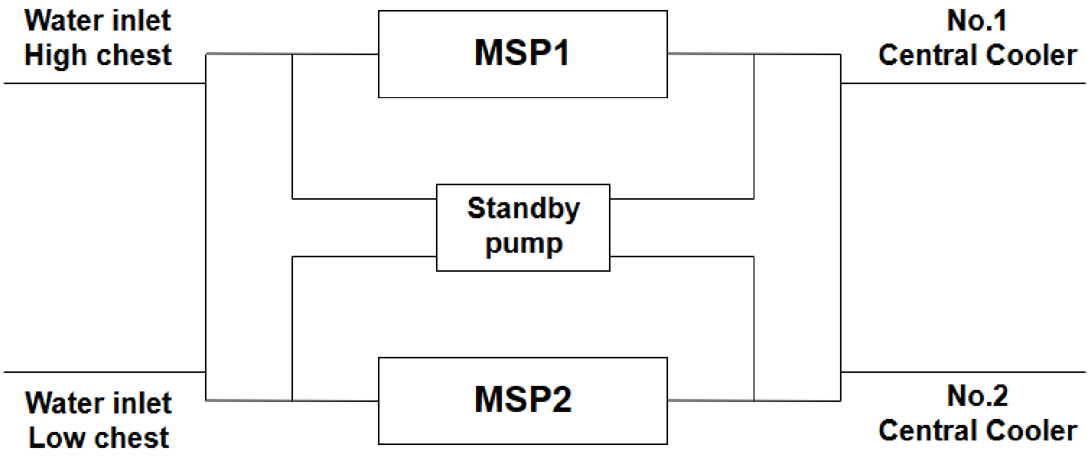


Figure 16: Simple Reliability block diagram of selected system

What to conclude from this is that even if this part of the cooling system is considered critical for successful operation of the ship, failure of 1 and even 2 pumps will not bring the system completely down because of a high degree of redundancy. It makes sense that the system is designed this way, as a vessel may be at sea for weeks without any form of support if a critical failure were to happen. Ships need to be designed with a high degree of redundancy to be prepared for the worst possible scenario.

3.3.3 Identification of Faults

The historical data does not provide a clear picture of each failure cause, but components mentioned in mechanical failure remarks include:

- Impeller
- Bearings
- Mechanical seal
- Seal ring
- High vibration cause by damaged Inducer
- Shaft
- Shaft key

Machine type: Pumps	**Symptom or parameter change**									
Examples of faults	**Fluid leakage**	**Length measurement**	**Power**	**Pressure or vacuum**	**Speed**	**Vibration**	**Temperature**	**Coast down time**	**Oil debris**	**Oil leakage**
Damaged impeller		•	•	•	•	•	•	•	•	
Damaged seals	•	•		•	•	•				
Eccentric impeller			•	•	•	•	•	•		
Bearing damage		•	•		•	•	•	•	•	•
Bearing wear		•				•	•	•	•	
Mounting fault						•				
Unbalance						•				
Misalignment		•				•				

• Indicates symptom may occur or parameter may change if fault occurs.

Figure 17: Pump fault matched to measurement parameters and techniques (ISO17359, 2011)

3.4 Select appropriate maintenance strategy

This step of ISO17359 is generally about determining whether a fault is measurable or not. If it is measurable, condition monitoring can be applied. If it is not measurable, a CM or PM strategy should be used. DOM is also an option if it’s not measurable, or one can be on the complete safe side and don’t use the machine at all.

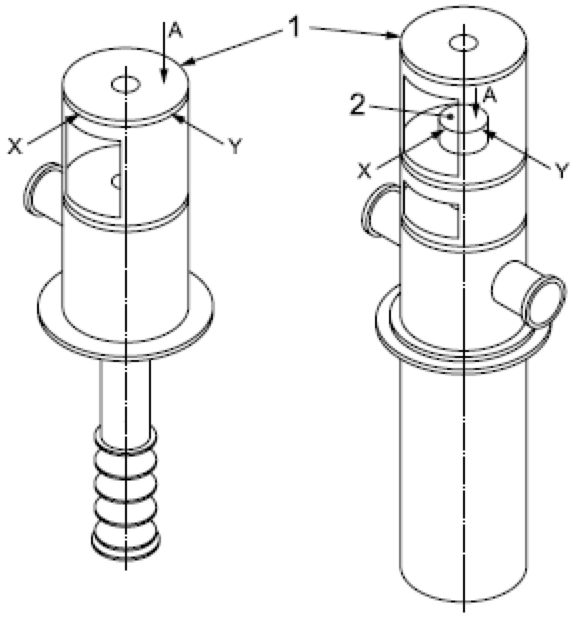
Comparing the list of identified mechanical faults in chapter 3.3.3 with Figure 17, which matches pump faults to measurable parameters of specific typical faults, it confirms what was stated earlier in chapter 3.1.2, that vibration monitoring could have detected all of these mechanical faults before they resulted in CM. It means that the faults are measurable, and that a CBM strategy can be applied to detect the faults before they result in CM.

3.5 Select monitoring method

Based on the parameter or symptom selected to be monitored, the right monitoring technique has to be applied. In many cases one or more monitoring techniques may be relevant and to be considered. If measurement only need to indicate a fault, a simple monitoring technique may be sufficient. If it is desirable with a more detailed picture of a fault and precision measurement, a different kind of technique may be applied. Different needs require different solutions.

As stated in the previous section, the parameter to be monitored on MSP is vibration, and naturally the type of monitoring technique needed is vibration monitoring. This was already chosen as the monitoring technique to focus on initially, as it was presumed that it was the most relevant for monitoring the pumps.

The recommended measurement locations on vertical mounted pumps is illustrated in Figure 18. ISO10816-7 (2009) specifies that the vibration of non-rotating parts shall be measured at the bearing housing of the pump and that vibration measurements are normally made on exposed parts of the pump that are accessible. Further Information on evaluation parameters, transducer type, measurement location and directions regarding can be found in ISO13373-1 (2002). An extraction from this standard is shown in



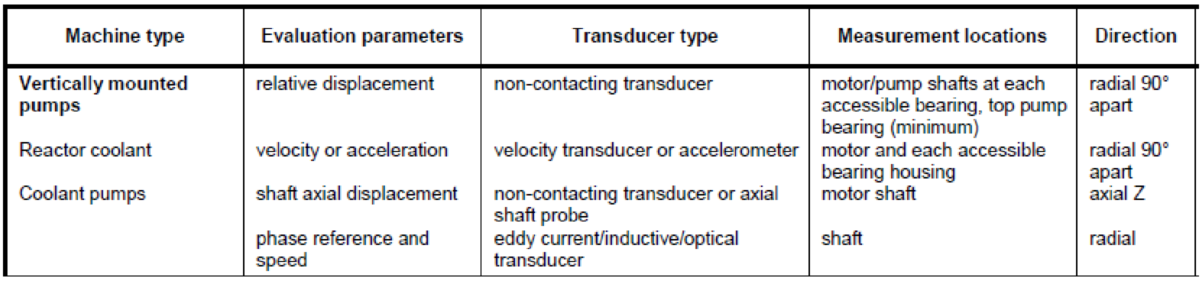
Key

1 driver mounting surface/lower motor bearing

2 pump bearing housing. Preferably this location has to be chosen if within reach, otherwise the lower motor bearing housing can be used.

NOTE X, Y are the two orthogonal radial measurement directions; A is the axial measurement direction.

Figure 18: Measurement locations on vertical pumps (ISO10816-7, 2009)



Machine type	Evaluation parameters	Transducer type	Measurement locations	Direction
Vertically mounted pumps	relative displacement	non-contacting transducer	motor/pump shafts at each accessible bearing, top pump bearing (minimum)	radial 90° apart
Reactor coolant	velocity or acceleration	velocity transducer or accelerometer	motor and each accessible bearing housing	radial 90° apart
Coolant pumps	shaft axial displacement	non-contacting transducer or axial shaft probe	motor shaft	axial Z
	phase reference and speed	eddy current/inductive/optical transducer	shaft	radial

Figure 19: Types and locations of measurement - Vertically mounted pumps (ISO13373-1, 2002)

3.6 Data acquisition and analysis

The 5 previously steps of ISO17359 (2011) covering cost benefit analysis, equipment audit, reliability and criticality audit, selection of strategy and selecting monitoring method have all been about processes happening outside of an operational environment. It covers assessment of system and mapping of undiscovered potential. The steps have not been exposed to the explosive technological development that have happened the last decade to a high degree. Other that cheaper and better sensors to consider when selecting monitoring method, the methods and procedures included in this part has not been changed a lot for some years.

The real driver in making CBM a strategy that is highly relevant in today's industrial environment have happened in the data acquisition and analysis section of the standard. It is not how to analyse vibration monitoring data and determine the condition that has changed a lot, but it is how fast we can do the analysis, how remotely we can do it, how outsourced we can do it and how automated we can do it that have made it delivering long promised benefits. It has really become one of the corner stones of Industry 4.0 making companies operations more reliable, safe and cost-efficient.

The data acquisition and analysis step can be described as the operational layer of the standard. It is where data is being collected, transmitted and analysed continuously to be used as tool in decision making. The previous steps have been followed as the standard has presented them, but this step will follow a bit different approach to address how this process from raw vibration sensor data to advisory generation practically and logically can be done onboard a vessel.

What differentiates onshore and offshore implementation of CBM? The sensors are the same so data acquisition of vibration measurements happens the same way. The way raw vibration measurement data is being transformed from noise to useful information through Fast Fourier Transformation (FFT) and alike is not different at sea. Neither is the fundamentals behind diagnostic and prognostics analysis. It is the lack of connectivity that is the real bottleneck in enabling offshore CBM as it is worshipped and presented onshore. There already exists established methods for the seven steps presented by ISO13374-1 (2003) in processing, communication and presentation of data in condition monitoring. What is more interesting is to explore how solve it when connectivity is taken out of the equation.

To see how we can overcome or walk around this problem, let's make some qualified assumptions first to not completely diverge from topic.

- Connectivity at sea is limited and does not support a continuous stream of large amount of data in a cost-effective manner

- While in port, there is connectivity
- A useful prognostic analysis needs human intervention and interpretation
- A useful advanced diagnostic analysis needs human intervention and interpretation
- A simple diagnostic analysis based on broad-band values of velocity can be done automatically and continuously by a machine.
- The crew onboard the vessel will not have the competence to do advanced diagnostics or prognostics.

Based on these assumptions the following concept of a high-level network architecture is presented in Figure 20.

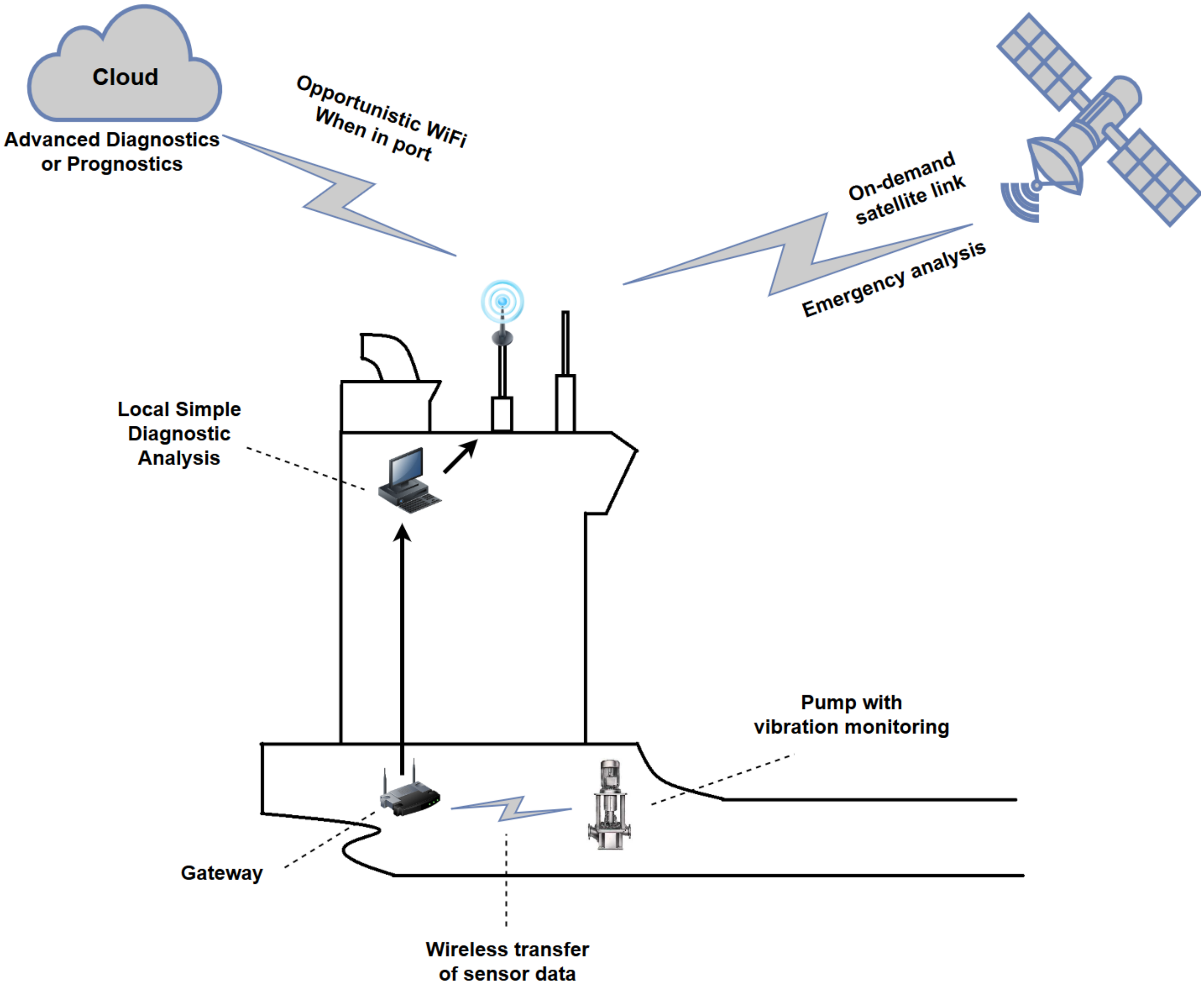


Figure 20: High-level Network Architecture of CBM system

Local simple diagnostic analysis performed of a stand-alone system onboard is necessary because the vessel and crew need to be aware of impending failure without having to wait for a diagnostic or prognostic report that may arrive when its too late. The way simple diagnostic works is that is calculates broad-band overall r.m.s velocity levels and compare it with pre-set limits as shown example of in Figure 21. Alarms and trips are set to be triggered at certain levels. This will give an indication of the pumps condition, but it will not be able detect what may be the reason of a developing failure. This must be done with advanced diagnostics.

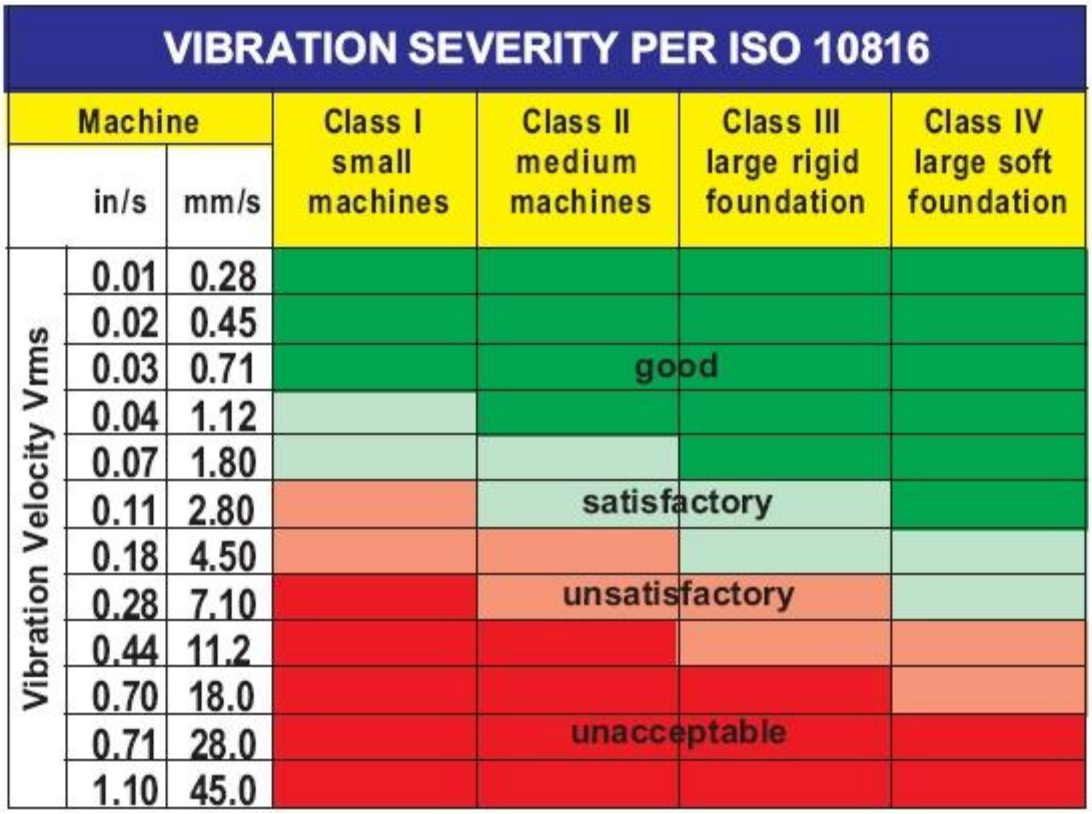
ISO10816-7 (2009) defines the limits and zones shown in Figure 21 as follows:

Zone A (dark green): The vibration of newly commissioned machines normally falls within this zone.

Zone B (light green): Machines with vibration within this zone are normally considered acceptable for unrestricted long-term operation.

Zone C (orange): Machines with vibration within this zone are normally considered unsatisfactory for long-term continuous operation. Generally, the machine may be operated for a limited period in this condition until a suitable opportunity arises for remedial action.

Zone D (red): Vibration values within this zone are normally considered to be of sufficient severity to cause damage to the machine.



VIBRATION SEVERITY PER ISO 10816

Machine			Class I small machines	Class II medium machines	Class III large rigid foundation	Class IV large soft foundation
	in/s	mm/s				
Vibration Velocity Vrms	0.01	0.28	🟩	🟩	🟩	🟩
	0.02	0.45	🟩	🟩	🟩	🟩
	0.03	0.71	🟩	🟩	🟩	🟩
	0.04	1.12	▨	🟩	🟩	🟩
	0.07	1.80	▨	▨	🟩	🟩
	0.11	2.80	🟧	▨	▨	🟩
	0.18	4.50	🟧	🟧	▨	▨
	0.28	7.10	🟥	🟧	🟧	▨
	0.44	11.2	🟥	🟥	🟧	🟧
	0.70	18.0	🟥	🟥	🟥	🟧
	0.71	28.0	🟥	🟥	🟥	🟥
	1.10	45.0	🟥	🟥	🟥	🟥

Figure 21: Broad-band Overall Vibration Velocity Limits (Reliability Direct, 2018)

Based on assumptions made, combined with Figure 20 and Figure 21, a concept of a high-level system architecture is presented in Figure 22.

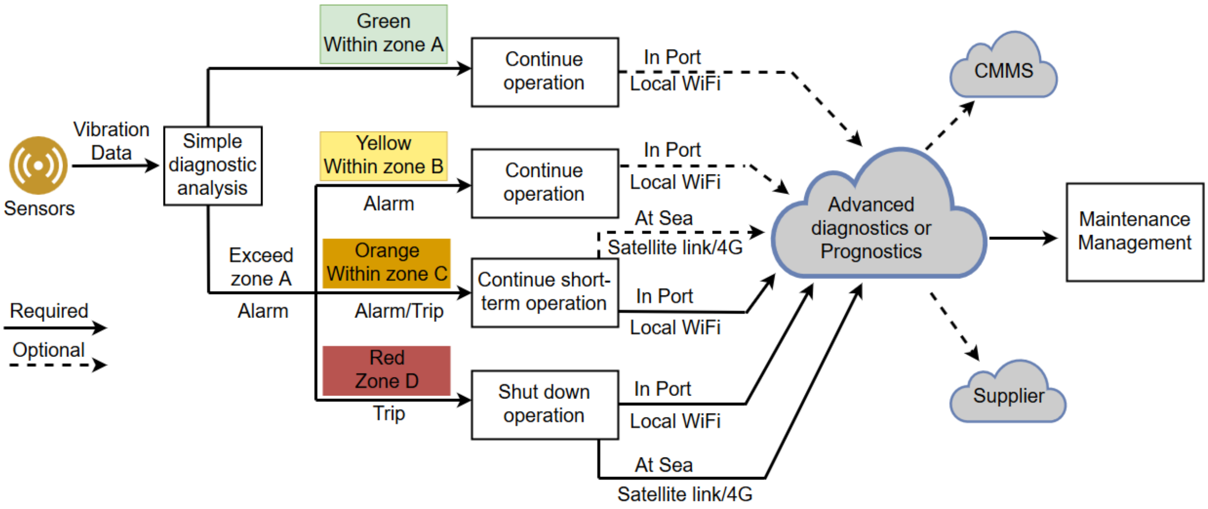


Figure 22: High-level system architecture of CBM system

3.7 Determine maintenance action

3.8 Review

The general purpose of a review is to check if the implementation of a condition monitoring system delivers what is to be expected. New relevant technology might have emerged since the last review or it might be techniques applied to the existing system does not perform as it should. Comparing the performance against KPI, baselines or benchmark established in the cost benefit analysis is supposed to give an indication of that. Review is also a important step in emphasizing that condition monitoring is an ongoing continuous improvement process.

Such a review and comparison has been done on MSP as a part of the case study. The result of the review is presented in chapter 3.8.1, 3.8.2, 3.8.3 and 3.8.4 below. It shows how vibration monitoring could have detected the mechanical faults before they happened, and ultimately avoided expensive CM. The review shows how many manhours could have been saved if a vibration monitoring system had been present.

How to interpret the data in chapter 3.8.1, 0, 3.8.3 and 3.8.4:

- Figure 23 is the benchmark for MV Balao established in chapter 3.1.1. This figure contains the baseline for regular planned maintenance in addition to identified CM. It works as the basis for comparison with a CBM scenario,
- Figure 24 is the CBM scenario for MV Balao. This figure presents the potential effect CBM would have had on the benchmark if implemented instead of time-based PM.
- Figure 25 shows the comparison of required maintenance manhours between Figure 23 and Figure 24. In other words, it is comparing maintenance manhours of the benchmark and a CBM scenario on MV Balao.
- **Feil! Fant ikke referansekilden.** compares the number of manhours in benchmark and a CBM scenario on MV Balao and highlights the % decrease in maintenance manhours CBM would have had.

Apply this logic for all of the comparisons.

3.8.1 MV Balao

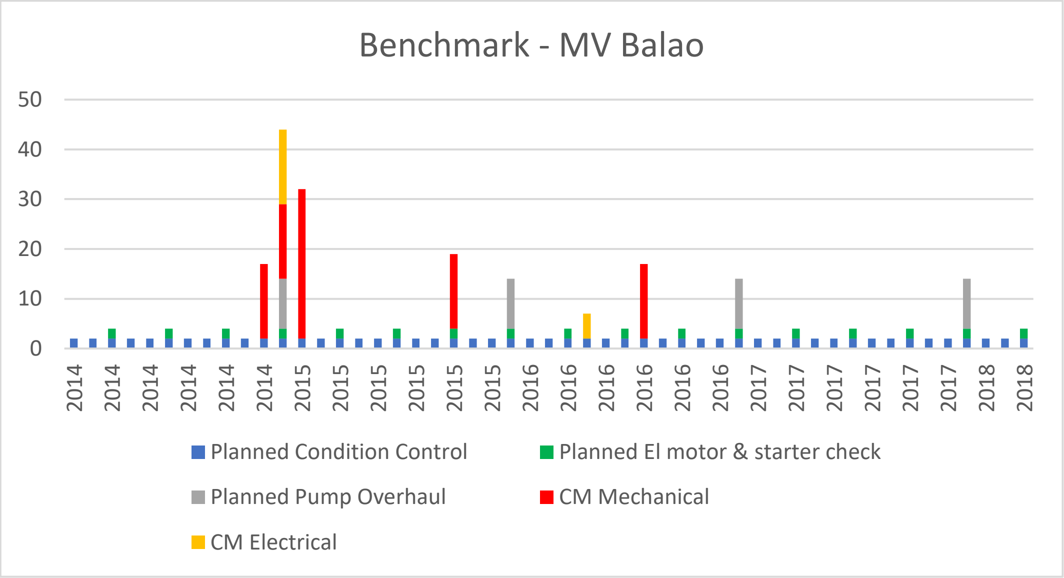


Figure 23: Benchmark - Basis for Comparison - MV Balao

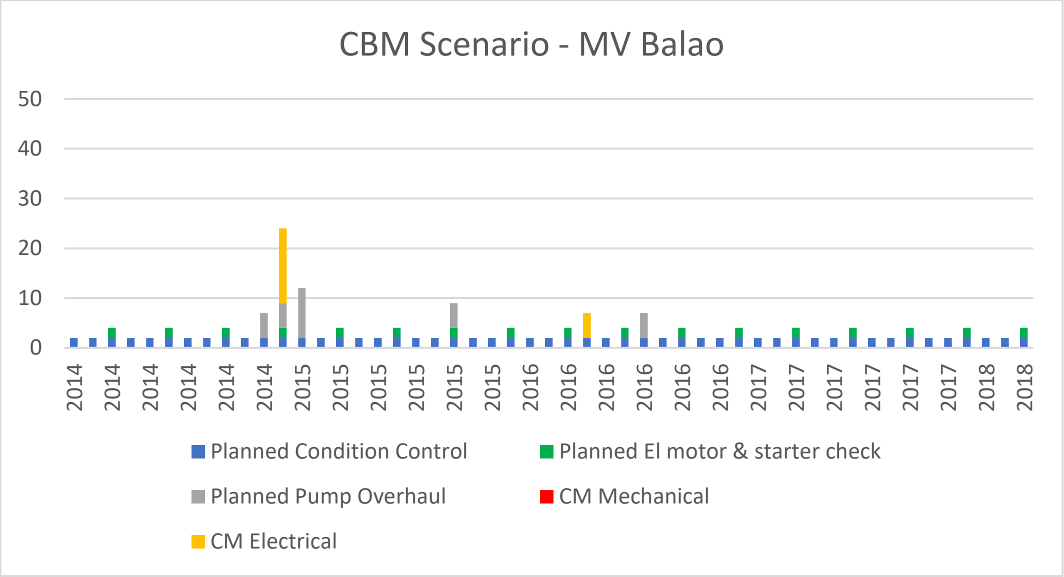


Figure 24: CBM Scenario - MV Balao

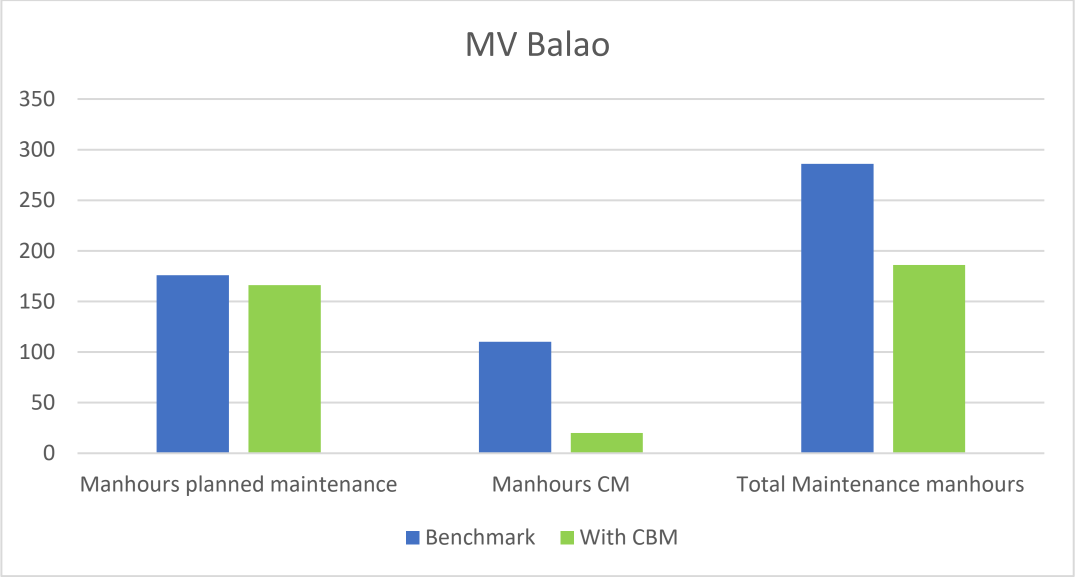


Figure 25: Benchmark Compared with CBM Scenario - MV Balao

Table 7: CBM Scenario - Decrease in Maintenance Manhours - MV Balao

	Benchmark	**With CBM**	**Decrease %**

Manhours planned maintenance	176	166	**-5,68**
Manhours CM	110	20	**-81,82**
Total Maintenance manhours	286	186	**-34,97**

3.8.2 MV Balsa

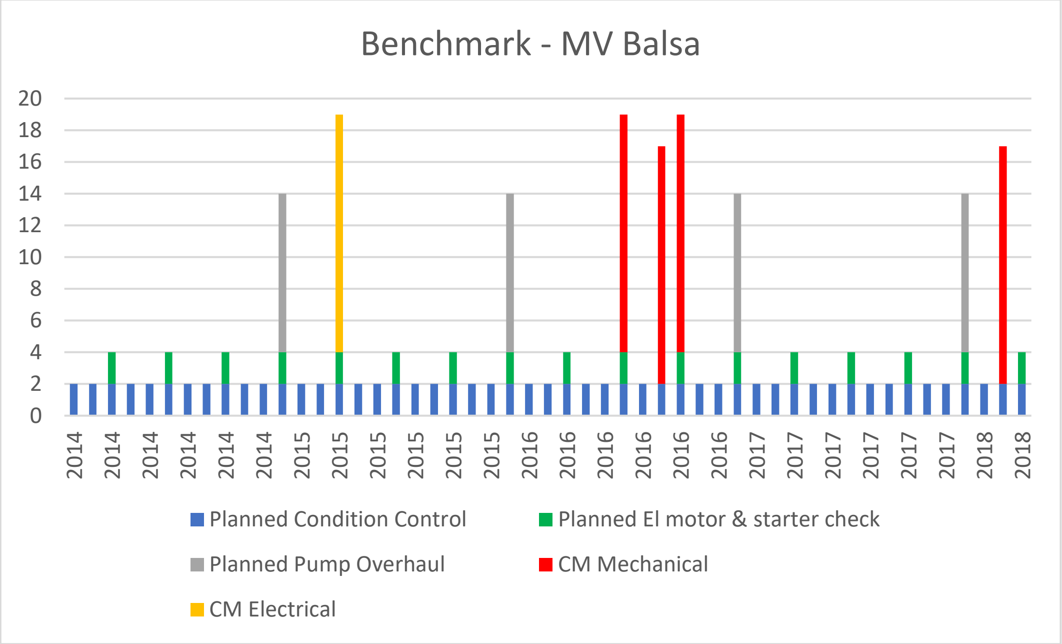


Figure 26: Benchmark - Basis for Comparison - MV Balsa

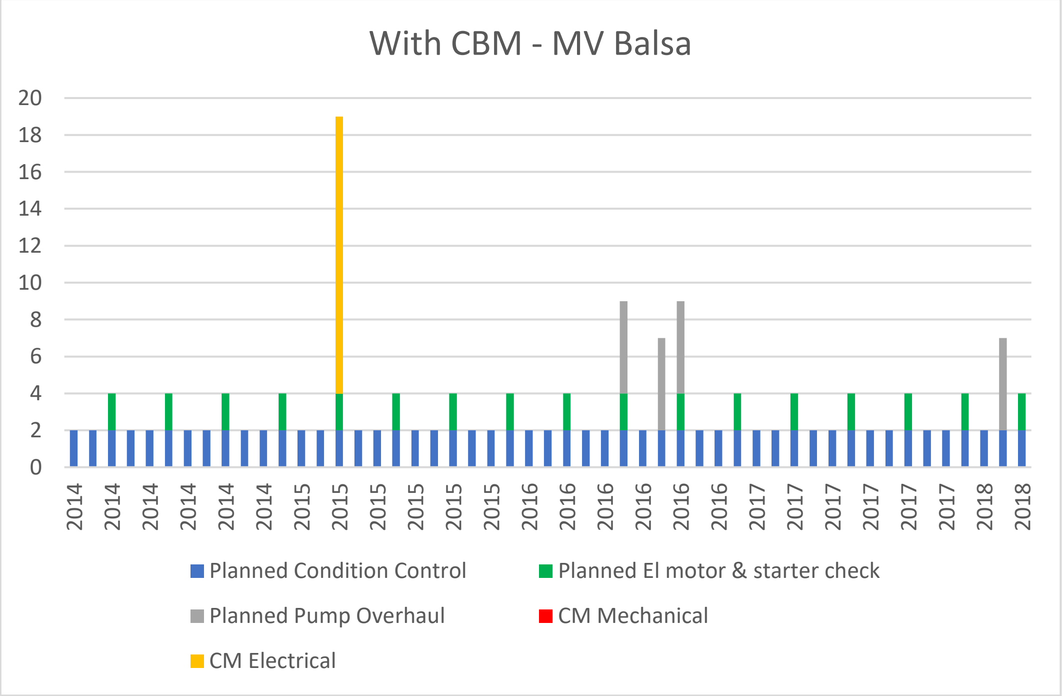


Figure 27: CBM Scenario - MV Balsa

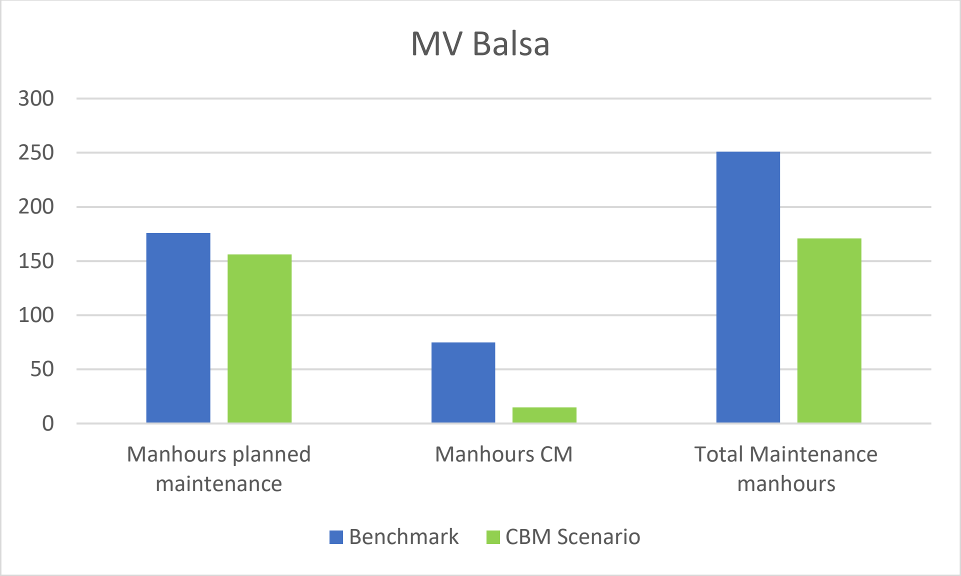


Figure 28: Benchmark Compared with CBM Scenario - MV Balsa

Table 8: CBM Scenario - Decrease in Maintenance Manhours - MV Balsa

	Benchmark	**CBM Scenario**	**Decrease %**
Manhours planned maintenance	176	156	**-11,36**
Manhours CM	75	15	**-80,00**
Total Maintenance manhours	251	171	**-31,87**

3.8.3 MV Ballenita

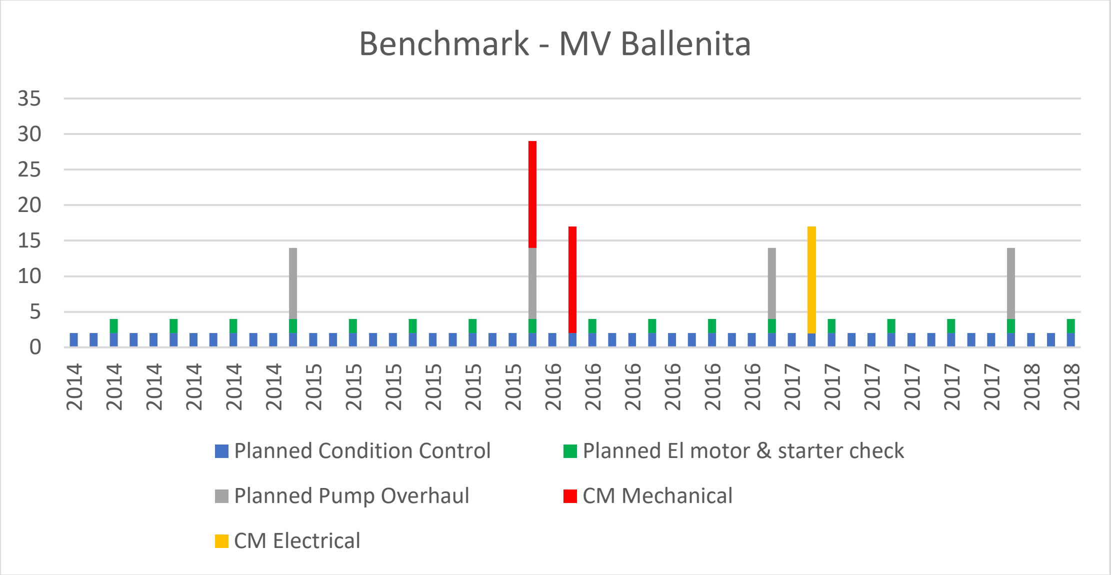


Figure 29: Benchmark - Basis for Comparison - MV Ballenita

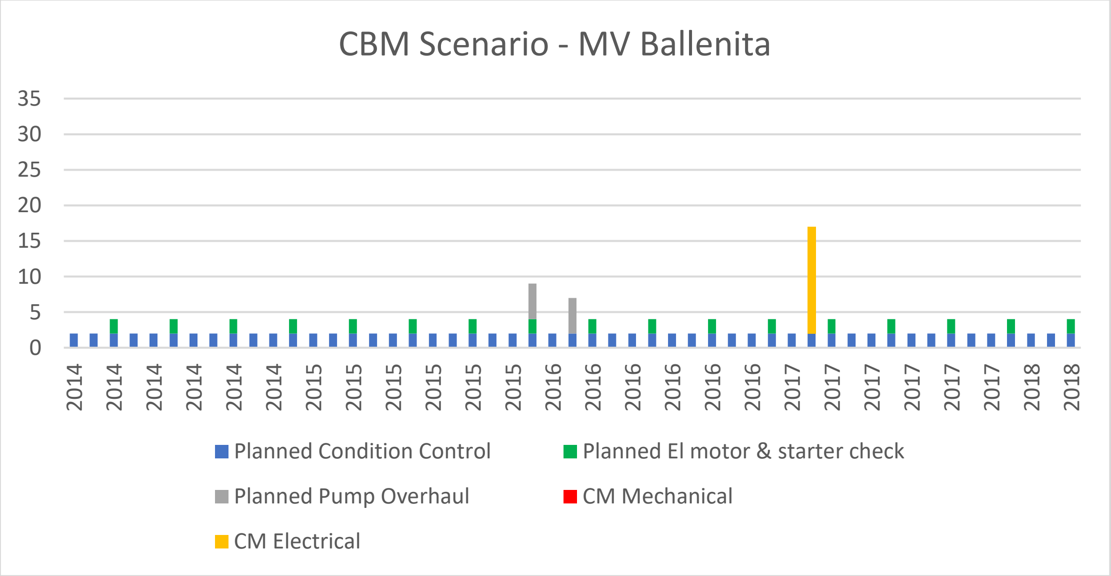


Figure 30: CBM Scenario - MV Ballenita

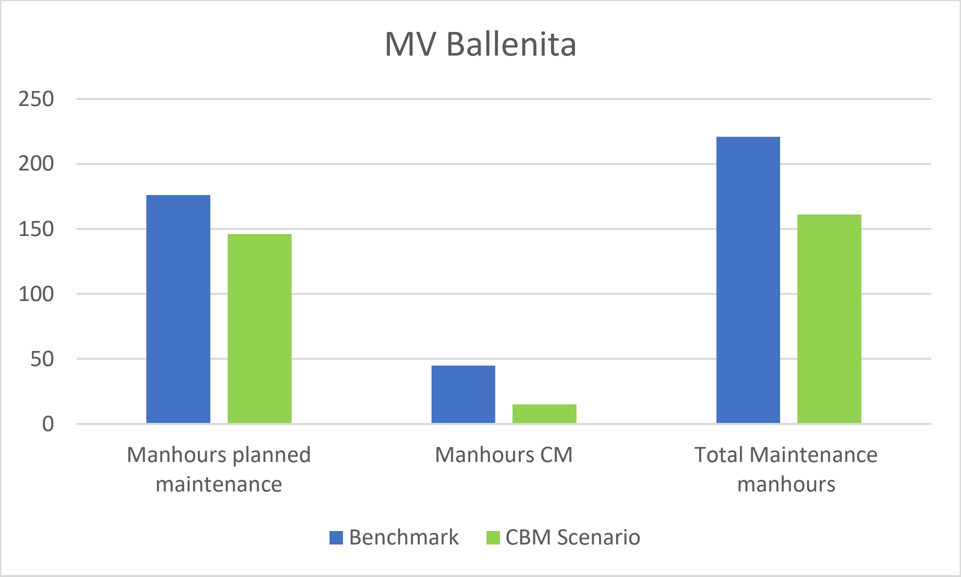


Figure 31: Benchmark Compared with CBM Scenario - MV Ballenita

Table 9: CBM Scenario - Decrease in Maintenance Manhours - MV Ballenita

	Benchmark	**CBM Scenario**	**Decrease %**
Manhours planned maintenance	176	146	**-17,05**
Manhours CM	45	15	**-66,67**
Total Maintenance manhours	221	161	**-27,15**

3.8.4 Vessels Combined

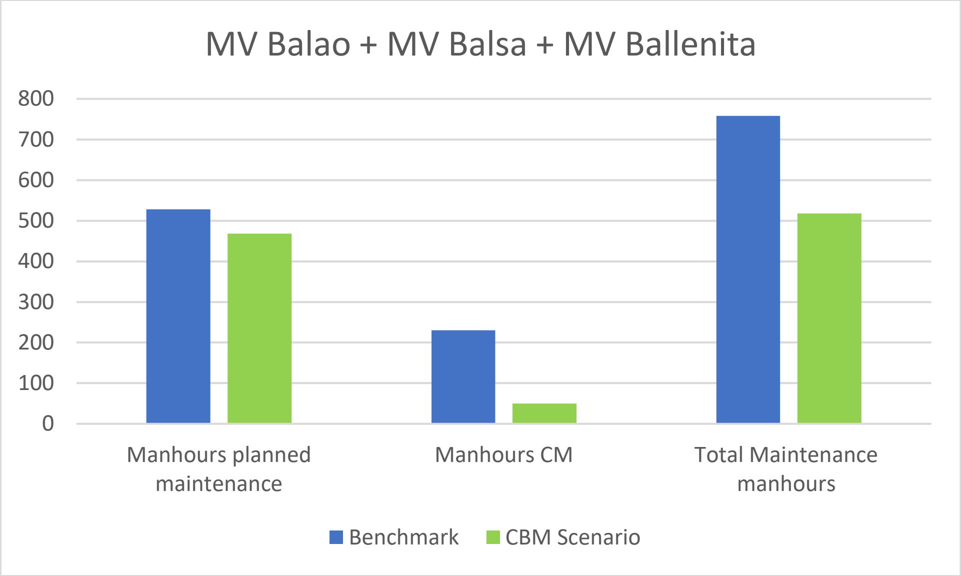


Figure 32: Benchmark Compared with CBM Scenario - Vessels Combined

Table 10: Average Decrease in Maintenance Manhours - Vessels Combined

	Benchmark	**CBM Scenario**	**Decrease %**
Manhours planned maintenance	528	468	**-11,36**
Manhours CM	230	50	**-78,26**
Total Maintenance manhours	758	518	**-31,66**

3.9 Outlook/Holistic approach/

Follow ISO17359 and ISO13374

- Selection of component/subsystem
- Assessment of historical data
    - Map planned maintenance: Identify maintenance tasks
    - Map corrective maintenance: Identify faults/failure mode
- Select monitoring techniques best suited to minimize/eliminate planned maintenance and predict failures before it happens. In this case we have already selected vibration monitoring as technique, but other techniques might be relevant.
- What will the system architecture look like?
    - Limitations: Connectivity (at sea and on board vessel), Technology (Diagnostic and prognostic capabilities), Competence of crew.
    - Local real-time diagnosis + opportunistic cloud for prognostics
- How will the information/data be handled?
- Potential/Benefits
    - Benchmark with historical data
    - Back it up with literature and success stories
    - P-F curve

4 Results and Discussion

The study shows that implementing vibration monitoring on MSP as a part of a predictive maintenance system will reduce manhours related to maintenance with 31.6% on average across three container vessels. It also shows that what previously was defined as CM now is performed in a preventive manner. This is because unpredicted failure is detected before it happens, and maintenance can be planned in advance of a failure. The result of this is that total CM could have been reduced with 78% if condition monitoring were implemented. The factor keeping it away from potentially reaching 100% reduction in CM is that electrical CM was included in the benchmark, but not considered applicable for vibration monitoring in this thesis.

5 Conclusion

Start with answering the research question.

The thesis confirms the expectation that implementing vibration monitoring on the pumps as a part of a predictive maintenance system would significantly impact OPEX. Total reduction in manhours related to maintenance is estimated to be 31.6 % on average across all three vessels. The thesis presents how vibration monitoring as part of a predictive maintenance system can be implemented using standards. It also presents a high-level network architecture and a high-level system architecture of a CBM system onboard a vessel developed with regards to limited connectivity at sea. The two architectures show how a vessel can benefit from a CBM strategy even due to limitations at sea by applying the right technology.

The study also shows that what previously was defined as CM now is performed in a preventive manner. This is because unpredicted failure is detected before it happens, and maintenance can be planned in advance of an impending failure. The result of this is that total CM could have been reduced with 78% if condition monitoring were implemented.

The thesis highlights the benefit of using standards, specially in terms of interoperability. As the world becomes more connected and IoT seriously starts to show its true potential, it is important that systems that are being developed and implemented have taken interoperability into account to be functional in the future. With an incremental implementation of a predictive maintenance system, it is essential to request that suppliers is basing their system on standards so that it is compatible with other systems implemented in the years to come.

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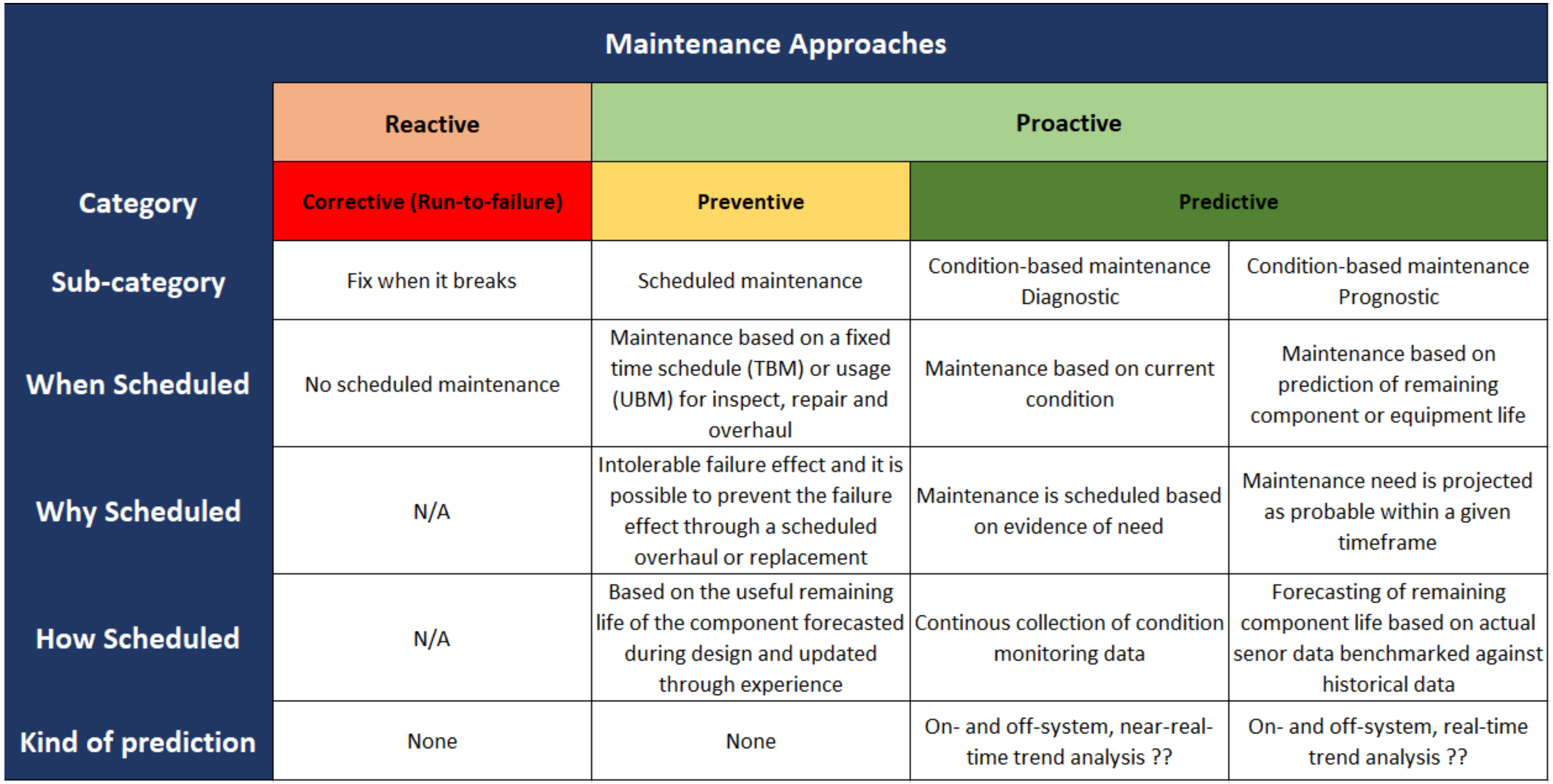
Appendix 1: Maintenance Approaches



Maintenance Approaches				
	Reactive	Proactive		
Category	Corrective (Run-to-failure)	Preventive	Predictive	
Sub-category	Fix when it breaks	Scheduled maintenance	Condition-based maintenance Diagnostic	Condition-based maintenance Prognostic
When Scheduled	No scheduled maintenance	Maintenance based on a fixed time schedule (TBM) or usage (UBM) for inspect, repair and overhaul	Maintenance based on current condition	Maintenance based on prediction of remaining component or equipment life
Why Scheduled	N/A	Intolerable failure effect and it is possible to prevent the failure effect through a scheduled overhaul or replacement	Maintenance is scheduled based on evidence of need	Maintenance need is projected as probable within a given timeframe
How Scheduled	N/A	Based on the useful remaining life of the component forecasted during design and updated through experience	Continous collection of condition monitoring data	Forecasting of remaining component life based on actual senor data benchmarked against historical data
Kind of prediction	None	None	On- and off-system, near-real-time trend analysis ??	On- and off-system, real-time trend analysis ??

Appendix 2