Improving Maritime Maintenance through Condition Monitoring and Condition Based Maintenance

Bachelor Thesis - Research Report

December 16th, 2016
Vlissingen, the Netherlands

Author:
P.J.H.M. Potmeer Student no. 64494

1st Supervisor:
Ir. J.P.C. Wubben

2nd Supervisor:
A. de Groot

Bachelor Maritime Officer
De Ruyter Academy
HZ University of Applied Sciences

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1st Supervisor: Ir. J.P.C. Wubben
2nd Supervisor: A. de Groot

Case Study: LNG/c Coral Energy

Anthony Veder Rederijzaken B.V.
Parklaan 2
3016 BB Rotterdam
The Netherlands

ABSTRACT

While condition-based maintenance (CBM) has been established as an effective maintenance strategy in comparison with time-based maintenance (TBM), it has not garnered popularity in the maritime industry. Instead, TBM has been established as the norm for most maintenance programs on board ships. Research indicates that under some circumstances TBM is an ineffective strategy, however, and that using CBM as a complement to TBM wil solve that problem.

A case study involving the LNG carrier Coral Energy explores the possibility of expanding the use of CBM and determining how it will improve the state of maintenance on board. The literature provides information on how implementation of CBM is best accomplished.

It turns out that the maintenance program on the Coral Energy is poorly developed. Time-based maintenance is mostly reserved for the main engine and auxiliary engines, while most other critical equipment is maintained reactively, with maintenance performed as a result of periodic equipment inspections that are used to discover failures. Run-to-failure maintenance is also common, but is only principally used for machines that are implemented with redundancy.

Condition monitoring systems are present for the engines and several other applications, but are not used as part of a developed CBM strategy. There is a potential for further development. Data acquired in the monitoring process is often of poor quality and not suitable for processing. Another problem is that in the situations where TBM is being used, components are giving out before their allotted lifetime has been completed, thereby causing unexpected failures.

While the crew is hardly aware of the existence of CBM and the theory behind it, they can see how the quality of the maintenance system could be improved. They are also open to change to the maintenance culture on board the ship.

It is found that for practical implementation of solutions to the problems identified, the best investments are made in training and awareness, with a goal of utilizing simple CBM methods that use conventional tools rather than complex systems. There are also condition monitoring systems already in place that could be used to greater effect.

These implementations should solve the problems identified. Training and instruction of engineers should also increase awareness of maintenance strategies, which will increase the quality of work.

These points, in summary, provide a method to improve the state of maintenance on board the Coral Energy using CBM and general improvement of system quality. It is recommended that the company look into ways to provide training and instruction to its engineers as the way forward into a more proactive maintenance culture across the fleet.

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1. Introduction

Among several established maintenance strategies, Condition Based Maintenance (CBM) has emerged as a new maintenance strategy over the past decades (Rao, 1996). CBM has proven, in comparison with preventive or time based maintenance, to be more economical in terms of material cost and man hours and to be more effective in preventing unexpected mechanical failures (Knutsen et al., 2014). Today, CBM is the leading decision-making model used in maintenance strategies for the aviation industry and has proven itself to be of great effectiveness (Rao, 1996). Not only have maintenance costs lowered, but passenger safety has greatly improved, with the amount of passenger fatalities per year showing a downward trend since 1980 even though the amount of passengers has been increasing (see fig. 1). The use of CBM in the maritime industry is far less common when compared with the aviation industry and other fields (Algelin, 2010).

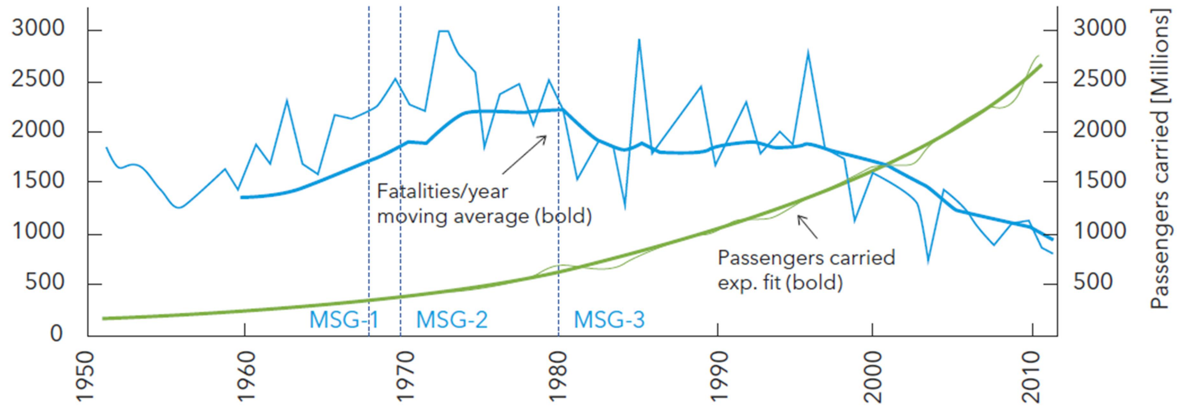

Figure 1 - Fatalities per year (left axis) vs passengers carried (right axis). Obtained from Knutsen et al. (2014).

Motivation

Knutsen et al. (2014) explain that the main reason for CBM's increased effectiveness over time based maintenance (TBM) in preventing failures can be attributed to the statistical pattern of mechanical failures. TBM is only effective in preventing failures that occur due to wear out of a component. After all, a component will only fail at the end of its lifetime and replacing the component before it reaches the end of its lifetime should ensure minimal frequency of failure. But in practice, it turns out that many recurring mechanical failures remain that do not follow a pattern which can be reliably predicted. In fact, research found that, in the aviation industry, 89% of mechanical failures followed a random pattern. This is not necessarily a problem, as Markovian probability is still applicable to determine maintenance intervals that provide high rates of reliability even for components displaying random failure rates (Rijsdijk, 2015). This approach, however, always assumes a worst-case scenario. As a result, in many cases, the preventive maintenance carried out is unnecessary. In these cases the component has usually not nearly approached the end of its life cycle. A pure TBM strategy geared towards maximum reliability for components with random failure rates is therefore inefficient and expensive.

TBM is not uniquely inefficient in the aviation industry. Between 71 and 77% of mechanical failures in the maritime industry follow the same random failure patterns that make time based maintenance a less effective method (Knutsen et al., 2014). Clearly, the approach to maintenance in the maritime industry is not perfect. 23% of all shipping accidents are caused by mechanical failures, with insufficient maintenance stated as one of the main causes of failure (Algelin, 2010).

Problem statement

From the aforementioned research the following problem emerges: TBM is the dominant method for maintenance decision-making in the maritime industry while CBM is hardly applied, but CBM could also be applied in order to account for random failures and provide increased reliability.

The problem is states as follows: Because CBM is not applied on a comparable scale as within other transportation areas, shipowners might spend more money on maintenance than necessary at the same level of availability and health.

Problem analysis

Why is TBM the dominant maintenance strategy aboard ships (Algelin, 2010; Knutsen et al., 2014)? Classification societies such as Lloyd's Register and DNV provide machinery surveys based on planned intervals, which allows them to verify the seaworthiness of classed ships. The five-year interval for the Special Survey Machinery (SSM) is the standard, but there are alternative methods. Lloyd's register (2013) provides several alternatives to SSM, but most of them are still based on periodic inspection and fixed maintenance intervals. Condition monitoring (CM) and CBM systems are acceptable to class under the right conditions, but research indicates these options are very rarely used. Knutsen et al. (2014) reported that 2% of all classed ships used class-approved CM schemes as part of their planned maintenance system. A survey of Swedish maritime companies indicated that no ships used the class-approved CBM system at all, against 62% using staggered planned maintenance schemes that spread the surveys out over a five-year period as an alternative to the five-yearly total maintenance survey in the SSM. Roughly half the ships surveyed used CM techniques, but only incidentally and under special circumstances rather than as part of a global maintenance strategy (Algelin, 2010).

It can be concluded that the maritime maintenance industry as a whole is dependent on a maintenance strategy that has proven to be insufficient for full prevention of all mechanical failures. Regardless of attempts to innovate, the industry appears to cling to TBM as its primary maintenance method, while failing to utilize the opportunities offered by different maintenance strategies, particularly CBM. As a result, the approach to maintenance strategy in the maritime industry remains poorly developed and inefficient.

Research objective

The research objective is to validate the hypothesis that the shipping industry would save money by increasing the application of CBM.

It would appear that incorporating CBM into a ship's maintenance strategy is likely to increase reliability, decrease the occurrence of unexpected failures, and may be both directly and indirectly more cost-effective. This hypothesis needs to be validated. The research intends to discover how the maritime industry can move towards a general maintenance strategy that still includes elements of TBM, but also incorporates CBM to the aforementioned benefits.

Rather than focusing on a wide examination of the maritime sector, however, this research will attempt to contribute to examining the possibilities for expanding the use of CBM by means of a case study. The intention of the research is also to identify any barriers or problems that may impede further implementation CBM into the sector. The Coral Energy, a LNG tanker operated by Anthony Veder, will be the subject of this case study.

Research question

The main research question becomes: "How can maintenance performance in the maritime industry be improved by (further) implementing the condition-based maintenance strategy, what are the benefits and how should that be done?"

When related to the case study, the question becomes: "How can maintenance on the Coral Energy be improved by (further) implementing the condition-based maintenance strategy, what are the benefits, how should that be done and to what extent are the results applicable to the maritime industry in general?"

The sub-questions necessary to answer the main research question are:

Theoretical

- T1. What is the value of CBM when compared to TBM and other traditional maintenance strategies?
- T2. Is CBM generally applicable in the maritime industry, or are there constraints?
- T3. What is the optimal way to implement CBM, and what are the challenges?
- T4. Why has CBM not been extensively implemented in the maritime industry already?
- T5. What requirements do class societies have for the use of CBM on ships?

Empirical, focused on the current situation on the Coral Energy

- E1. What are the current maintenance strategies used on board the Coral Energy and to what extent is CBM already being used?
- E2. Which problems occur when employing the current maintenance strategy, and could they be solved by implementing CBM techniques?
- E3. What is the current attitude and position of the crew in regards to the implementation of CBM techniques?

Analytical, for determining the requirements

- A1. What investments are required to make further implementation of CM and CBM possible in terms of modifications, tools and training?
- A2. What improvements are expected as a result of (further) use of CBM?

2. Theoretical framework

This section of the report is intended to clarify the theory behind CBM and its value when compared to TBM. It also aims to establish why CBM has not developed into a generally used maintenance strategy in the maritime industry.

T1. What is the value of CBM compared to TBM and other traditional maintenance strategies?

Time-based maintenance is a traditional maintenance technique. It is defined as a technique that determines maintenance intervals solely based on statistical analysis of failure time. TBM assumes that the failure rate of equipment is predictable. The most popular model for analysing failure data is the Weibull distribution model, which can be used to generate three failure patterns: decreasing (infant mortality), constant, and increasing (wear-out). These three patterns are combined to generate the so-called bathtub curve (Rosmaini & Kamaruddin, 2012). Knutsen et al. (2014) explain that, while the Weibull model is applicable, its use does not account for all mechanical failures that occur (see fig 2). As a result, most mechanical failures that occur within the maritime industry (i.e. those that are not prevented by TBM) can be said to be unpredictable using the assumptions that support the use of TBM. Allen (2001), verifying the findings of a U.S. Navy survey dating from 1961, also concludes that in the majority of failures occurring on U.S. Navy submarines, there remains no relationship between overhaul times and the occurrence of failures, which implies that the use of solely TBM is insufficient for maximizing reliability.

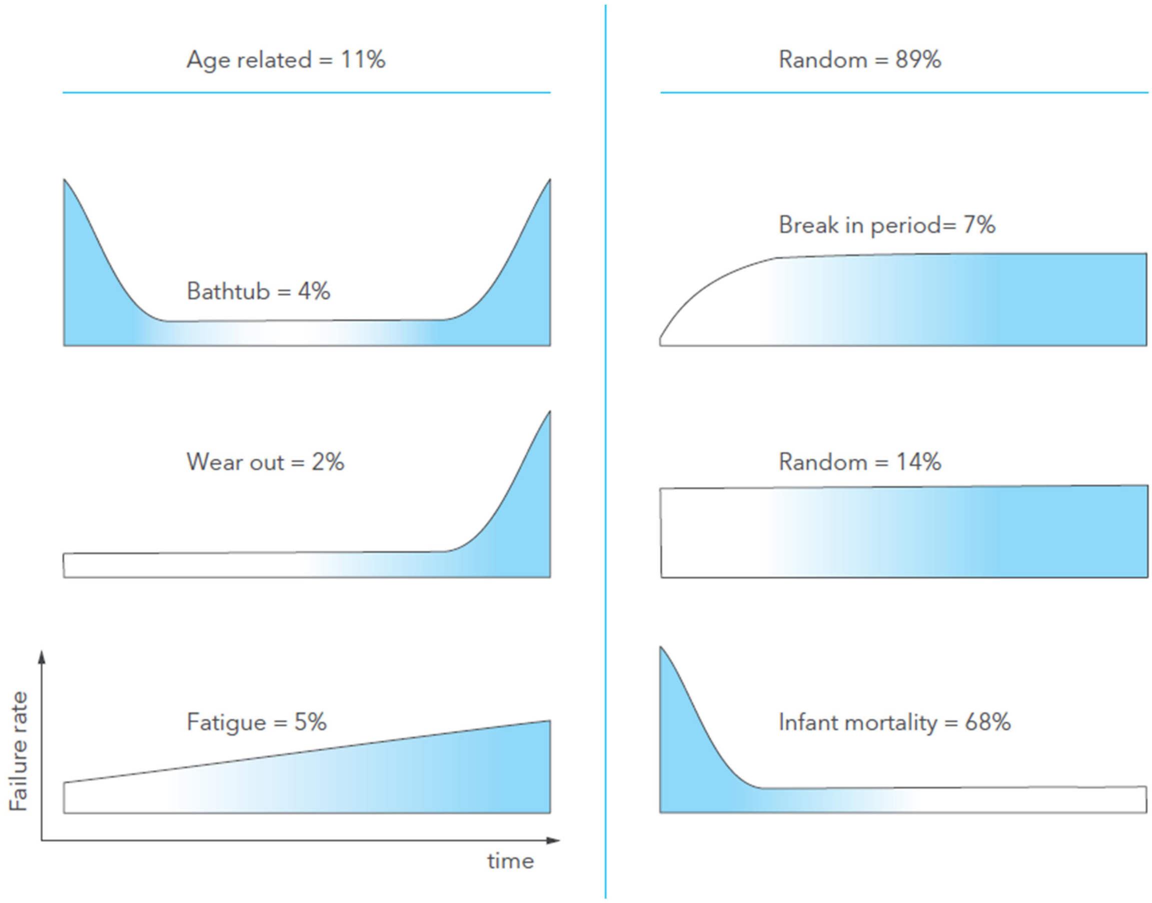

Figure 2 - Failure rate curves and the distribution of their occurrence in the aviation industry (Knutsen et al., 2014)

Rosmaini & Kamaruddin (2012) conclude that, “as 99% of equipment failures are preceded by certain signs, conditions, or indications that such a failure was going to occur” (p. 146), CBM becomes a more beneficial maintenance method compared to time-based maintenance. Jardine et al. (2005) also conclude that “in many situations, especially when both maintenance and failure are very costly, CBM is absolutely a better choice than the conventional ones.” (p. 1500) in reference to TBM and failure-based maintenance as some of the conventional choices.

Therefore it can be concluded that, when the goal is to avoid unexpected mechanical failures, TBM is a method that cannot account for all types of mechanical failure. In case of critical failures that show unpredictable patterns, CBM is an excellent method for complementing TBM in order to maximize reliability and minimize risk of unexpected failure. When unexpected failures are not a problem, failure-based maintenance is usually the most economical solution.

T2. Is CBM generally applicable in the maritime industry, or are there constraints?

It is necessary to note that, while CBM is applicable to many items of machinery, there are also systems for which it is not useful or necessary. As discussed by Knutsen et al. (2014), items of machinery that display age-related failures are best maintained by using TBM. Their lifespan is easily predictable, and performing repeated measurements in order to determine the state of wear, as would be the case when applying CBM, is relatively pointless: it is already known when a measurable indication of failure will occur based on previous experience.

We should therefore decide whether or not CBM is applicable on whether it can be considered useful, i.e. whether it is effective and whether it is efficient. Gits (1992) describes how the effectiveness of different maintenance approaches can be determined. He states, for example, that CBM is only theoretically effective when a measurable prognostic characteristic is known. A prognostic characteristic is a physical property which gradually changes from an initial ‘good-as-new’ value, to a fatal value, at which failure occurs. If there is no prognostic characteristic available, CBM is completely pointless. For TBM the effectiveness is dependent on there being an increasing likelihood of failure in a particular component over time. If the failure rate is constant, TBM is pointless, while if the failure rate is decreasing, TBM can even increase the likelihood of failure.

Gits (1992) also determines how the efficiency of a maintenance model can be evaluated. He differentiates between individual efficiency and combinatorial efficiency. In the case of individual efficiency, a comparison is made between the costs saved in preventing a mechanical failure when compared to the costs accrued in performing maintenance to protect that failure. Simply put, if preventively maintaining (either through TBM or CBM) a component is cheaper than having to deal with the results of an unexpected failure, the approach used can be considered efficient.

Combinatorial efficiency is about the trade-off between the benefits of combining simultaneous maintenance operations opposed to the possibility for an increased frequency of these operations. Specifically, it is about reducing the costs accrued when performing a ‘set-up’, which is an operation required to prepare for a maintenance operation (such as disassembly and reassembly, shutdowns and startups, etc.). Performing different maintenance operations at once will reduce the amount of set-ups, but compromises in maintenance intervals have to be made to make such a combination possible, meaning some operations may be performed too often or not often enough, which reduces efficiency.

In conclusion, it is clear that the applicability of CBM in the maritime industry is determined by whether it is effective and efficient. Whether or not it is effective is determined by whether it is possible to find a prognostic characteristic. If there is none, CBM is not applicable. Whether it is efficient depends on whether the benefits obtained outweigh the costs of failure. These two factors need to weigh into whether it should even be attempted to incorporate CBM methods into a vessel's maintenance strategy.

T3. What is the optimal way to implement CBM, and what are the challenges?

Jardine et al. (2005) describe that CBM consists of three key steps:

1. Data acquisition
2. Data processing
3. Maintenance decision-making

The article (Jardine et al., 2005) further distinguishes between two different methods of data acquisition: diagnostics and prognostics. Diagnostics is a method that attempts to detect faults as they occur. Prognostics, on the other hand, attempt to predict faults and how soon those faults will occur. Quote: *"Diagnostics is posterior event analysis and prognostics is prior event analysis. Prognostics is much more efficient than diagnostics to achieve zero-downtime performance. Diagnostics, however, is required when fault prediction of prognostics fails and a fault occurs. A CBM can be used to do diagnostics or prognostics, or both. No matter what the objective of a CBM program is, however, the above three CBM steps are followed."* (Jardine et al., 2005, p. 1485) Specific methods for diagnostics and prognostics are extremely diverse, and depend on the type of machinery they are performed on (Jardine et al., 2005).

Rosmaini & Kamaruddin (2012) describe three particularly popular CM techniques: vibration analysis, acoustic analysis and oil analysis or lubricant monitoring. Other less popular techniques mentioned include electrical, temperature and physical condition monitoring. Rosmaini & Kamaruddin (2012) also describe the two main methods for decision making under CBM: diagnostics and prognostics. Specifically, they point out that diagnostics provide an early warning sign of an impending failure. The diagnosis of a fault may indicate that the machine is running abnormally, but it does not mean that it has failed. The diagnosis is then used as a signal to begin prognosis to determine when the machine is expected to fail, and to perform preventive maintenance before that time.

Many examples are available where the implementation of CBM turned out to be a sound investment. An Austrian paper manufacturing company reported a payback time of 1.57 years on an investment of approximately 170,000 USD when the technology was still relatively new (Brüel & Kjaer, 1987). An aviation company obtained a yearly rate of return on their investment of 54% after introducing CBM (Rao, 1996, p.94). In both situations, however, the gains were calculated in comparison to a purely corrective maintenance strategy, not in comparison to time based maintenance.

Failed implantation of CBM occurs relatively often, and is a known problem. What happens is a CBM system is implemented, but after a few years it falls by the wayside, and the motivation to continue using it is lost. This is not an uncommon story (Knutsen et al., 2014;

van den Berge et al., 2016; Rao, 1996). What has been made clear through research is that for the successful implementation of a CBM system, a culture shift is necessary. Knutsen et al. (2014) describe how the process of this cultural shift happened in the aviation industry. It also provides some recommendations to managers of maritime companies wanting to implement CBM. In Rao's Handbook of Condition Monitoring (1996, p.43) there is an excellent description of the type of situation that seems to occur with those companies that try to implement CBM and fail. It describes how new users of CBM experience a lowered frequency of failures as a result of its implementation. The system works, the measurements keep coming in and their quality continues to increase. Failures are predicted shortly before they can occur, and are prevented. It is at this point that certain people tend to argue for the CBM system's retirement, as it has 'obtained the intended results' through lessening the frequency and severity of failures. Slowly, the CBM measurements start happening less and less often, until they are simply not performed at all, and the maintenance effectively returns to time based maintenance or even run-to-failure. This demonstrates how important it is to continue to motivate people to keep using the system, even when it has been implemented long ago and has been running smoothly up until that point.

In their research on the implementation of a CBM system in the Wagenborg company, van den Berge et al. (2016) described that a large part of the reason for failed implementation was due to a lack of knowledge among the engineers responsible for maintenance aboard the ships. The progress of the system being implemented and eventually ending up in complete disuse is one that resembles the lines set out by Rao (1996) described in the previous paragraph. A lack of instruction and training was put forward as one of the underlying reasons for this failure.

T4. Why has CBM not been extensively implemented in the maritime industry already?

Rosmaini & Kamaruddin (2012) indicate some challenges with the implementation of CBM. There is a current lack of user-friendly and practical data architectures, meaning that the use of computer systems specifically designed for the use of organizing CBM data is either inefficient or too challenging for non-expert users. Furthermore, several CBM measurement techniques lack clear and effective indication of the failure limit, which is the measured limit at which maintenance is carried out. Lastly, they point out problems with data availability, indicating that while data on wear and tear may be measureable in an experimental situation, but not in a practical environment.

Van den Berge et al. (2016) researched the causes of the failed implementation of a CBM system utilizing shock-pulse measurement, an advanced form of vibration measurement. They indicated that the prime cause of the implementation's failure was twofold. Firstly, there was not enough external involvement from the company to encourage the crew to use the new method. Crew was not trained in use of the measurement equipment, which meant the system could not be reliably used. Secondly, lack of communication between crew and company during the implementation phase meant that the benefits of the new system went underemphasized, causing the crew to lack motivation to use it, and fall back on the existing TBM system they had been using at first.

In a survey of Swedish ships, the reasons stated most often by owners and managers of ships to not incorporate a CBM strategy were (Algelin, 2010):

- Financial cost

- Bad experiences
- Inconsistent data evaluation
- Quality of CM equipment

Developers of CM and CBM equipment and software have been working hard to increase the quality of their products (Algelin, 2010; Knutsen et al., 2014). Reliability, robustness and ease of use have increased by leaps and bounds since the first introduction of CM and CBM equipment in the maritime sector in the 1980s.

T5. What requirements do class societies have for the use of CBM on ships?

Lloyd's Register (2016) provides extensive requirements to class-certified CBM systems used on board ships. Firstly, the rules assume that any ship receiving a CBM notation on its class certificate must also have a notation for a planned maintenance system. It furthermore only accepts methods that submit to specific ISO norms, as well as users to hold specific certification. These rules make specific reference to techniques such as oil analysis and vibration analysis.

The American Bureau of Shipping (ABS, 2016) provides recommendations for specific CBM techniques to be used. There are many of the well-known technical applications, including vibration monitoring, oil analysis, temperature monitoring, non-destructive testing methods and more. Of note is that ABS also describes how observation and surveillance techniques (i.e. visual, audio and touch inspections) can be an excellent method for condition monitoring when used as a supplement to other techniques. ABS also provides a list of machinery that is ineligible for the use of CBM:

- System Piping (All)
- Valves (All)
- Sea Chests
- All Operational Tests
- Fire Fighting Equipment
- All Safety Devices, Trips and Relief Valves
- Air Receivers with associated Relief Valves and Safety Devices
- Heat Exchangers and Unfired Pressure Vessels with design pressures over 6.9 bar (7 kgf/cm2 , 100 psi) and associated Relief Valves

Other classification societies do not provide specific recommendations of requirements for the use of CBM on board classed ships. In many cases, the use of CBM is defined as a possibility to be individually evaluated by the society.

3. Research method

The process for the choosing the best research method is described by Verhoeven (2004). Because the problem described is one that applies to most of the maritime sector, a scope of research that covers the entire maritime sector would be the most effective. However, there are no means for such an enormous study. Instead, a smaller subject is taken and studied directly in an attempt to find results that may be applied to the industry as a whole. This method is known as the case study. The case study entails that only a single subject will be studied in an attempt to find results that indicate conclusions that can be drawn broadly across the field of study. The subject in case is the LNG carrier Coral Energy. The study is expected to provide a general impression of the situation across the Anthony Veder fleet as well as in the maritime industry in general.

The conclusions resulting from the method are not expected to be universally applicable. Approaches to maintenance strategy differ from company to company. Cultural differences as well as differences in financial prosperity, availability of technology, and much more vary worldwide. The gas transport industry is also a very specialized branch. It stands to reason that circumstances on board the Coral Energy cannot apply to every ship in the world. Instead, the intention is to provide ideas which may be used to research a method that can be more broadly applied to increase the use of CBM in the industry in general. We are as such dealing with a qualitative exploratory case study.

Table 1 contains a matrix that describes the relationship between the chosen research methods and the subquestions. A more detailed discussion of the methods used per subquestion follows afterwards.

Table 1 - Subquestions and related methods

	Observation	Content Analysis	Interviews	Practical trials
E1. Current strategies	X	X	X	
E2. Occuring problems	X		X	
E3. Current attitude			X	
A1. Investments				X
A2. Improvements				X

E1. *What are the **current** maintenance **strategies** used on board the Coral Energy and to what extent is CBM already being used?*

The first step before any attempts at improvement can be made is establishing the current situation on board the ship. This is the natural beginning point for any practical research.

The primary method for obtaining data on the current situation on board the Coral Energy will be participatory observation. By participating in the work performed in the engine room and examining the maintenance process first hand, a clear impression will be obtained of the strategies that are used. Maintenance jobs carried out can be identified as fitting in a particular strategy. This way, it can be identified how each strategy is employed, and how often. A second method is the interviews, which also include questions on which type of maintenance strategies are most often used. Interviews with the ship's engineers will include questions on what is perceived as the most important maintenance method. See also the section on the subquestion regarding the crew's current attitude.

Lastly, content analysis of documents such as the maintenance information system, log books, ship-shore communications, etc. will provide information on the methods used, as well as the results obtained.

*E2. Which **problems occur** when employing the current maintenance strategy, and could they be solved by implementing CBM techniques?*

Having examined the current approach to maintenance, it is expected that problems will become apparent. The next step becomes to qualify these problems and identify whether the implementation of CBM could possibly provide a solution.

This information will also be obtained by means of participatory observation. They may also come forward in the interviews that are to be performed with the crew members. Content analysis of maintenance reports in log books will also be a valuable source of information in this regard. Problems might be faults that pop up repeatedly or unexpectedly, unanticipated failures, and patterns that may appear in the manner in which they are resolved.

*E3. What is the **current attitude** and position of the crew in regards to the implementation of CBM techniques?*

Having identified existing problems, and proposed possible solutions for them, the next step becomes evaluating whether there is a fertile ground for implementation. The optimal way of implementing CBM methods has been established in theory. The goal here is to establish whether the required maintenance culture is already present or could be readily achieved when implementing the proposed solutions.

Interviews will be conducted with the ship's engineers in order to establish their current experience with CBM, their views on the current maintenance procedures and how they might be improved, and to gauge their openness to a possible change in approach. Interviews will be conducted with as many engineers as possible; the Coral Energy has three engineers, each of which is periodically changed in the crew change process, ensuring at least six candidates of varying experience will be interviewed. The interviews will be half-structured: a list of questions is prepared, but the interest and input of the interviewee will lead the direction of the interview (Verhoeven, 2004). The following questions will be asked during the interview:

1. What different maintenance strategies are you familiar with?
2. Are you familiar with condition-based maintenance?
3. Of these strategies, which would you consider the most useful?
4. Do you think there could be any improvements made in the way maintenance is performed on the ship?
5. Do you know of any problems that are caused by the way maintenance is performed?
6. What do you think of the way ship-shore communication is currently handled in regards to maintenance?
7. If you could change the way how maintenance is performed on board, what changes would you make?
8. Do you think we could solve [maintenance problem] by [CBM method]?

The main lines of questioning are designed to explore specific factors. First, there is awareness: how aware is the respondent of his own actions in regards to maintenance strategy, and how aware is he of the possibility of applying and the existence of different strategies? Secondly, willingness: is the respondent willing to see and enact change, or is he opposed, and will he obstruct it? How does he feel about the way things are currently handled? Lastly, there are more practical questions, asking him which problems he identifies, and what solutions he sees.

A secondary purpose of the interview is to evaluate the usefulness of the proposed CBM solutions. It would be remiss not to make use of the considerable practical experience of seasoned engineers. Their opinion is of great value.

*A1. What **investments** are required to make further implementation of CM and CBM possible in terms of modifications, tools and training?*

Another prerequisite to the implementation of CBM solutions is to establish which investments must be made in terms of material, training and manpower to make implementation possible. The goal is to find the simplest and cheapest reliable method, that is the method that requires the smallest investment for the intended result.

The intent is to perform practical trials with condition monitoring techniques and to discuss maintenance decision-making based on the results. This is challenging, however. Condition monitoring equipment is often expensive, and the scope of this research does not immediately allow for the financial investment required to perform practical tests using such equipment. Actual methods that are to be tested will therefore have to be performed using ordinary tools, which drastically reduces the amount of methods that can be applied.

An evaluation will be made of how difficult the tested methods would be to implement, and what would be required. Methods that are surmised to be useful but cannot actually be tested due to the aforementioned constraints can still be evaluated according to investment cost criteria.

*A2. What **improvements** are possible as a result of (further) use of CBM?*

Unfortunately, given the short term of the research, operationalization of the proposed benefits is not possible. These become measurable over a period of several months if not years.

Instead, the possibility for improvement will be the result of the summation of all previous questions. The benefit of CBM has been proven in theory. The best way to implement the strategy has been discussed and the challenges and requirements are known. Interviews with the crew have established whether they will accept the change. The new methods have been judged by their benefits and costs, and may have even been tested.

If all the circumstances are positive, the implementation of the new method will be successful, and there will as such be an improvement.

Research Validity

In performing qualitative research validity is of great importance to ensure the research's reliability. Validity can be divided in internal validity and external validity, and pertains to whether that which the research aims to measure is actually measured. Validity constructs for this research project are based on those described by Verhoeven (2004).

Internal validity regards to the measure in which the results from empirical research can adequately be interpreted and whether these interpretations can be considered correct. One way in which to obtain validity is by employing triangulation: obtaining data from different sources each with their own perspective. In this research, triangulation is obtained by approaching the problem from both an academic angle through theoretical research, and from a practical angle by participating in actual day-to-day maintenance operations in the Coral Energy's engine room and . An additional source of internal validity is the supervisor, who regularly provides feedback and advice on the research process.

External validity refers to whether the results obtained from the research can be generalised to other environments and circumstances. As we are dealing with a case study, a lack of external validity is to be expected: the results obtained are only intended to apply to the case at hand, in this case the practical situation on board the Coral Energy. Instead, the goal of a case study is to generate a potential source of external validity for further research. Authors may refer to this project as an example to base more generalized findings on.

Similarly, the reliability of the research has to be proven. Reliability is dependent on the consistency and replicability of the research. It is safeguarded by consistent and defined use of terminology. Triangulation of data sources, in this case by the use of multiple methods of data acquisition, also guards internal reliability.

4. Results

The following section will discuss the results that came forward when answering the different subquestions.

Current situation on board the Coral Energy

The first part of the research focuses on the empirical questions that are intended to explore the current situation on board the Coral Energy. These are intended to find those problems that can be solved by the use of CBM, leading to an improvement in the state of maintenance.

E1. What are the current maintenance strategies used on board the Coral Energy and to what extent is CBM already being used?

This section will cover the main maintenance strategies that are employed in the Coral Energy's engine room. The goal is to determine what the predominant maintenance strategies are and how they are applied.

StarIPS

The Coral Energy's class machinery survey is based on the implementation of a class-approved planned maintenance system. This maintenance system is represented in a software suite called StarIPS. StarIPS not only includes a maintenance planner, but also serves as a repository for ship's data such as documents, inventory and the safety management system. Those functions will not be discussed here, as they are irrelevant to the study at hand.

For each piece of machinery on board the ship, StarIPS includes a list of periodic maintenance jobs. The periods are based on either running hours or calendar days. Examples of jobs in StarIPS range from a weekly test of the concentration of cooling water additives, to major 48.000 running hour main engine overhauls. Daily work planning is, for the most part, based on the jobs that appear on StarIPS. Of course, StarIPS does not account for all work done in the Coral Energy's engine room. Besides operational activities, unscheduled repair jobs and cleaning, other maintenance activities include daily rounds and several weekly inspections that are not listed in StarIPS. Still, for the vast majority of maintenance tasks, StarIPS is the source.

Whenever a job is completed in StarIPS, the responsible engineer files a job report. These reports include descriptions of the work performed as well as results of inspections and measurements. Job reports are filed in the job's history, which remains available for an indefinite time. Data from StarIPS is not only available from the ship's servers, but also synchronized with remote servers located at the company offices. This makes the data available to engineers, but also the superintendent and other shore-based personnel.

Many of the functions present in StarIPS go unused or are bypassed. This is chiefly due to the fact that StarIPS is designed for use on a far larger scale. The system provides infrastructure for complex maintenance operations, where jobs are distributed through work orders, with functions included for intermediate status updates, parts requisitions, responsibility management, etc. In an engine room which is manned by three or four engineers who are almost always able to communicate directly and orally, such extensive possibilities are simply not necessary for the chief engineer to maintain proper oversight.

While examining the different scheduled maintenance jobs listed in StarIPS, it became apparent that, contrary to expectation, most jobs were not TBM-based. In fact the vast majority of jobs listed were monitoring jobs, intended to assess the current state of maintenance, and judge whether actual maintenance was necessary. A selection of ship machinery was made, and a list created of all the jobs scheduled for that piece of machinery. The list is contained in table 2.

Table 2 - Machinery and associated maintenance tasks

Steering gear	Weekly, monthly, quarterly, yearly, two-yearly inspections and tests are performed to ensure good state of operation.
	Manufacturer-mandated leak oil test, an extensive test which measures the condition of the seals on the hydraulic actuator by measuring the amount of discharged oil under overpressure and time required for rudder actuation. Specific tolerances are set up to indicate when replacement of the seals becomes necessary.
	Yearly oil sample is collected from the hydraulic system and sent off for analysis. Maintenance may be performed based on report.
	The only scheduled maintenance is a yearly replacement of the solenoids, which was mandated by manufacturer's instruction following reports of low reliability on solenoids. Upon receipt of this instruction, new solenoids were dispatched and the old ones replaced. Now solenoids are scheduled to be replaced yearly.
Bowthruster	There are three yearly jobs: inspection of the coupling spider by means of feeler gauges; a check and test of the electric system; and an hydraulic oil sample to be sent off for analysis. Any maintenance is dependent on the results of tests and inspections.
Hoisting devices	Yearly and monthly inspections of hydraulic system, wires, etc.
	Yearly oil sample analysis.
	Yearly scheduled maintenance consists of replacing a single filter and retightening all bolts to specified torques.
Anchor and mooring winches	Regular operational inspections and lubrication by deck department are scheduled.
	Yearly oil sample is sent for analysis.
	Six-monthly maintenance routine involves mainly system condition checks and inspection/cleaning/replacement of oil filters.
	Hydraulic control systems inspected yearly to verify good condition of pump couplings and to check filters.
Lifesaving and fire equipment	'Weekly routine' consists almost entirely of checks and inspections to see whether maintenance is required. Actual maintenance is only carried out when deemed necessary.
	Several jobs with an interval of a month or more exist, but these jobs consist of more thorough checks and lubrication rather than planned maintenance.
Main engine	Planned inspections and maintenance of oil mist detector according to manufacturer's specifications (mostly verification of correct function and filter cleaning).
	Regular testing of alarm systems and proper working of sensors and transmitters.
	Annual crankshaft deflection measurement.
	Scheduled maintenance at:
	1000 hrs: check of engine fastening, replacement of pilot fuel and turbocharger air filters.
	2000 hrs: checks of control systems and overspeed trip device,

	leak test of gas system, visual inspection of valve rotators, yoke and valve clearances, oil change for governor, change oil mist detector air filter.
	4000 hrs: check of connectors and cables to switch- and control boxes, camshaft inspection, crankshaft alignment measurement, check waste gate valve and actuator, cleaning of charge air cooler, checking of main engine alignment.
	6000 hrs: inspection of fuel injectors, replacement of nozzles is described as optional, inspection of expansion bellows, supports of exhaust fucting, flexible pipe connections.
	8000 hrs: measurement of adjustment of pressure control valve.
	12000 hrs: grease secondary shaft of turning gear, clean air filter, renew flexible pipe connections only if deemed necessary, dismount and clean turbocharger, inspect and replace turbocharger bearings, general overhaul of waste gate valve and actuator.
	18000 hrs: complete change of injection valves, full maintenance/inspection of gas system, replace main gas admission valves (already performed well before engine reached 18000 running hours), overhaul of fuel injection pumps, oil sample from vibration damper to be sent for analysis.
	24000 hrs: oil change for turning gear, operational condition of hydraulic jacks, general overhaul and test of ME governor and actuator to be performed by service engineer, general overhaul of booster servomotor to be performed by service engineer, measurement of thrust bearing clearance, inspection of camshaft driving gear, inspection of big end bearings, inspection and honing of cylinder liners, visual inspection of governor driving gear, drawing of all pistons and measurement of clearances, renewal of piston rings, check of piston cooling gallery, dismantling of valve rotators for cleaning and inspection, inspection of small end bearing and piston pin, check tightening of engine fastening bolts, inspection of one (1) main bearing, replacement of vibration dampers in control cabinets, changing of expansion bellows when found necessary, inspection of turbocharger and overhaul by service engineer, overhaul of cylinder heads, inspection/overhaul of attached pumps, overhaul of starting valves, replacement of pilot fuel pump.
	36000 hrs: change crankshaft seal, change injection pump elements, inspection of camshaft bearings, overhaul of starting air distributor, replacement of small end bearings, changing of intermediate gear thrust bearings and bearings, dismantling of vibration dampers and dispatch to manufacturer for complete overhaul, replace charge air cooler if deemed necessary.
	48000 hrs: Replacement of flywheel bearings, replacement of thrust bearings, cleaning of cylinder cooling water channels, check of bearing clearance in tappets and rocker arms, change valve rotators and guides, change governor drive bearings, replace big end bearings, replace main bearings, change fuel pump tapper roller pins and control sleeves, change exhaust pipe support plates, change expansion bellows (TC air inlet), change control mechanism bearing bushes and ball yokes, replace turbocharger rotor, replace inlet and exhaust valves and valve seats.

For every job listed in table 2 there is an underlying reason why it was included in the maintenance system. The vast majority is based on either SOLAS (Safety of Lives at Sea, see glossary) requirements (such as weekly tests of the emergency generator and lifeboat engines) or maintenance instructions obtained from the manufacturer. Additional jobs can be added according to instruction in service letters obtained from the manufacturer. They can be also added at the chief engineer or superintendent's discretion, but this is very rare (and, especially in case of the chief engineer, more often accomplished by oral instruction).

The planned maintenance system or PMS takes an important place in the Coral Energy's overall maintenance strategy. Nominally a PMS employs TBM, but this aspect of the PMS appears poorly realized. The majority of jobs is based in monitoring, where the results of a periodic inspection are logged for future reference. If any faults or failures are detected, repairs can be carried out, but this is mostly a reactive process and resembles failure-based maintenance more closely than it does CBM in the diagnostic sense. Diagnostics in CBM would involve a proactive and constant method of monitoring where a fault is detected as soon as it occurs and is resolved before it can compound in a failure. In this case, however, the monitoring is only done intermittently and at the prompting of the PMS.

What is apparent is that the data obtained from the different jobs could probably be used for various methods of data analysis. In fact, we are looking at the first step of a proper CBM process. The second step, data analysis, which would lead to a third step (maintenance decision-making), is not being taken for the most part. Exceptions to this exist, such as in the case of oil sample analysis, where the sample is sent to the lab for analysis, which returns a report providing advice on what maintenance activities should be performed as a result.

Condition monitoring equipment

As mentioned, many jobs in the PMS are based on equipment monitoring. Data acquisition for these jobs is performed using indicators, such as thermometers, manometers or level gauges. Oil sample analysis is also occasionally employed. Far more common, however, is the use of observation techniques to determine the current state of wear on a system or component. The choice for the latter is not made out of preference, but due to the fact that an objective means of data acquisition (such as a temperature or pressure measurement) is not present.

The absence of objective data acquisition equipment is often a matter of material or practical constraints. For example, when determining whether cleaning an oil filter is necessary, the decision is often based on a differential pressure measurement. In several applications a gauge for this measurement is not available, making an observation of the filter element the defining criterion. It should be noted that while the interval for such an inspection is planned, the decision to clean it (even when it is most often made to the affirmative) is not. We are not technically dealing, therefore, with TBM. A TBM approach would mandate the changing of the filter no matter its condition, while the current system allows for the decision to be made not to change it. There are also examples in which condition assessment is outsourced to the original manufacturer. The manufacturer is then responsible for performing all steps of the maintenance process. However, due to the infrequent and irregular nature of these measurements, they can hardly be considered an actual proactive form of CBM.

In addition to the jobs prescribed under StarIPS, various monitoring systems are in place on much of the engine room machinery. Alarm systems and monitoring systems provide early and timely warning of faults and failures. These systems are controlled electronically, and serve to notify the engineer of any abnormal condition.

The engines (main engine and two auxiliary engines) are fitted with extensive electronic condition monitoring systems. Electronic measurements of a plethora of parameters are relayed to a computer system located in the engine control room. The data is constantly recorded, making it possible to review graphical representations of many operating parameters over the course of a chosen period. Data remains available from the first delivery of the ship. This makes it possible to compare current operational parameters to those of the past. This is a far more extensive means of data acquisition and processing than is the standard, which is recording measurements in the log book at a handful of specific times during the day, and the system can therefore be considered as a 'true' CM system, as opposed to the periodic monitoring activities that have been described before. The system does not, however, have an actual role in the long-term maintenance strategy. Its use is mostly relegated to a tool for post-mortem analysis of the causes of failures and other problems. No data analysis is performed on the information obtained. While it is sometimes recognized as a tool that can be used for early detection of impending failures, it is definitely not used for making proactive maintenance decisions in that regard.

In terms of maintenance strategy, the automated alarm system can be described as fitting in two separate approaches. The first is viewing the alarm system as a rudimentary condition monitoring system. Many alarms trigger on conditions that may indicate a fault or an impending fault. For example, a spike in combustion temperature on a single cylinder as an engine's load is increased does not necessarily mean that the engine has failed and must be stopped. It might however indicate a problem with the fuel injector on that cylinder, which can be classified as a fault, and would necessitate maintenance. Ignoring the fault on the long term may lead to extensive thermic stress on or burning of the components inside the combustion chamber.

On the other hand, automated alarm systems often are little more than a trigger condition for failure-based maintenance. The distinction is simply determined by the complexity of the alarm instrumentation. Less critical equipment is equipped with fewer alarms. As such, when these devices do generate an alarm, the alarm is often designed only to indicate total failure rather than a partial fault. The alarm becomes simply the trigger condition for a failure-based maintenance action.

Failure-based maintenance and redundancy

Finally, a remark should be made on the principal choice for failure-based maintenance. This method is most commonly seen used in electric motors and pumps. While lubrication is performed periodically, no other maintenance is performed. It is therefore likely that any failure will be unexpected. The risks involved with an unexpected failure are mitigated, however, by implementation of redundancy. Simply put, whenever a pump fails, there is always a second pump available on stand-by to take over the first pump's function. Especially when repair or replacement is not a particularly time-consuming job, this strategy is employed to success.

There are, however, two schools of thought on how it should be employed. These involve the pattern in which the redundant components are 'switched out', deciding which component is used how often. The first school of thought argues that the running times of each pump should be kept as close to each other as possible, meaning that use of either redundant component is constantly altered. This maximizes the amount of time the components will be running until a failure occurs. For example, if the lifetime of a pump is 10,000 hours, this method will ensure 20,000 operational hours without failure.

The second school of thought argues that this method is actually very risky. It instead advises a single redundant component is only used until it fails, after which the second component comes into use. This method takes stock in the assumption that both components have an equal lifetime. Each will fail at the end of its lifetime, and the first method ensures they will reach the end of their lifetime almost simultaneously. Simultaneous failure of both redundant components is therefore more likely (the second component may fail while the first one is still being repaired, for example), resulting in a total system failure, which is potentially extremely problematic. Of the two chief engineers serving on board the ship during this research project, each argued a different one of the two schools of thought described here.

Given the fact that it has been established that the lifetime of many rotating components cannot be predicted accurately and is not expected to be equal even for two identical components (Allen, 2001; Knutsen et al., 2014), the basis for the second school of thought is invalid. Especially when machines are operated for similar amounts of time but different loads, it is impossible to predict accurately when they will fail. There is no significant added risk involved in attempting to maximize usage before a failure, as described in the first method.

The implementation of redundancy is not always used as a system that supports the use of failure-based maintenance. It is certainly used that way with pumps and compressors. On the other hand, redundancy is also provided by the use of multiple auxiliary engines and the emergency generator when it comes to generating electricity. Another example is the availability of the PTH or Power-To-Home system. This system reverses the polarity of the shaft generator, turning it into a motor rather than a generator. This allows it to provide power for the ship's propulsion, albeit at only about half the main engine's power rating. This system therefore provides a certain degree of redundancy for the ship's main engine.

In summary, it becomes clear that, even though the ship has been classed with a planned maintenance system, TBM is certainly not the defining maintenance method when assessing the Coral Energy's maintenance strategy. TBM is mainly reserved for the ship's engines, and then for major overhauls only. For the rest of the maintenance program, there is a jumble of different elements rather than a clear vision. Failure-based maintenance occurs most often. Condition monitoring is performed, but usually not consistently or proactively. Large amounts of data are gathered constantly, but these are often filed and forgotten if an anomaly is not immediately apparent. As a result, the overall maintenance program remains mostly reactive.

E2. Which problems occur when employing the current maintenance strategy, and could they be solved by implementing CBM techniques?

The Coral Energy was delivered in 2012. It has been in service for only a few years, and has yet to receive its first dock survey. Very few persistent maintenance problems have had time to develop so far. There have, however, been a few.

TBM and limited lifetime

One identified problem is inherent to the use of TBM strategies. There are a few examples in which the proposed maintenance interval has been established too liberally. Failures occurred in several components prior to what had been established as the end of their lifetime, meaning that the interval chosen was too large. For example, at about 10,000 running hours, the main engine's fuel pump tappet springs were found to be worn out on the majority of the eight fuel pumps. All fuel pumps were dismounted, and the springs replaced. The planned maintenance schedule for the main engine, however, includes an overhaul interval for the fuel pumps at 18,000 running hours. As such, the springs had only achieved just over half of their proposed lifetime. The replacement was a significant time investment, but the springs were in stock and could be replaced. Luckily, the fuel pumps on the main engine are a backup for the common rail injection system, so the defect did not cause a total failure. The repair could be postponed until the next best opportunity.

The same happened with the main engine's solenoid operated gas admission valves, or SOGAVs. Combustion temperatures were found to fluctuate rapidly, which was caused by variations in the amount of fuel admitted. Upon dismounting the SOGAVs (which are electronically controlled to admit the correct dosage of fuel gases), it was found that the majority was very worn, with heavy corrosion on the magnetic contact surfaces and the springs inside worn out. Eventually, the full range of valves was replaced around 11,000 running hours, well before the planned maintenance interval at 18,000 hours. The exact same problem later occurred with the SOGAVs on the auxiliary engines. As the gas valves are precision-engineered electromechanical parts, an overhaul of the valves was not possible – each valve had to be replaced completely. These problems resulted in reduced availability of the engines and a significant financial investment in the replacement parts and labor.

In the current situation, due to Anthony Veder's spare parts stock policy, expensive spare parts are not kept in stock. As such, when reacting to the emergence of a fault, they are only ordered once the fault occurs. Extended delivery time means that the ship is forced to operate with the existing fault for several weeks. This may lead to problems, such as the fault compounding, leading to a failure. The result is costly delays and potential safety problems.

The problem is therefore that where TBM is applied, it is not applied effectively due to the fact that the chosen maintenance intervals are too long. The proposed solution to this problem is to adopt an altered decision-making structure for the replacement of the mentioned parts. The three-step CBM approach is suggested. In the data acquisition step, the electronic condition monitoring system automatically acquires measurements of the relevant operational parameters. The data processing step has the engineer observing the readouts from the CM system, and has him establishing whether the part is showing signs of wearing out (which, for example, with the SOGAVs, can be seen by seeing that combustion temperatures begin to fluctuate). The relevant decision-making step then becomes the decision to order new parts. Once in stock, they are kept ready to be replaced at the next opportune moment once a fault occurs.

Data acquisition and processing

When obtaining data to be used in maintenance decision-making, the data obtained must be of sufficient quality. Quality data must submit to three demands: it must be accurate, obtained in a timely fashion and it must be relevant (Wubben, 2016).

Problems with the quality of data obtained have been established. Another problem is that processing of the data is rarely performed, making the data acquisition mostly a futile gesture. As mentioned before, physical observation using human sensors is a commonly used method for data acquisition. This method, however, cannot be relied upon, as the data obtained is of insufficient quality.

To clarify what is meant by this, let us take an example: an air compressor is, for some reason, generating large amounts of condensate water. The amount of condensate is usually checked daily by an engineer, when he manually drains the air vessel of condensate. However, to determine whether there is an unusual amount of condensate, he does not use any objective measurements. There is no daily collection of condensate in a measuring cup, the amount of condensate written on a record, which can be referred to in order to spot a trend. Instead, the engineer sees (or in some cases cannot even see and has to judge by hearing and feeling) how much condensate goes into the drain, and judges himself whether or not it ‘seems like a lot’.

The described method of data acquisition and processing has problems compared to a method using objective measurements. The first problem is in the accuracy of the data obtained. The engineer responsible for making the measurements cannot provide accurate data on the measurements he performs: they are based on his subjective perception of the situation. That does not mean the data is by definition inaccurate. The accuracy of the engineer’s perception may be backed up by his own experience or that of his superiors if he chooses to relegate to them. Even the chief engineer, if unsure, can refer to external experts. When these backups are unavailable or go unused, however, the data’s accuracy is at significant risk.

When an objective means of measurement is used (manometers, thermometers, etc.), the accuracy of the data is much more reliable. In this case, the data’s accuracy is dependent on the quality of the measurement equipment and how well it is used. Assuming the measurement equipment is correctly calibrated, the data obtained can be considered accurate.

When discussing the timely acquisition of data we must look at inspection intervals. Many inspections are performed on a periodic basis depending on a certain amount of time having passed, usually a week or a month. If an inspection is performed and a fault emerges shortly after that inspection, it will be an entire inspection period before it goes detected, unless problems arise during use.

There is no easy way around this problem. One way is to increase the frequency of inspections, which will put a considerable burden on man hours. Another way is to incorporate continuous monitoring systems, which requires a considerable investment. An indirect way to avoid untimely collection of data is to apply prognostics. The predictive nature of the information obtained through this method means that it is by definition obtained in a timely fashion.

The relevance of data obtained is mostly determined by whether or not it can be used to any reasonable benefit in the maintenance process. There are problems with the relevance of data logged in the PMS maintenance report. A commonly heard complaint is that job reports often contain very little relevant data and information. A simple report containing the words 'job done, no remarks' might cover the factual circumstances, but provide absolutely no information on the current state of maintenance or results from the inspections performed. The underlying idea to this type of report appears to be something along the lines of 'there weren't any problems right now, so I'm not going to bother writing down all this data which is in nominal range anyway'. In short, it is little more than a checkmark to indicate the inspection was performed, rather than sharing and logging the results of said inspection, keeping them available for future reference. The job report might also provide a subjective assessment of the state of a component. For example, one report might state that a component looks 'a bit worn' while the report from the next inspection might say that the component is 'slightly worn'. How can the reader determine anything from these two reports? Is the situation the same? Is it worse? How gradually is it changing? These are questions that are pertinent if any form of trend is to be spotted, but they usually go unanswered. The problem here is therefore not so much that the data obtained is irrelevant, but rather that the relevant data which is available remains unregistered.

Having established that the data obtained in the maintenance process is of poor quality for various reasons, a second problem emerges. Due to the fact that quality data is unavailable, the second step towards a more effective maintenance system cannot be made. This second step, the data processing step, should eventually lead to maintenance decision-making, but it is not possible to perform data processing without quality data.

This is not the only problem, however. In the current situation lots of data obtained is of sufficient quality, but rarely referred to unless there is an immediate cause to do so (such as a fault occurring). This means that the data is only used as a reference for hindsight when performing failure-based maintenance. Using it for a proactive type of maintenance, such as prognostics in CBM, is definitely possible.

The solution to this problem must therefore be twofold. Firstly, to maximize the quality of data obtained by safeguarding those three factors which make it useful: accuracy, timeliness and relevance. Secondly, to proactively process data and transit into maintenance decision making. This would allow the maintenance strategy to incorporate the CBM process directly.

E3. What is the current attitude and position of the crew in regards to the implementation of CBM techniques?

In order to obtain an answer to this question interviews were performed with each of six different engineers working on the Coral Energy. Due to the semi-structured nature of the interview, responses to the questions varied in nature, and the interview took several different turns. Information from the interview was also used in determining the existence of maintenance problems as in the previous section. The following elements are highlighted: awareness and willingness.

Awareness

The first conclusion obtained from the interview is that the general opinion among the engineers is that the maintenance system is not as good as it could be. Most arguments revolve around the usefulness of StarIPS. While the system's potential uses are clear, it is often remarked that the system is not being used properly. One of the proposed functions is the proper recording and processing of data obtained from inspections. Currently, data is recorded, but not processed or analysed. One opinion is that while the company has access to the entire database, external specialists never review the data or provide advice on the relevant information unless directly prompted. Another complaint about StarIPS is the relative complexity of its use. Engineers do not all undergo special training to learn the proper use of StarIPS, making it difficult for them to utilize it to full potential. The complexity is also a barrier to use. In reference to maintenance record systems, one engineer stated: "The easier it is to use, the more people will use it."

General awareness of the theory behind the application of CBM was considered poor. Most engineers had never even heard of the term. Those that did, did not seem well versed in the correct way to execute it. Upon more clearly explaining the subject to them, however, it was not difficult for them to draw parallels between the idea of CBM and the potential for actual maintenance practices on the Coral Energy. One respondent declared that he preferred TBM as a strategy in which someone simply does not want to suffer the risk of unexpected failure. The statement was based on an assumption that CBM was unreliable due to the fact that condition monitoring systems could miss an imminent failure.

Willingness

The use of CBM as a solution to the proposed problems was well received, and in fact not considered a new idea. The constant improvement of reports and data logged in StarIPS was already considered a goal. The engineers were disillusioned about the prospect of receiving external data processing services. Currently, such activities are only performed upon direct prompting, and even then are problematic in execution.

One example of such problems is approaching the engine manufacturer. Their online inquiry service is available, but extremely cumbersome in use due to the extremely low internet speeds on board the ship. Furthermore, it does not allow the user to upload images (such as pictures of components or screenshots of trend lines). The chief engineer instead resorts to approaching the manufacturer through e-mail, which often means a slow response and repeated requests from the manufacturer for the engineer to use the online service. This puts a large amount of strain on the communication lines. Often it may take several weeks of back and forth and waiting for replies before a suitable answer is received to a particular question.

Several barriers to the implementation of new CBM solutions were identified. First, the communications problem described above. Outsourcing of data processing is necessary, as ship's personnel is not trained to do this job. Currently, however, there is insufficient capacity for all data to be processed by existing personnel, and reliable and speedy communication is not possible.

The second barrier is the spare parts policy. Anthony Veder employs a 'zero-spare' policy, which means that spare parts stock is kept as small as possible. However, because supply times are generally quite long due to the nature of the business, the result is often an immediate shortage when parts are needed, meaning that the ship has to operate for weeks if not months before a replacement part is supplied. When the failure in question has a direct impact on the main operation of the ship, a solution can often quickly be supplied. When the results of the failure are not quite as immediate, however, supply is often postponed to the long term. The periodic inspections performed at the prompting of the PMS may indicate that a maintenance operation is necessary, but if supply of spare parts from that time takes a few weeks, the replacement part may simply arrive too late. This means that either supply times will have to be drastically reduced (increasing delivery costs), or that the only option becomes the use of prognostics, allowing the necessity for a spare part to become known some time in advance.

Another problem is what is perceived by the engineers as a lack of the company's willingness to invest in improvements. Investment in more costly CM systems is considered unlikely now that the ship is in service. So no overhauls, no retrofits, no expensive new systems. Such systems might be implemented on new ships coming into service as new build or refits, but not on ships in service. Instead, implementation of CBM would have to be of proven benefit before any significant costs can be invested. A small investment will probably be supported by the company. Perhaps over a longer period in which these applications can be proven to be of merit the step can be made to invest in more extensive systems.

The human factor is also important. One engineer described the likelihood of any new system being successfully implemented as dependent on three factors: ease of use, usefulness, and financial reward. Simply put, anyone using a new CBM system would need to be trained to use it properly. This way, the system becomes usable and its usefulness becomes apparent. A financial reward is at the discretion of the company.

In summary, it becomes clear that the crew is generally open to the implementation of improvements to the maintenance system, as the problems with current strategies are apparent to everyone. Of key importance is properly informing the crew of what any improvements entail, why they are improvements and not merely changes for the sake of change, and ensuring that the improvements can be witnessed to be successful. These prerequisites conform to what the literature describes as the proper way to implement the changes. It can be concluded that the implementation of new CBM solutions would most likely be well-received.

Requirements

For the purpose of determining the requirements and application of solutions to the problems that have been identified, two practical applications will be discussed. Additionally, there will be the discussion of ideas for further solutions that have not been tested in practice, but may still provide useful.

The first practical test was performed with the condition assessment of the main engine's foundation. The foundation is constructed of a series of rubber chocks that are placed between the main engine and the ship's hull. Together with the flexible coupling between the crankshaft and the gearbox, this application reduces vibrations transmitted between the main engine and the rest of the ship. Due to the flexible nature of the connection, however, the correct alignment between the main engine and the drive shaft is an issue.

The second practical test was performed with direct evaluation of the performance of the SOGAVs on the auxiliary engines. As mentioned earlier, the SOGAVs on both the main engine and the auxiliary engines were found not to reach their full lifetime. The use of the computerized CM system connected to the auxiliary engines allows for a very clear comparison between the functioning of both engines, and makes it possible to correctly predict when a SOGAV is about to fail.

The research in this section focuses on the requirements for the implementation of these and potentially other solutions. What these requirements are and what the potential gains to be had are will be made clear.

A1. What investments are required to make further implementation of CM and CBM possible in terms of modifications, tools and training?

The goal for the implementation of CBM solutions is to solve the existing problems with the maintenance system. Therefore, any new implementation should directly relate to these problems. Broadly speaking, the possibilities for improvement vary wildly in scope. ABS (2016) provides a long list of CBM methods, many of which can be used, but most of which can be dismissed as practical out of hand.

The primary factor is financial cost. As discussed, low-cost solutions should be preferred over high-cost solutions, as the company is unlikely to be willing to invest in the latter. Therefore CM solutions such as vibration analysis, ultrasonic analysis, radiography, and other methods which require investment in expensive equipment and special training are not considered a viable option.

The computerized CM system for the engines, however, is certainly not being utilized to its full extent. A wealth of data is automatically obtained and available to be used in trend analysis. Instead it just sits there, mostly unused and occasionally referred to as a means of diagnosing the cause of a fault.

The reason this data is not correctly being processed is because ship's personnel lacks the training and prompting to do so. Engineers are simply not trained to perform data analysis to an extent that it can translate into maintenance decision making. A goal should be to increase engineers' understanding of the data processing and decision making process, so that it can be more effectively performed by themselves. Another possible solution is to outsource data processing and maintenance decision making. This would require investing in more reliable lines of communication with the various experts that would be responsible for processing the data. The company could hire a data analyst responsible for processing the data which is obtained and logged in StarIPS, for example.

Main engine foundation

In the first practical example, this last process is the method of choice. Appendix 1 contains a service letter from the engine manufacturer containing instructions for the six-monthly condition assessment of the main engine foundation. The letter clearly describes that the rubber elements need to be checked for deterioration due to contact with cooling water and oil. It also describes that the material has a natural amount of creep, causing the elements to deform over time, which is of negative consequence to the engine's drive shaft alignment.

Included are instructions for measurements to determine the amount of creep. These measurements are made by determining the distance between the engine block and the foundation brackets. The longitudinal, transverse and vertical distance between the engine and the foundation is thereby determined. Comparing the results of the measurements from those obtained at delivery, the amount of creep in the foundation and the resulting shift in the engine's alignment can be determined.

Unfortunately, the proposed measurements have never been made. The reason why is unclear, but appears to be simple negligence. There is no record of a conscious decision to forego the measurements. Either way, there is a three year gap in the data. Furthermore, while the original measurement report from delivery is available, the measurement points that were used and marked at the initial alignment have been painted over and are gone. It is impossible to determine exactly at which points the original measurements were made.

In the current situation alignment measurements are performed by an external expert with the use of laser shaft alignment tools. A report of one such operation is contained in appendix 2. It includes photographs of the measurement setup used, and concludes with a recommendation to realign the main engine. The realignment process is detailed in the service letter (appendix 1).

Rather than having to hire an external expert to perform the measurements, the measurements could be performed by the crew themselves. It was found that the alignment measurements described in the service letter were easy to perform using conventional tools, namely an inside calliper and a metric calliper. Concise instructions for the method were drawn up, intended to make it possible for anyone to perform the measurements and draw up a report. These can be seen in appendix 3.

The problem, however, was processing the data and comparing it to previously obtained measurements. There was, in fact, only one set of measurements: the measurements provided at delivery. Because it was unknown at what physical points these measurements had been taken, it became impossible to verify that the new measurements had been taken correctly. The manufacturer was contacted to provide insight, but they too did not know how the original measurements had been made.

Instead, an alternative solution was proposed. First, the alignment would be performed using the laser alignment tools, which do not require a previous frame of reference to provide an accurate measurement. Afterwards, new baseline measurements are obtained using the newly established measurement method contained in the instructions in appendix 3. These will form the basis for future reference to shifts in the main engine's alignment. The last necessary step is to make it possible for the crew to perform the main engine alignment independently. This will mainly require the purchase of new tools (the shims and hydraulic jacks described in appendix 1). The company has already invested in the shims, as these are required to be in stock for the expert to do his work. The jacks are not available, as the expert would supply these himself. An instruction given to the chief engineer by an external expert is also required. This could be accomplished when the alignment is performed the first time.

SOGAV performance and replacement

The second practical example tested was utilizing the computerized CM system for the engines to determine when it becomes necessary to replace the SOGAVs. The process involved is very simple. Refer to figure 1.

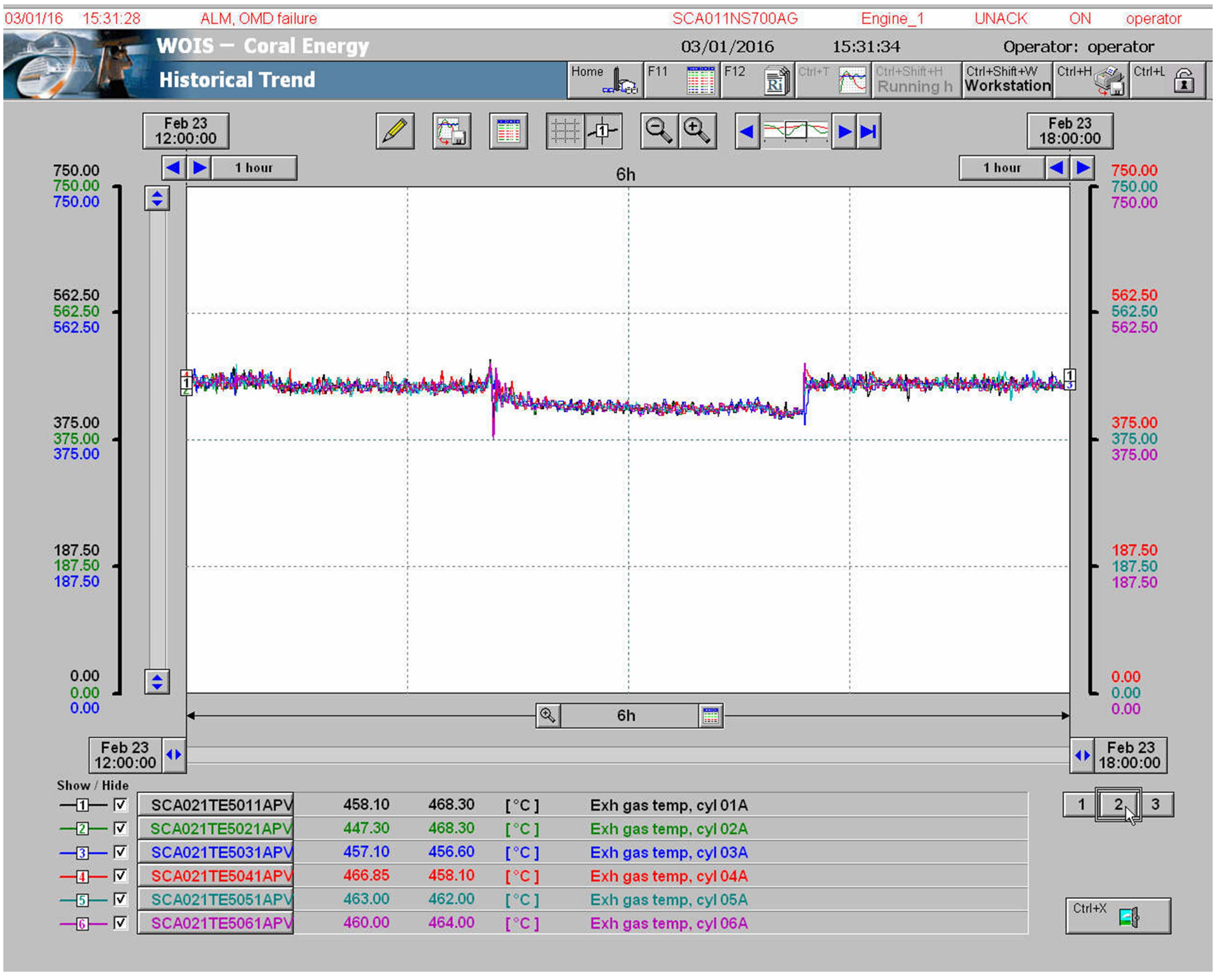

Figure 3 – Exhaust gas temperatures per cylinder, all SOGAVs in good state

In figure 1, we see a graphical representation of the exhaust gas temperature per cylinder on auxiliary engine #1 over a period of six hours. The engine is running in gas mode. As can be seen, the exhaust gas temperatures fluctuate slightly over time, an average of about 30 to 50 degrees C. The major shifts, occurring at the first and second third of the period are caused by changes in engine load, because auxiliary engine #2 is also running during that time.

In figure 2, we see the same graph over the same time period, but for auxiliary engine #2.

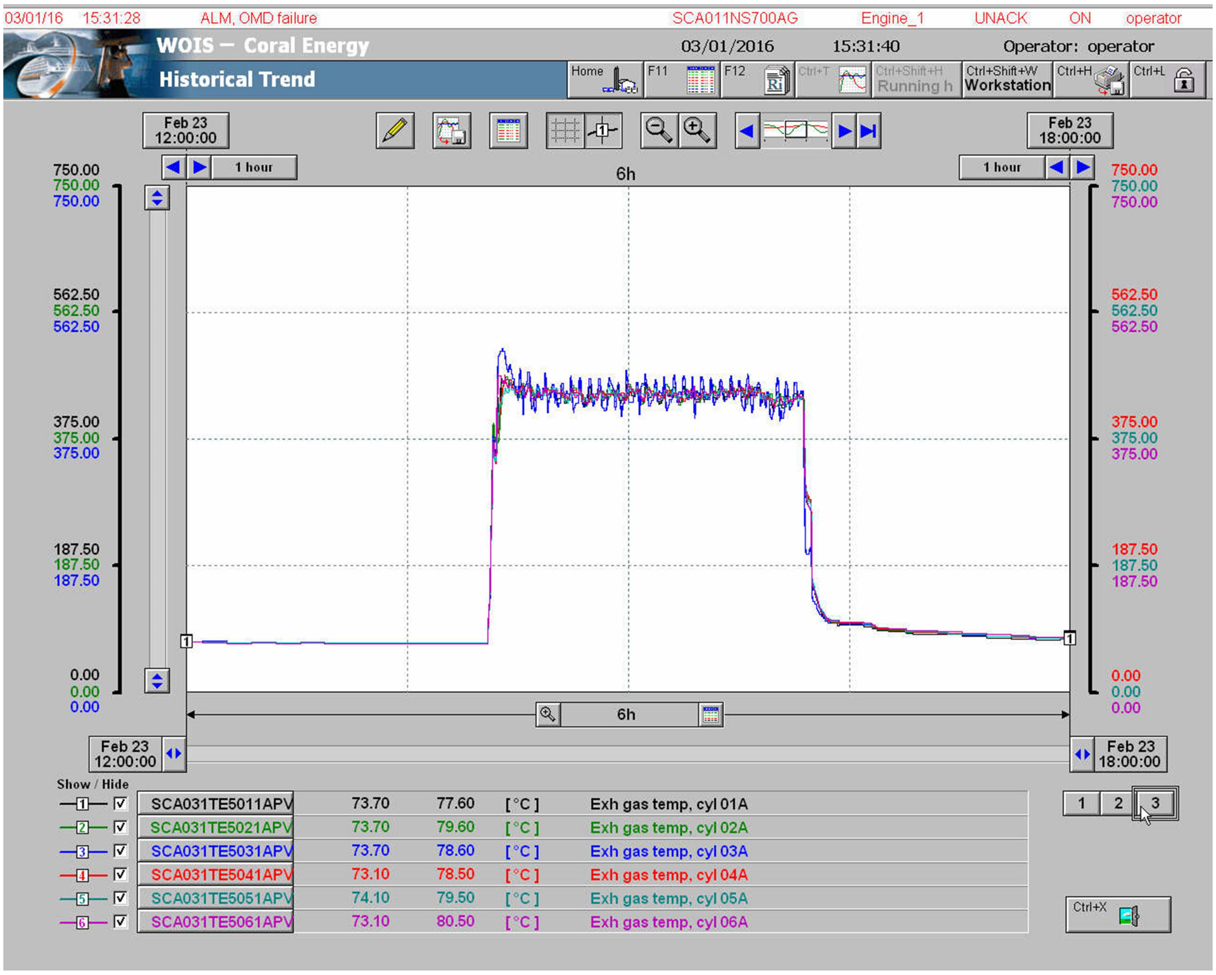

Figure 4 – Exhaust gas temperatures per cylinder, SOGAV #3 close to failure

The engine here, too, is running in gas mode. As can clearly be seen, the dark blue line, which represents the exhaust gas temperature at cylinder #3, fluctuates far more widely than the other lines. It was later determined that the SOGAV on that cylinder was not functioning properly. The springs that were responsible for closing the valve when the solenoid was not energized had severely worn out. This meant that the valve did not close quickly enough. The result was a delayed response to the electronic signal from the controller, resulting in an increased proportional gain, and thereby a less stable regulation. The large temperature differential would at times trigger a gas trip, resulting in the system automatically switching the engine over to diesel mode.

The data above was obtained in hindsight, when it became clear that the SOGAV was malfunctioning. At this time, gas trips were common, and caused by an exhaust gas temperature deviation on cylinder 3. Dismantling the SOGAV revealed that the valve springs were worn out, and the magnetic contact surface for the solenoid was heavily eroded. Examining the data as it became available could have provided early indication of the impending failure, making it possible to order the required spare parts well in advance.

Utilizing the data for prognostic purposes is relatively simple. No further material investments are required, as the system exists, and is easy to use. More important however, becomes training engineers in recognizing the signs of an impending failure. While this knowledge can be obtained through experience, sharing that knowledge is also an option. There must also be a clear incentive to regularly observe and analyse the data. Obtaining readings from regular performance tests could be an option, and would only require adding an extra job in the PMS.

In summary, it becomes clear that the proposed investments for CBM solutions are intended to be of low impact when it comes to materials. The purchasing of expensive monitoring systems and tools should not be the goal. Instead, the focus should be on training the crew in becoming autonomous in performing the CBM process, and to incentivize the proper performance of that process.

A2. What improvements are expected as a result of (further) use of CBM?

We have established two major problems that can hopefully be tackled by the use of CBM. We have also established that the way in which CBM is used in the current maintenance system can be improved upon. Lastly, we have examined two practical examples and identified what investments would be necessary to implement them. Beginning with the practical examples, we can easily predict what the benefit of their use would be.

For the purposes of determining whether there are improvements, we will specifically focus on two aspects: effectiveness and efficiency. How these are measured for CBM systems has been explained previously (Gits, 1992).

The performance of alignment measurements and the use of those measurements for autonomous main engine alignment can be accomplished by an investment in the required tools. The largest cost is contained in the hydraulic jacks that are required to support the engine while the foundation elements are adjusted. Training this operation is done by participating the next time it is performed by the external expert.

The effectiveness of this type of maintenance has been confirmed by the manufacturer (see appendix 1, their service letter). The measurements, as performed, are sufficient to determine whether alignment is necessary. The effectiveness is mainly dependent on proper communication with the manufacturer and their feedback on the measurements obtained, allowing them to indicate whether adjustments are necessary. As determined by Gits (1992), CBM is effective when there is a measurable prognostic characteristic. In this case, it is the alignment of the main engine, which is measurable in the method described. The 'good-as-new' value would be the original measurements obtained from a proper alignment of the main engine, while the critical value is determined as the limit at which poor alignment starts generating problems, such as vibration, uneven pressure distribution on shaft bearings, etc. This limit has to be established by the manufacturer.

Efficiency is mostly determined by a reduction in costs. A very loose estimate for a return on this investment can be made. The costs are the purchase value of the tools. The manufacturer recommends a yearly alignment session performed by the expert. These are the savings. The actual financial figures could not be obtained, but the estimated costs for dispatching a specialist for one day are estimated at about 1000-1500 euros, where the hydraulic jacks are liberally estimated to set the buyer back 1000 euros at most. This puts the return on investment at approximately one year, starting from the next time an alignment is performed, with a yearly savings of 1000 euros.

The effectiveness of using the computerized CM system for prognostics will provide early warning of impending engine faults and failures. Preventing these from occurring may result in prevention of unexpected engine failure which could potentially result in delays or even accidents (such as collisions and groundings). The benefits are therefore smoother operation and greater navigational safety. In the case of SOGAV performance, the prognostic characteristic is the variance in exhaust temperatures. The ‘good-as-new’ value can be obtained from a reference to values at initial placement, while the critical value is obtained from reference to the state at previous failure.

The measure provides efficiency in comparison to the TBM approach for two reasons. The first is that a spare parts requisition can be sent once the failure is expected, not when it occurs. This gives a significant amount of notice allowing the parts to be delivered in a timely fashion, giving the opportunity for maintenance before a failure occurs. Secondly, by preventing failures from actually occurring rather than reacting to them, the ship’s operation runs more smoothly without unexpected delays, which can be extremely costly, and without failures of main propulsion and electric systems, which can have potentially catastrophic consequences.

By investing in crew training it is also expected that the awareness of the maintenance process and therefore the quality of work will increase. A common maxim in education is that it’s not only important to get a result, but also to understand why and how the result is obtained. In increasing awareness of the maintenance strategy that is used, it can change from seeming like an office-mandated set of procedures, and actually becoming an integral part of the engineer’s day-to-day mindset. This will be a boon to the quality of his work.

5. Discussion

The validity and reliability of the research were intended to be safeguarded by approaches described in the research method. For the most part, it appears sufficiently safeguarded. The results of practical tests are replicable. Multiple sources of information have been consulted. Still, there are a number of interesting conclusions that pose additional questions.

One conclusion is that while the ship nominally employs a TBM strategy in the form of its type-approved planned maintenance system, the TBM strategy is poorly developed and limits itself mostly to main propulsion and generator machinery. The Coral Energy's maintenance strategy appears poorly developed and mostly reactive.

The internal validity of the research is mostly warranted by the fact that the conclusions compare the external view of academics to the working practice on board the ship. However, the fact that there is a dissonance between the two is worrisome. It implies that at least one of the two views is incorrect.

According to the criteria held by Algelin (2010) and Knutsen et al. (2014), the Coral Energy is a ship that chiefly utilizes TBM. That is to say, the Coral Energy's class certificate has a PMS notation: a type-approved planned maintenance system, namely StarIPS, is employed. However, results obtained on board the Coral Energy clearly indicate that TBM is not the dominant strategy. It certainly is when we look at the class certificate, but the class certificate mostly concerns itself with the main propulsion machinery. Peripheral systems are maintained differently.

Immediately concluding that the literature is incorrect is a step too far, however. The external validity of the research is in no way justified by the chosen method. The results can therefore not be generalised, and thus not serve as a basis for discounting, for example, the conclusions presented by Algelin (2010) and Knutsen et al. (2014).

The question that remains to be answered then, is whether the results of this case study can be generalized. If so, what appears to be a lack of effectiveness of a TBM strategy may simply be the fact that its use is poorly developed. Indeed, if we look back at the distribution of failure rates described by Knutsen et al. (2014), also contained in figure 2, we see that the vast majority of failure patterns is described by infant mortality. Is it that there are so many naturally occurring failures that follow this pattern? Or could it be simply that a large number of machines fail as a result of poor execution of a TBM strategy? One explanation could be that TBM is very effective, but the emergence of early-onset failure is due to the fact that after maintenance is performed, tasks like reassembly are sometimes performed incorrectly. At such a time it becomes obvious that the equipment would fail again in a short amount of time, or not end up failing at all – a pattern not unlike infant mortality.

So what is the image that is generated across the industry? Is it one where engineers operate clearly-defined, well-designed TBM systems in maintaining their engine room and the rest of the ship, but still have to deal with problems? Or do we see an image where problems stem from a lack of clear vision, muddled communication lines, substandard execution and a narrow scope? The case study performed on the Coral Energy suggests the latter. Whether or not this is the case across the industry cannot be proven, but it seems unlikely that we are dealing with the former in all cases.

The reliability of the research seems valid. Comparisons were made between the participatory observation of working practice, the content of ship's documentation and the answers obtained from engineers in the interviews. The results obtained mostly agreed with each other that, while the ship nominally employs a TBM strategy, the practice is poorly developed and highly reactive.

Results from the interview claimed that the company would be unwilling to make large investments in CBM systems. These results were only obtained from the experience of engineers, however. The company has since proceeded to begin rolling out a new information system for the PMS called BassNet, which will eventually replace StarIPS and is geared towards overcoming many of the problems associated with it. Furthermore, the company has announced to begin in 2017 without outfitting all ships with vibration monitoring equipment that will be used as part of the maintenance process in the entire fleet. It must therefore be explicitly stressed that the report does not conclude that the company is unwilling to make investments. Instead, the choice for low-cost solutions is made on the basis of prudence as well as practicality. It stands to reason that small investments that serve as proof of concept will lead to gradually larger investments and more extensive improvements over the course of time. This approach mitigates the risks involved with potential failed implementation or a lack of results. Furthermore, practical trials with complex equipment simply did not fit into the scope of the research, making low-cost solutions the only testable alternative.

6. Conclusions and recommendations

The research was conducted to answer a central question: Can maintenance in the maritime industry be improved by (further) implementing the condition-based maintenance strategy and if so, what are the benefits and how should that be done? The second main question was: Can maintenance on the Coral Energy be improved by (further) implementing the condition-based maintenance strategy and if so, what are the benefits, how should that be done and to what extent are the results applicable to the maritime industry in general?

It has been established how, in theory, CBM can lead to better maintenance results when used as a supplement to a TBM strategy. We have also seen how the concept of CBM could be brought into practice on board the Coral Energy. The fundamentals required for incorporating CBM into the maintenance strategy are in place, but the missing step, that of data processing and analysis, is the crucial factor.

In establishing the maintenance process on the Coral Energy, two key problems were identified. The first, that where the TBM strategy was used, it was found to be insufficient due to the fact that components had a shorter lifetime than expected. The second, that the primary method used for equipment monitoring, being observation with the senses, is not an objective method, which puts its effectiveness at risk.

While ship's crew was found to be poorly aware of the theory behind CBM, its practical use and benefits were mostly understood. The crew is willing to learn about new concepts and open to the idea of improvements to the maintenance system. There is a fertile basis for change. The main goal should be proper instruction and motivation of the crew during the process.

Two analytical subquestions were posed and answered. They are reiterated here.

A1. What investments are required to make further implementation of CM and CBM possible in terms of modifications, tools and training?

Two practical solutions to some of the problems discussed have been tested. The first concerned main engine foundation measurements, the second was for active monitoring of SOGAV performance using the engines' CM system.

For the foundation measurements the investments confine themselves to the purchasing of simple tools and instructing the crew. The measurements can be performed using conventional tools. The adjustments are performed using shims and hydraulic jacks, the latter of which still have to be purchased.

The condition monitoring of SOGAVs was discussed. Early warning signs of imminent SOGAV failure have been identified, and can be spotted in the future to allow for timely acquisition of spares and planning of maintenance with minimal impact on ship operations.

On the whole we see a common theme emerging. The quality of the Coral Energy's maintenance system could be greatly improved by investing in increased awareness of the crew in terms of how to approach maintenance. The quality of data acquired for the maintenance process must be improved. Reliable data processing methods need to be implemented, and made to lead to actual maintenance decision-making. Achieving all of this is a matter of training and instruction. The company must incentivise improvement of the maintenance process by making it more accessible and understandable for the engineers.

A2. What improvements are expected as a result of (further) use of CBM?

Both practical tests performed were concluded to be both effective and efficient, therefore the practical problems that the tests would tackle

The two practical solutions discussed were found to have a good return on investment as well as positively influencing ship's operations as a whole. Furthermore, training and instruction is expected to increase the general quality of the work performed by engineers, be it as part of CBM operations or as part of the existing maintenance strategy.

From the practical tests it has been shown that a simple, low-cost approach to CBM can be extremely effective in achieving results. The defining factor is awareness. This also appears to be the reason why the existing maintenance program appears to be obtaining poor results: engineers seem to be unaware of the existence of different maintenance strategies, and even of the wider world of the theory behind maintenance management. Education, therefore, becomes a key player in creating that awareness and allowing the engineer to improve the quality of his own work by exploring the benefits and drawbacks of using different maintenance strategies in practice. Maritime companies should certainly not assume that the main road to an effective CBM system is through purchasing of costly CM systems. Such implementations are likely to fail, as has been proven by van den Berge et al. (2016). Instead, knowledge and awareness should be the first stepping stone before investing in expensive systems.

The conclusion is that while CBM can certainly play a role in improving the state of maintenance on the Coral Energy as well as across the fleet, of far greater importance is improving the engineers' awareness of how they can properly implement existing maintenance techniques as well.

Recommendations

If Anthony Veder as a company intends to increase the use of CBM on board her ships, as well as increase the quality of the existing maintenance system, some further groundwork will need to be done. The following recommendations are made:

- The primary investment required for the implementation of new CBM systems as well as general improvements to the maintenance process is in training and awareness. The company must research exactly how crew must be trained to increase the effectiveness of maintenance methods. Such training should be given to as many engineers as possible, to allow not just chief engineers but also their juniors to improve results when moving towards the future. Prioritize training over investment in tools and systems, as the latter cannot be used to effect without the former.
- Communication is key! The company must provide support to the ships and engage directly with engineers when it comes to factors such as high-quality data acquisition, data processing and maintenance decision-making. Clear lines of communication between the crew and shore-based experts will achieve effective maintenance and allow the company to maintain oversight.
- Means must be established to share new ideas for practical CBM methods throughout the company. The alignment measurement method described, for example, seems promising, but was found almost serendipitously by reading through an old service letter. Specifically researching such methods is likely very challenging,

but by enacting a concerted effort to find and share ideas, the process can be shared widely. This also invests in awareness.

- Further research could focus on whether problems involving maintenance in the maritime industry can be considered due to either a lack of effectiveness of the TBM strategies used (as has been part of the hypothesis for this research) or rather due to poor quality in implementation and execution of those strategies. This may provide a clearer hint as to whether the situation is to be found in supplementing systems by using CBM, or simply by working on shoring up the quality of maintenance systems as a whole.

A different view on maintenance based from the ground up, intended to be simple to follow for engineers, simple in execution, simple in implementation, may provide a new way of looking at maintenance in the maritime industry. CBM can be an important tool in such a view, but what is clear is that awareness and training should be the first priority.

Glossary

CBM

Condition-based maintenance, a maintenance strategy that employs periodical measurement or constant monitoring of a system's physical condition to determine whether maintenance is necessary.

Classification society

Classification societies, also called class societies or class, such as Lloyd's Register, Det Norske Veritas (DNV) and Germanischer Lloyd (GL) are companies that primarily serve to provide so called Certificates of Class to ships. These certificates are extended after survey by the society, and serve to prove that the ship has been constructed according to the society's standards, and continues to conform to those standards throughout its life. This procedure is called classification, and a certified ship is said to 'have class'. Ship's class is a basic requirement for practically all forms of maritime insurance. Class societies are often also authorized by national governments to carry out inspections to determine whether a ship complies with that nation's legal requirements.

CM

Condition monitoring, technique that employs metrics of a system's operating conditions in order to obtain information about the system's functioning.

CSM

Continuous Survey Machinery is an alternative to the SSM (see entry) that involves periodic inspections of the machinery listed on the survey. Rather than a complete overhaul, specific parts of the machine are opened for inspection to determine its general state of maintenance. These surveys must be carried out at least once every five years, but are generally spaced out over that period in order to even out the workload. Furthermore, most (but not all) of these surveys can be performed and reported on by the ship's chief engineer rather than a class surveyor.

LNG

Liquefied Natural Gas is a type of ship cargo carried by specialized tankers. Natural gas is brought to a low temperature (approximately -150 degrees Celsius), causing it to liquefy and thereby vastly increase in density, making overseas transport viable.

SOLAS

The SOLAS convention, or the International Convention for the Safety of Lives at Sea, is an international maritime treaty which requires signatory states to ensure that ships flagged by them to certain minimum standards of safety and operation. The SOLAS convention governs certain aspects of ship construction, but also of the design of machinery spaces and how they must be monitored. SOLAS also includes instructions for the safe maintenance of safety implements, such as lifeboats.

SSM

Special Survey Machinery. The part of ship's class that is related to the ship's propulsion and navigation machinery (as well as certain other machinery) is covered under the SSM. In its simplest form, SSM requires a ship to completely overhaul all machines under survey every five years, under supervision of a surveyor from the society, in order to retain its class. This is generally done during the five-yearly docking period that is mandatory under other sections of the class certificate. The class societies offer several alternatives to the five-yearly overhaul, such as the continuous survey, or specific maintenance schemes.

TBM

Time-based maintenance. A maintenance strategy that performs maintenance operation based on either a calendar schedule or equipment running hours. TBM is the same as planned maintenance.

Bibliography

American Bureau of Shipping (2016). *Equipment condition monitoring techniques.* Houston: ABS.

Algelin, G. (2010). *Maritime Maintenance Systems: A survey of maritime maintenance systems and utilisation of maintenance strategies.* Gotheburg: Chalmers University of Technology.

Allen, T.M. (2001). *U.S. Navy analysis of submarine maintenance data and the development of age and reliability profiles.* Portsmouth.

Brüel & Kjaer (1987). *Machine-condition monitoring using vibration analysis: permanent monitoring of an Austrian paper mill.* Naerum: Brüel & Kjaer.'

van den Berge, B.; Bookelaar, L.; Janse, M.; Markusse, S.; van der Wulp, T. (2016). *Condition based maintenance.* Vlissingen: HZ University of Applied Sciences.

Gits, C.W. (1992). *Design of maintenance concepts.* Amsterdam: Elsevier Science Publishers B.V.

Knutsen, E.; Manno, G.; Vartdal, B.J. (2014). *Beyond condition monitoring in the maritime industry.* Høvik: DNV GL.

Jardine, A.; Lin, D.; Banjevic, D. (2005). *A review on machinery diagnostics and prognostics implementing condition-based maintenance.* Toronto: Mechanical Systems and Signal Processing.

Lloyd's Register (2013). *ShipRight: machinery planned maintenance and condition monitoring.* London: Lloyd's Register.

Lloyd's Register (2016). *Rules and regulations for the classification of ships.* London: Lloyd's Register.

Rao, B. (1996). *Handbook of condition monitoring.* First edition. Oxford: Elsevier Advanced Technology.

Rijsdijk, C. (2015). *Studiemateriaal minor Equipment Maintenance Technology.* Vlissingen: HZ University for Applied Sciences.

Rosmaini, A. & Kamaruddin, S. (2012). *An overview of time-based and condition-based maintenance in industrial application.* Penang: Computers & Industrial Engineering.

Verhoeven, N. (2004). *Wat is onderzoek?* Den Haag: Boom Lemma Uitgevers.

Wubben, J.P.C. (2015). *Studiemateriaal minor Equipment Maintenance Technology.* Vlissingen: HZ University for Applied Sciences.

Appendix 1 – Wartsilä Service Letter

ReportApp1.pdf

Appendix 2 – Work Report ME alignment

ReportApp2.pdf

Appendix 3 – Measurement instructions ME foundation alignment

ReportApp3.pdf