An RCM approach for assessing reliability challenges and maintenance needs of unmanned cargo ships

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ABSTRACT

Unmanned autonomous cargo ships may change the maritime industry, but there are issues regarding reliability and maintenance of machinery equipment that are yet to be solved. This article examines the applicability of the Reliability Centred Maintenance (RCM) method for assessing maintenance needs and reliability issues on unmanned cargo ships. The analysis shows that the RCM method is generally applicable to the examination of reliability and maintenance issues on unmanned ships, but there are also important limitations. The RCM method lacks a systematic process for evaluating the effects of preventive versus corrective maintenance measures. The method also lacks a procedure to ensure that the effect of the length of the unmanned voyage in the development of potential failures in machinery systems is included. Amendments to the RCM method are proposed to address these limitations, and the amended method is used to analyse a machinery system for two operational situations: one where the vessel is conventionally manned and one where it is unmanned. There are minor differences in the probability of failures between manned and unmanned operation, but the major challenge relating to risk and reliability of unmanned cargo ships is the severely restricted possibilities for performing corrective maintenance actions at sea.

1 INTRODUCTION

Autonomous and unmanned cargo ships are projected to change the maritime industry. Compared to a conventional cargo ship (CS), the unmanned cargo ship (UMS) is expected to reduce operational costs and fuel consumption and simultaneously improve safety and increase cargo capacity [1]. Others have cautioned that removing the human operators from the ship may present other yet unknown issues and that the proposed improvements may not be so easily gained. Some are raising concerns about the reliability of ship systems and the possibility of handling failures at sea without the presence of an onboard crew. Bertram [2] reasons that even if UMS could cope with all normal operation conditions, the repair of failures on these is unlikely to be handled satisfactorily. He explains that failures in existing ship machinery systems happen much too often and despite expected reliability improvements, future cargo ship operations will still be dominated by onboard maintenance. Rødseth and Mo [3] explain that the robustness of machinery systems will be a challenge for unmanned shipping.

Reliability of machinery components and the limited possibilities of dealing with failures at sea are clearly issues that must be addressed for UMS. The EU-funded project Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) concludes that a high level of redundancy in the machinery systems is required on UMS and suggests that complete redundancy of all machinery function may be necessary. An existing sea water cooling system for a CS is evaluated by Abdelmoula, et al. [4] using Fault Tree Analysis (FTA) and Failure Mode and Effect Analysis (FMEA). To achieve sufficient reliability for the system to be used on a UMS, they propose changes to the machinery arrangements through reconfiguration and added redundancy.

Reliability is considered in the design of each machinery component and the design of the vessel itself, but maintenance also affects reliability [5]. Modern cargo vessels are complex systems constructed from numerous sub-systems and individual equipment units provided by multiple different suppliers and assembled by a third party. Maintenance management systems for these vessels can be constructed by the shipping or technical management company or yet another specialised third-party company. The maintenance management systems are traditionally developed mainly based on company experience, legal or class requirements and recommendations from equipment manufacturers. Traditional maintenance strategies do not consider the reliability of the ship systems and sub-systems as a whole. To cope with the reliability challenges on UMS, Rødseth and Mo [3] propose that new maintenance strategies must be developed and used, and they suggest that Reliability Centred Maintenance (RCM) could be a suitable method.

The RCM method was developed in the aviation industry during the 1960s and 70s. RCM is defined by Moubray [6] as *''a process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context''*. Jones [7] further explains that a system perspective is used in the RCM analysis of system functions, failures of the functions and prevention of these failures. The background, structure and use of the RCM method has been extensively covered by many authors such as Nowlan and Heap [8], Moubray [6] and Bloom [9]. The RCM method has many proponents but also received criticism. A point of concern raised by some is that the original RCM method is too costly to perform [10]. Hence, streamlined versions which simplifies one or more of the RCM steps have been proposed. Other authors, such as Moubray [11], however, argues against the effectiveness of such simplified versions of the method. The limited application of RCM on hidden failures is addressed by Rafiei, et al. [12]. Mokashi, et al. [5] mentions, amongst other issues, the lack of reliability data and FMEA from equipment suppliers as a barrier in the use of RCM. Despite these concerns the RCM method has since its introduction in aviation been used extensively and successfully in other industries, such as manufacturing and power generation [9].

In a marine context, RCM has been extensively used in the offshore oil and gas industry [9] and in naval forces, such as the US Navy and the British Royal Navy [6, 13]. Several classification societies are advocating the use of RCM on commercial cargo ships and some offer RCM analyses as a service to maritime customers, such as Lloyd's Register, DNV GL and Bureau Veritas. ABS [14] explains that RCM can improve equipment and system reliability and has published a comprehensive guidance note on RCM for use on commercial cargo ships. Despite the successful implementation in other maritime industries, RCM has not yet gained traction in the commercial maritime transport industry [15]. According to Mokashi, et al. [5], there are several reasons for this, but most stem from the relative uniqueness of each commercial ship design, making it necessary to conduct the resource-intensive RCM analysis separately for each ship and system. Commercial cargo ships are often one-off designs or part of a small series of sisterships which can still have considerable differences in machinery equipment and systems. Therefore, in most cases RCM analysis for one ship cannot be directly used for another ship.

RCM's lack of implementation in the maritime transport industry seems to mostly result from resource and cost issues and not applicability, and a number of studies explore the use of the method or parts of the method on commercial cargo ships. Lazakis, et al. [16] develop a holistic maintenance strategy to increase the operational reliability of ships in which RCM principles are utilised. Conachey, et al. [17] examine the use of ABS guidance notes [14] on RCM to improve reliability of machinery systems and to fulfil certain machinery survey requirements. Mokashi, et al. [5] conduct an in-depth analysis of the use of RCM in commercial maritime operations and conclude that the method has the potential to increase reliability and reduce maintenance costs but also identify problems specific to commercial ship operation that may hinder its practical implementation. Mokashi, et al. [5] also note that most attempts to implement RCM on cargo ships have so far been done by shore-based consultants or academics.

Some work has also been done on the use of the RCM method on autonomous and/or unmanned systems, mostly relating to aircrafts. Martinetti, et al. [18] create a framework for a scalable maintenance program for an unmanned aircraft system based on the RCM method. Walker [19] uses the principles of RCM to define the requirements for a real-time prognostics and health monitoring system for an unmanned aircraft.

A few studies have been done in the specific field of autonomous and/or unmanned ships. Jacobsen [20] uses RCM principles to identify barriers in the design of machinery systems on commercial cargo ships. The focus of the analysis is on how the maintenance tasks implemented for manned vessels today can be done on UMS. New issues arising from unmanned operation, however, are not specifically addressed. Sjøholt [21] uses RCM to construct a maintenance program for an autonomous and unmanned passenger ferry in the Trondheim harbour. The analysis offers insights into some fundamental questions of unmanned operation, but as the ferry is very small with electric propulsion and a short operation range, the findings relating to reliability issues for machinery systems have limited application to large commercial vessels. Rødseth and Mo [3] propose a novel maintenance concept suitable for unmanned shipping which is inspired by and includes elements of the RCM method.

RCM has the potential to be a valuable method in the assessment of maintenance needs and reliability issues on UMS. However, as in all applications, there are specific operational challenges of unmanned operation that affect the applicability of the RCM method. So far, there has been no examination of the RCM method when used on UMS nor an investigation of how potential challenges can be solved. Hence, the objective of this paper is to explore and address this issue by: (i) analysing the applicability of the RCM method in the examination of reliability and maintenance of machinery systems on large commercial cargo ships operating without a crew onboard for long periods at a time; (ii) proposing amendments to the RCM method to improve the examination of reliability and maintenance issues on unmanned cargo ships; and (iii) verifying the amended method in a case study through the analysis of a real machinery system.

2 Methodology, important concepts and data collection

This section describes the RCM methodology used in the present paper and introduces the most important concepts. Definitions of reliability and risk are explained, the concepts of systems and maintenance are briefly introduced and the relation between maintenance and reliability is described. The concept of the UMS in the context of this paper is also introduced. Lastly, the data used in the analyses and the method used for collecting this data are presented.

2.1 The RCM Methodology

The development of the RCM method is generally credited to Nowlan and Heap [8] in their work on optimising maintenance management and improving reliability in the commercial aviation industry. The RCM method is typically described through seven basic questions about the asset or system [6, 9]:

1. Functions and Performance Standards - *What are the functions and associated performance standards of the equipment in its present operating context?*
2. Functional Failures - *In what ways does it fail to fulfil its functions?*
3. Failure Modes - *What is the cause of each Functional Failure?*

4. Failure Effects - *What happens when each failure occurs?*
5. Failure Consequences - *In what way does each failure matter?*
6. Preventive tasks - *What can be done to prevent each failure?*
7. Default Actions - *What should be done if a suitable preventive task cannot be found?*

Literature for the RCM method used in this paper is taken from Moubray [6], Bloom [9] and ABS [14]. The analysis in this paper follows the structure of the seven questions or steps described above, with some amendments, as presented in Section 3.

2.2 CONCEPTS USED IN THE PRESENT ANALYSIS

2.2.1 Reliability

Reliability is the probability of non-failure over time [22]. Some types of equipment will fail less often and are therefore more reliable than other. Reliability may be expressed in terms of a failure rate, i.e., failures per unit time. The failure rate does not reveal when a failure will occur, and reliability is therefore inherently coupled with uncertainty. Uncertainty is an obvious challenge in regard to machinery systems which must be designed with some resilience towards the effect of failures. Uncertainty also poses a challenge to maintenance planning where flexibility must be allowed to accommodate for unforeseen failures.

2.2.2 Risk

Failures are rarely of interest without an assessment of consequences. The product of probability and consequence is risk [14] or as defined by the International Organization for Standardization; the *"effect of uncertainty on objectives"* [23]. Risk can relate to consequences to human health and safety, operational delays and system availability, negative environmental impact, economic losses, etc. In this paper, risk is related to failures of machinery. Risk of failure to machinery is, at least from the perspective of system owners and operators, an undesirable but unavoidable attribute of the operation of machinery systems. Less risk is better, but risk reduction typically comes at a cost. There is no universal standard for which level of risk is acceptable, it depends on the situation and must be defined by the user [6]. In general, the risk relating to failure of machinery systems can be reduced either by improving the reliability of equipment units and/or preventing or mitigating the consequences of the failures.

Similar to risk, the term criticality can be defined as the product of probability and consequence [24]. Criticality is sometimes used instead of risk, synonymous to risk or as a measure of risk when it is related to failure modes, failure of components and its effects [14, 24]. Confusingly, criticality is sometimes regarded as a subset of risk and in other contexts risk is regarded as a subset of criticality [25]. The possible differences in meaning between criticality and risk in different contexts is recognized but it has not been found necessary to distinguish between the two terms in this paper. Hence, the term risk is used throughout the text to describe the product of probability and consequence.

2.2.3 Systems

A system can be broadly defined as an assemblage or combination of elements or parts forming a complex or unitary whole. In the context of this paper, a system is a machinery system, such as a lubrication oil system or a cooling water system. The machinery systems are composed of equipment units with one main function such as a pump or compressor [26, 27]. The case study presented in this paper is an analysis of a machinery system, namely a low-temperature cooling water system.

2.2.4 Maintenance

Maintenance can be defined as a *"combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function"* [24]. Maintenance can be divided into two main groups: preventive maintenance which is carried out to prevent a failure from occurring and corrective maintenance which is carried out to correct a failure after it has occurred.

Preventive maintenance includes both predetermined maintenance where tasks are carried out at a predetermined interval and condition-based maintenance [24]. In condition-based maintenance, tasks are carried out based on the assessment of the condition of the equipment unit through inspection, testing and analysis. A further subset of condition-based maintenance is predictive maintenance where the useful end life of the equipment unit can be estimated through repeated or continuous condition measurements in combination with known parameters about the degradation of the unit.

Predetermined maintenance is a very simple and cost-effective strategy for parts or units with an established correlation between wear and operating or calendar time. However, for some parts this correlation does not exist, and failures will occur at seemingly random intervals [28].

Condition-based maintenance is already used for CS today. For condition monitoring to be effective there must be one or more measurable potential failure “indicators”. Much of the condition monitoring consists of low-level jobs, such as visual inspections and simple operational checks. More advanced tasks, such as partial disassembly of equipment units for inspection and measurements, megger testing of electrical resistance, thermography of electrical installations, vibration monitoring of bearings etc., are typically also part of the existing maintenance schedule. On larger equipment units, such as main engines, boilers and generators there will typically be continuous online monitoring of bearing temperature and lube oil pressures at various subcomponents etc. which are used as “failure indicators”.

The benefits of condition-based and predictive maintenance are obvious, since performing maintenance when a potential failure is approaching better utilizes the remaining useful life of the equipment unit. When failures can be predicted, shutdowns can be planned with as little disruption to the operation as possible and collateral damages due to failures can be avoided. However, condition-based, and predictive maintenance is not possible or technically feasible for all equipment units or parts [9]. Not all failures have measurable indicators and some failures progress so rapidly that failure detection is not practically feasible. There is a cost related to each failure mode with a corresponding measured indicator. If the measurement data is to be transmitted via satellite ashore and processed by a third party for predictive maintenance this will typically incur an additional cost. For many non-critical smaller equipment units, condition-based maintenance will not be cost effective and a deliberate run-to-failure strategy or is often chosen if predetermined maintenance is also not an option [6]. For small equipment units which provide an output essential for other larger processes, complete stand-by redundancy of the unit is often used as a strategy to avoid operation stops.

Maintenance can reduce risk by either decreasing the probability of the failure occurring or by limiting the consequences of the failure if it does occur. Preventive tasks of the machinery system will reduce the probability of a failure occurring but generally have no impact on the consequences of failures [14, 29]. Corrective maintenance tasks can reduce the consequences by restoring the functions of the failed equipment units and prevent cascading effects at a system level. Since corrective maintenance is done after a failure has occurred it will not have any impact on the probability in the period leading up to the failure. However, the work done to correct the failure may change the probability of failure after the corrective maintenance actions.

2.2.5 Operational scenario

Several different standardized definitions of unmanned and/or autonomous ships exists, see e.g. IMO [30], Lloyd's Register [31] and Rødseth and Nordahl [32], but none are yet uniformly recognized within the industry. Common for these definitions is that they focus primarily to the navigation and collision avoidance ability of the ships and tell very little of the automation level and ability of the mechanical systems. As the focus of this work is on the ships machinery systems the use of any of the standardized definitions has not been found sufficiently detailed. Instead the operational scenario is described in the following.

The concept of UMS used in the present paper follows that of the MUNIN project as detailed by Rødseth and Tjora [33]. During normal operation at sea, the cargo vessel is unmanned but may have the option to accommodate a crew during sea passages in certain situations. Since the vessel must be capable of unmanned operation, however, the analyses in the present paper are done based on the assumption of the cargo ship being unmanned at sea. All maintenance must therefore be done when the vessel is in port. During normal operation, the onboard control system is capable of operating the machinery systems within predefined boundaries without human control. One or more shore control centres continuously monitor the UMS remotely and can take over control of the cargo ship and its systems at any time. If the predefined limits of the control system are exceeded, a shore control centre will be prompted to take over control. It is assumed that all the equipment in the ship's machinery systems can be remotely operated and monitored onshore in the same way as from the ship's engine control room onboard a conventionally manned cargo ship.

2.3 Data and data collection

To evaluate and amend the RCM method, a case study on a cargo ship's machinery system was performed. For the case study, descriptions and diagrams of the analysed system were needed along with quantitative reliability data. The expert knowledge about the operation and maintenance of commercial cargo ships and related systems, as well as the RCM method, is mainly based on the engineering and system knowledge of the authors and a working group consisting of four participants from Kongsberg Maritime. The corresponding author has domain knowledge as a marine chief engineer responsible for operation and maintenance of technical marine systems with seven years of experience. Input to the practical application of RCM in a maritime context comes from the participants from Kongsberg Maritime, who have expert knowledge of system design, RAMS & FMEA and Regulatory Compliance and Safety. Four meetings were held during the autumn of 2019 where the methodology and results were discussed and evaluated.

The descriptions, diagrams and information about the analysed system were generously supplied by Kongsberg Maritime. Unfortunately, no data has been available for the reliability of the specific installation onboard the ship. In general, very little reliability data is available for marine systems. Therefore, the data used in the paper has been collected from the Offshore and Onshore Reliability Data (OREDA) handbook [27]. The OREDA handbook is one of the main sources of reliability data in the Oil and Gas industry [34]. While not completely identical, marine systems and the way the systems are operated on a cargo ship do not significantly differ from an offshore installation. The exposure to the hostile environment of corrosive seawater and salty sea air is comparable between offshore installations and ships. Machinery systems of both offshore installations and cargo ships are enclosed in compact metal structures subject to heat and vibration. Both offshore installations and ships are generally self-contained units producing their own power and relying on their onboard crew for operation, maintenance and emergency response. Ships are more mobile than offshore installations both geographically and regarding motions in the sea, but this is not believed to make a substantial difference in the context of machinery reliability.

The OREDA data is gathered from running systems and thus gives a "realistic" non-idealised picture of which failures the equipment units experience and how often. Data is typically gathered over a period of two to four years and usually excludes the beginning and end of component life [27]. Failure rate distributions from the OREDA handbook are assumed to be constant over the life of the equipment. The systems from which the OREDA data is gathered are maintained and the effect of the maintenance tasks on reliability is implicitly included in the failure rate values. However, no information about the maintenance tasks and intervals is available. It must also be noted that reliability data is aggregated from many different similar but not identical equipment units from several different installations and companies with different maintenance management systems.

Maintenance schedules and histories have not been available for the specific installation in the case study. Instead, maintenance data from four commercial cargo vessels has generously been made available by the Danish shipping company Lauritzen Kosan. The maintenance schedules and records from Lauritzen Kosan are used as a reference for which maintenance tasks would typically be carried out and at which intervals for a machinery system similar to that of the case study in this paper. The Lauritzen Kosan ships and machinery systems are slightly larger than the vessel used in this analysis but are otherwise comparable in functionality and layout. Details of the maintenance tasks are presented in section 4.5.

3 Proposing amendments to the RCM method for UMS

Since the introduction of the RCM method in the aviation industry, there have been many different adaptations and versions of the method in order to meet the particular constraints and requirements of other applications [9]. The overall steps of the method, as described in section 2.1, might remain the same, but the details of each step may change for different implementations. In this section, the applicability of the RCM method when used to evaluate maintenance needs and reliability issues on UMS is analysed and amendments to the method are proposed. In section 3.1, the RCM method is analysed using CS as a reference through each of the seven steps of the RCM method as described in section 2.1. Based on this analysis, amendments to the RCM method are proposed in section 3.2.

3.1 Analysis of the differences and similarities between CS and UMS

3.1.1 Step 1 - Functions and Performance Standards.

The definition of Functions and Performance Standards mostly depends on the physical systems under analysis, the equipment units that make up the systems and the operational situation under which the system is expected to perform. Some systems, such as the sewage system, may not be needed on a UMS depending on the operational scenario. Other systems or units, such as telecommunication and remote actuators will be required on a UMS to a greater extent than a CS. Systems such as the cooling water systems will be needed regardless of the presence of an onboard crew, and the primary function of providing a flow of water for cooling, for example, is not likely to change.

Many of the so-called secondary functions such as structural integrity, containment of liquid and safety functions of the systems will also be the same, but some might differ. On a UMS, the noise level, for example, might not be of any concern whereas remote monitoring and remote operation capabilities, for example, will be critical.

The Functions and Performance Standards completely depend on which system is being analysed and, equally important in this case, under which operating conditions the system will be running. It is important that all the possibilities and limitations that unmanned operation entails are thoroughly considered from the beginning of the analysis. The CS is a good starting point, but the systems on these cargo ships, and the existing maintenance schedule designed for these, are designed based on assumptions about failure detection, accessibility and manual intervention, which affects the possibility of performing corrective maintenance and which might be drastically different on a UMS.

3.1.2 Step 2 & 3 - Functional Failures and Failure Modes.

Functional Failures, and by extension Failure Modes, are directly related to the specified Functions and Performance Standards and relate to the physical equipment units in the system. If the definitions of functions change so will the Functional Failures and the related Failure Modes.

3.1.3 Step 4 - Failure Effects

The physical Failure Effects can initially be expected to be very similar for CS and UMS, as there will not be any differences in how the equipment unit fails. However, how the failure is detected and the possibilities of performing corrective maintenance during operation will vary greatly depending on the presence of an onboard crew. In the description and evaluation of Failure Effects, careful consideration must be made for the likely restricted possibilities of failure detection and repair of the UMS while at sea. The longer the ship is inaccessible, the more time is available for a potential failure to develop from insignificant to critical. Detecting potential failures is critical in avoiding or limiting Failure Consequences but detecting a failure once it has happened will not help if nothing can be done to stop it. The length of the voyage also increases the probability that failures will occur in multiple equipment units in systems with redundancy.

3.1.4 Step 5 - Failure Consequences

When a failure occurs, the outcome depends on the possibilities for corrective maintenance tasks, and therefore the Failure Consequences can be expected to be significantly different from CS to UMS.

For some Functional Failures which would harm or endanger the onboard crew, such as a main engine crankcase explosion or accidental release of CO_2 into the engine room, the immediate consequences for human life can be expected to be much lower on the UMS since there is no one onboard during the voyage. Removing humans from the cargo ship, however, does not mean removing the risk to human life altogether. Repair crews must come onboard to maintain the ship's systems during port stays if maintenance cannot be done at sea. The risk to human life may therefore move from sea to port and cannot be expected to disappear entirely from the UMS because the occurrence of some work-related accidents is likely to follow the maintenance tasks.

For many Functional Failures, the Failure Consequences on UMS may be higher since there are no people present to return the equipment unit or system into an operational state. Failures which result in operation stops are particularly critical on UMS, since the corrective maintenance action that is possible on a UMS is very limited until it can be accessed by repair personnel. If failures critical to the propulsion of the vessel cannot be repaired, the UMS may be left "dead in the water" with major economic and safety consequences as a result.

3.1.5 Step 6 - Preventive tasks

No amendments to the decision logic used for maintenance task selection, such as that of ABS [14] used in the case study in the present paper, is found to be needed for the application of RCM on UMS. The result of applying the decision logic may, however, be very different between a UMS and a CS if the risks related to the potential failures differ. If the risk is found to be higher due to the cargo ship being unmanned, more Preventive Tasks may need to be assigned to reduce the probability of failure. Condition based maintenance is still preferable whenever technically feasible. Unmanned operation is, however, likely to affect the possibilities for doing certain condition monitoring tasks as described in section 2.2.4 and further discussed in section 5.2. The breakeven point of when a condition monitoring task is cost effective is also likely to change since the strategy of run-to-failure followed by corrective maintenance cannot be relied on to the same extend as on a CS.

Maintenance on a UMS can only be done during port stays instead of throughout the operation of the vessel. The infrastructure for maintenance support from shore might not be available in all ports. It is also likely that the cost and quality of maintenance support from external contractors will vary from port to port. If inhouse maintenance support is used it is likely that ship operators will want to concentrate their resources in a few centralized locations. Because of this it might be necessary or preferable to concentrate more maintenance tasks into a few concentrated maintenance campaigns in specific ports rather than doing maintenance at each port of call. Since the main purpose of port calls is the loading and unloading of cargo, the operation will also put constraints on which machinery systems can be maintained. Some systems may only be accessible during either loading or discharging. Others, such as ballast water systems which are used both during loading and discharging, might not be accessible without interfering with port operations. These operational constraints along with the need for doing more maintenance tasks simultaneously within a confined space and time will require more detailed maintenance planning.

The possibility of performing Preventive Tasks on a UMS, however, is not expected to very different than on a CS. Preventive Tasks are by nature planned tasks which for most ships would be possible to plan and carry out during port stays. However, some compromises between the wish to extend maintenance intervals to achieve maximum useful life of an equipment unit or part and the need or wish to concentrate maintenance tasks into fewer campaigns might have to be made. The intervals between periodic tasks on a UMS also naturally cannot be shorter than the voyage length of the vessel.

3.1.6 Step 7 - Default Actions

Where Preventive Tasks alone are not enough to reduce the risk to an acceptable level, or are not technically feasible, Default Actions must be taken. Default Actions can be "failure finding tasks", "redesign" or "no scheduled maintenance" [6]. Failure finding tasks are scheduled tasks aimed at determining whether a failure that does not in itself have an evident effect on the function of the equipment has occurred. Detection of failures while the vessel is underway can be expected to be more difficult on unmanned cargo ships in general. Since failure finding tasks are scheduled tasks, however, they can most likely be planned to be carried out when the UMS is in port. As with preventive tasks, the interval cannot be shorter than the voyage length for tasks which require human intervention. Operational testing of stand-by equipment may be possible to perform without a human presence depending on the remote operation and monitoring system employed. For evident failures where the risk cannot be reduced to an acceptable level, redesign is necessary.

3.2 Amending the RCM method to be used on UMS

The RCM method is at an overall level applicable for the use on UMS based on the analysis in section 3.1, but some limitations were found.

Long periods of unmanned operation pose unique challenges for the assessment of reliability of machinery systems. System may be required to operate in a partially failed state for long periods of time without the possibility of repair and corrective maintenance. It is an assumption in the conventional RCM method that corrective maintenance actions are made in a "timely manner" [9]. If corrective maintenance actions can be made in a timely manner, a failure may not continue to develop in severity after detection and multiple failures in systems with redundancy of machinery are not likely to happen.

The aviation industry, where RCM originated from, and the nuclear power industry specify time envelopes within which the failure must be repaired to avoid the risk of additional failures. These time envelopes can be hours or days, airplanes can be grounded, and power plants can be forced to power down if they are not met. Voyages of cargo ships, however, may last for weeks. On a CS it is assumed that the onboard crew can carry out the majority of the corrective maintenance when the ship is at sea. Hence, even though it is possible to include the voyage length in an RCM analysis of a CS, the results will not change whether the voyage length is two days or two weeks. On a UMS, however, where the possibility for doing corrective maintenance at sea is severely restricted, the voyage length will have a huge impact on the result of the RCM analysis. On long unmanned voyages it will often not be possible to do corrective maintenance actions in the "timely manner" assumed in the conventional RCM method. Powering down a cargo ship in the middle of the ocean is likely to have significant economic and safety-related consequences and will rarely be a viable option. The amended RCM method must therefore specifically address the effect of long voyages on the failure development.

In the risk assessment in the RCM analysis, the initial evaluation is based on a scenario where no preventive maintenance tasks are carried out. It is important to remember, however, that this initial scenario already implicitly includes corrective maintenance tasks. Considerations on how failures are detected, how the consequences of failures can be mitigated until maintenance can be implemented and which corrective maintenance tasks are necessary to return the equipment unit to an operational state are included in the description of Failure Effects and Failure consequences. Corrective maintenance tasks are not isolated in the same way as the preventive maintenance tasks in the conventional RCM method and it is not always clear if the possibilities for corrective maintenance tasks adhere to the physical design of the system or the implicit assumptions about the operational situation. On a UMS, where the possibilities for corrective maintenance tasks are very different from conventional manned operation, the effects of both preventive and corrective maintenance tasks should be individually assessed. Hence, differences in the results between UMS and CS of the RCM analysis are likely, as shown in section 3.1, and there is a need for adjusting and amending the RCM method. In particular, Step 4 - Failure Effects and Step 5 - Failure Consequences, the application of the conventional RCM method is found to be of limited feasibility when used on a UMS. For these two steps, the following amendments to the conventional RCM method are proposed in this paper:

Step 4 - Failure Effects: In the assessment of Failure Effects, consider and describe both Immediate and Long-term Effects separately.

Step 5 - Failure Consequences: (i) make risk assessments specific to the intended voyage length. If the voyage length is not known precisely, make multiple risk assessments with different voyage lengths; (ii) make separate risk assessments showing the effects of preventive maintenance tasks and corrective maintenance tasks distinct from each other.

4 APPLYING THE AMENDED RCM METHOD IN A CASE STUDY

In this section, a real machinery system is analysed using the amended RCM method proposed in section 3. The seven steps of the RCM method are applied to the case study using the structure from the ABS Guidance Notes [14], but with the proposed amendments. The analysis is carried out for two situations: one where the cargo vessel is conventionally manned and one where it is unmanned. Due to the proposed amendments to the RCM method, the unmanned situations are further sub-divided into a short (UMS Short) and a long voyage (UMS Long) situation. A short voyage in this case is one day in duration and as an example of a long voyage a duration of fourteen days is used. The analysis explores the extent to which a maintenance strategy for a CS can be used on a UMS. Changes to the maintenance schedule and the design of the machinery system on a UMS are proposed where necessary.

4.1 STEP 1 - FUNCTIONS AND PERFORMANCE STANDARDS

4.1.1 Systems and boundaries

The cargo ship is approximately 75 metres in length with one main engine of about 2400kW powered by Liquified Natural Gas (LNG) for propulsion. The system chosen for the analysis is the Main Engine (ME) Low Temperature (LT) Fresh Water (FW) cooling water system which provides cooling for the ME lube oil cooler, ME gear lube oil cooler and ME LT charge air cooler as well as providing heat for the evaporation of the LNG fuel. An overview of the ME LT cooling water system can be seen in Figure 1. The system was chosen because it is a relatively simple system and relatively self-contained while simultaneously being critical for the operation of the vessel. If the LT cooling water system fails, the main engine will not be cooled, and it will shut down very quickly. In the setting chosen for this analysis, the main engine is the only source of propulsion, which is representative of a major portion of large ocean-going cargo vessels in operation today.

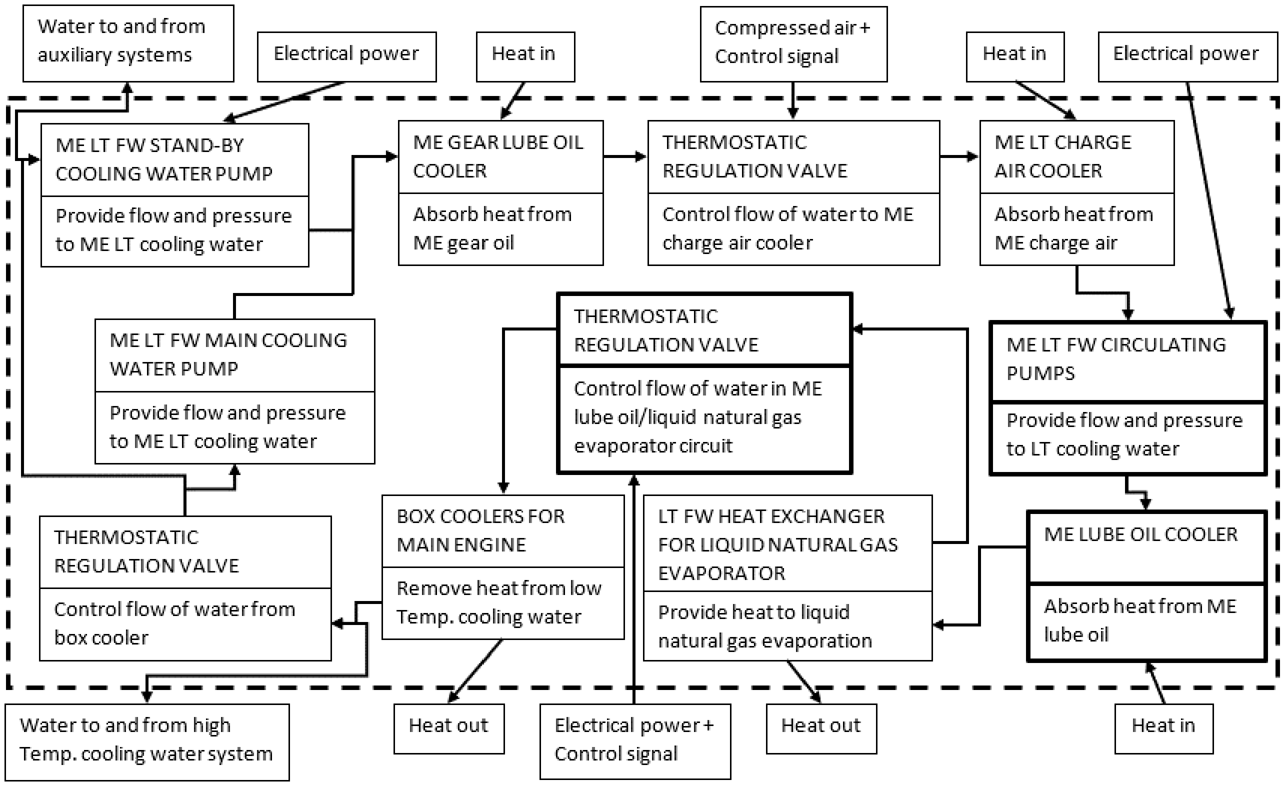

Figure 1 Block diagram of Main Engine (ME) Low Temperature (LT) Fresh Water (FW) cooling water system

The system under analysis is designed for conventional manned operation. When analysing the system under unmanned operation, the capabilities of the UMS, as described in section 2.2.5, are assumed but some additional assumptions must be made to make the comparison realistic. It is assumed that all valves that can be operated manually in the existing system can be remotely operated on the UMS. Some form of remote visual monitoring by cameras is also assumed. It is outside the scope of this paper to design the remote control and monitoring systems needed for unmanned operation. The increased complexity and possible new sources of failure that these systems introduce cannot be accurately assessed based on the available material and are therefore not evaluated in the analysis.

The system boundary is shown in the block diagram in Figure 1. Arrows inside the system boundary indicate the LT water flow in a simplified manner. There are more flow paths of the LT water than shown in Figure 1, but all heat exchangers are critical to the operation of the main engine, and by extension so are all the pumps and regulation valves. A failure anywhere along the simplified flow path will affect the propulsion. The analysis focuses on the physical operations and physical failures of the equipment. Instrument and control failures are only assessed if they impact the operation of the physical equipment.

It is evident from the System Block Diagram in Figure 1 that the system only consists of three different equipment unit types: pumps, heat exchangers and thermostatic regulation valves. The pumps are configured two-and-two, one providing stand-by redundancy for the other in two comparable pump sets. All equipment units are critical, as the failure of any of them can limit or stop the output of the system and by extension the propulsion.

There is not enough detail in the available material to differentiate one equipment unit from another of the same type with regard to reliability data. The RCM analysis, and most importantly the risk assessments, for similar equipment units will therefore be based on the same OREDA reliability data. The analysis of one equipment unit will be valid for all the equipment units of the same type. Because of this, only three equipment units are analysed: the ME LT FW circulating pumps, the ME lube oil cooler and one thermostatic regulation valve.

With the System Block Diagram in Figure 1 as a guide, Functions and Performance Standards of each of the system's individual parts are described for the three equipment units, an example of which can be seen in Figure 2.

Function item no	Function statement	Function type	Functional failure item no	Functional failure statement
B.1	Provide heat transfer of not less than 1270MJ/h	Primary	B.1.1	Critically fail to provide heat transfer

Failure mode item no	Failure Mode	Evident/hidden	Failure mechanisms	Failure characteristics
B.1.1.1	Insufficient heat transfer	Evident	Unknown	Wear-in Random Wear-out

Local effect	System effects Immediate	System effects Long term
No cooling of ME lube oil	Loss of cooling to ME lube oil, high lube oil temp, ME slowdown, eventually ME shutdown, complete loss of propulsion	Unknown

Corrective measures	Failure detection
Loss of propulsion until function is restored	ME lube oil temp high alarm, ME slowdown alarm, ME shut-down alarm

Figure 2 An example of the analysis of one Failure Mode of the ME lube oil cooler

4.1.2 Consequence setting

The consequence setting chosen for the analysis is "likely consequences", as opposed to "worst case consequences". Shipping is a safety-orientated business, but it is also a highly competitive business with small profit margins. Safety comes at a cost and must be balanced with revenue. Proposing a system that can deal with all conceivable failures will not be beneficial for a real-life application.

4.1.3 Operational boundary

Based on an initial analysis, a decision was made to focus on the consequences of failures to the propulsion of the vessel. There are no failures in the LT water system that are likely to have a direct impact on the environment. The LT water system is a low-pressure system that does not contain fluids or materials that are poisonous nor is it likely to cause serious harm to people in case of failure, and safety-related consequences are therefore limited. Some damage to equipment can be caused by failures but the magnitude of this damage is limited compared to the operational consequences. Failures to propulsion could of course lead to groundings, collisions or other dangerous situations at sea, but those situations should be examined in a risk analysis with the loss of propulsion as the hazardous event, instead of as a failure consequence as in this RCM analysis. The setting chosen in this case study is one where a failure of propulsion only has operational consequences which would translate to the cargo vessel being in open sea, in fair weather, with no immediate danger of collision or grounding.

4.1.4 Failure distribution

In the assessment of risk, a constant failure rate distribution is assumed for all equipment units following the practice of the OREDA handbook as described in section 2.3. The most important implication of this is that failures are considered to happen purely at random and completely independent of the age of the item [27].

4.2 Steps 2 & 3 - Functional failures and failure modes

With the System Block Diagram in Figure 1 again as a guide, Functional Failures are now designated for each Function described in Step 1 and one or more Failure Modes are further assigned to each Functional Failure. Failure Modes are all events that are reasonably likely to cause the Functional Failure [6]. The Failure Modes used in this analysis are the Failure Modes described in the OREDA Handbook [27]. Using the standard Failure Modes enables direct use of the failure rate data given for these in the OREDA handbook.

Failures and Failure Modes in the OREDA handbook relate to a failure of any of the required primary or secondary functions of an equipment unit. The failure of a safety function or an instrument for monitoring operational parameters can result in increased operational risk, and a sensible response would be to immediately stop the operation of the unit, but it does not necessarily impact the primary function of the unit directly. In this case study, only those Failures Modes that directly impact the primary function of a unit are considered.

An example of the analysis of one Failure Mode, "Insufficient heat transfer", for the ME lube oil cooler is shown in Figure 2. There are 10 Failure Modes for the ME lube oil cooler and 29 Failure Modes in total for the three analysed equipment units. An analysis is made for each of the identified Failure Modes as shown in Figure 2.

4.3 Step 4 - Failure Effects

Next in the analysis, the effects of each failure are described and divided into Local Effects and System Effects. A Local Effect is the direct consequence of the failure of the equipment unit such as leakage of oil, damage to bearings etc. A System Effect could be the loss of water pressure in a cooling water system.

Based on the amendments to the RCM method described in section 3.2, the System Effects are subdivided into Immediate Effects and Long-term Effects. For this case study, immediate System Effects are defined as those where detection and intervention cannot be reasonably expected before the consequence occurs. In the case of control failure, for example, or the blowout of a gasket, the effect will be sudden and there will be little chance to prevent or limit the effects of the failure. Long-term Effects are those that accumulate over time after the failure occurs. A minor leak of lubrication oil from a LT freshwater pump bearing housing, for example, will not have any System Effects before the lubrication stops, the bearing breaks down and causes the shutdown of the pump. The System Effects will entirely depend on the possibility of detection and intervention after the occurrence of the Functional Failure.

4.4 STEP 5 - FAILURE CONSEQUENCES

In this analysis, the assessment of risk is conducted using a risk matrix as seen in Figure 3. The risk matrix is based on the ABS Guidance Notes [14] but has been constructed specifically for this analysis. There is no risk matrix that fits all types of risk analyses, so an important prerequisite is to define it specifically for the system at hand [35].

The layout of the risk matrix in Figure 3 has been discussed with and approved by Kongsberg Maritime during one of the work group meetings described in section 2.3. The probability categories are identical to those of the ABS guidelines, but the consequence category descriptions are adapted to suit the specific implementation of this case study and the amendments to the RCM method proposed in section 3.2.

A risk level of Low, Medium or High is determined as a result of the probability and consequences for each Failure Mode of the three analysed equipment units using the risk matrix in Figure 3. The probability of each Failure Mode occurring is obtained from the OREDA handbook. The assessment of the consequences of each Failure Mode is based on the Local Effect and System Effects described in section 4.3, which in turn is based on system and engineering knowledge.

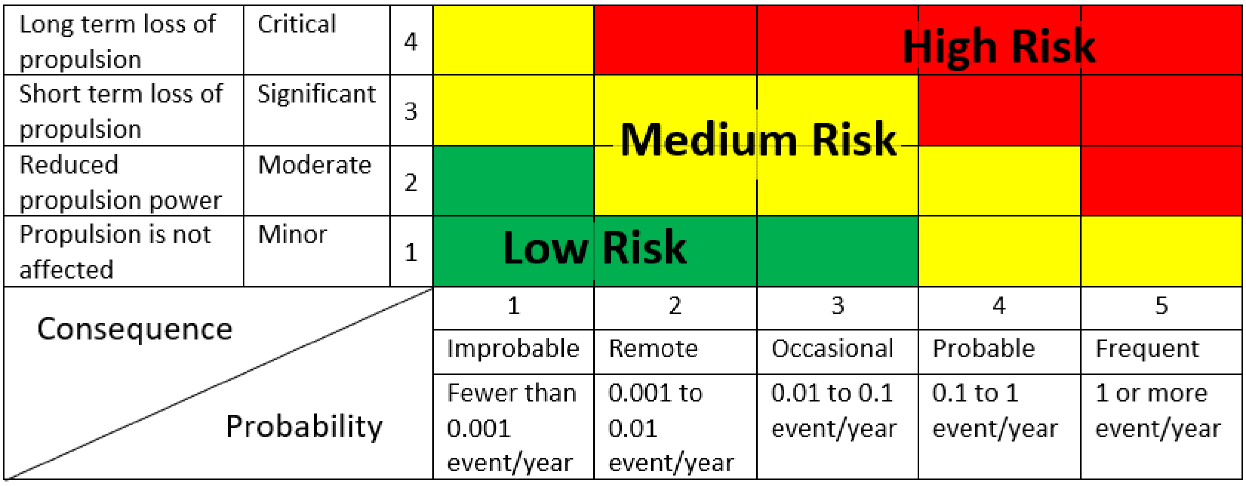

Figure 3 Risk Matrix for loss of propulsion

Using the amendments to the RCM method developed in section 3.2, the effects of preventive and corrective maintenance are separated into two separate scenarios. A third scenario including the effects of the proposed system redesign is also analysed, if applicable.

- Scenario 1: Preventive maintenance only
- Scenario 2: Preventive and corrective maintenance
- Scenario 3: After system redesign

The results of the assessment of risk for the three scenarios using the risk matrix in Figure 3 are explained in section 4.7 and presented in Figure 4, Figure 5 and in the Appendix in Figure A.1.

4.5 STEP 6 - PREVENTIVE TASKS

The As Low as Reasonably Practicable (ALARP) principle is used for determining the applicability of preventive maintenance tasks and/or default actions.

For Failure Modes with a broadly acceptable risk level (low in Figure 3), no Preventive Tasks or Default Actions are needed. If the risk level is in the ALARP region (medium risk in Figure 3), Preventive Tasks or

Default Actions must be assigned. For Failure Modes with risk level in the unacceptable region (high risk in Figure 3), Preventive Tasks or Default Actions must be assigned until the risk level becomes acceptable.

There is not enough detail in the available material to propose maintenance tasks for the specific equipment unit analysed in this case study, which typically would be based on a decision logic diagram as described in section 3.1.5. Instead, the maintenance data from Lauritzen Kosan as described in section 2.3, and as can be seen in Table 1 is used here as a reference for which preventive maintenance tasks will typically be carried out on a system similar to the one analysed in this case study.

Table 1 Preventive maintenance tasks for LT Cooling Water system (from Lauritzen Kosan data)

Job name	**Interval**	**Job description**
Cooling System Test	1 week	Testing of chemical properties of LT water. Chemical dosing is adjusted based on findings
Manual Opening & Closing of LT Cooling FW 3-Way Valve	1 month	Functional testing. Ensure that valve can operate over the full range of opened to closed
ME LT FW Stand-by Pump Routine	1 month	Failure finding task. Check that pump is able to start and provide pressure. Visual check of general condition of pump as well as check for leaks, vibration and noise.
Visual inspection of Rubber Bellows	3 months	Visual inspection for general condition and leaks.
Cooling Water Tank Check for Normal level	3 months	Visual inspection of level of tank
ME LT FW Stand-by Pump Maintenance	6 months	Intrusive testing. Check for electrical resistance of motor. Turn shaft by hand to check rotational resistance
Check of thermostatic valve	12000 hours	Intrusive testing. Ensure that valve functions as calibrated. Recalibrate or replace if necessary
Engine driven cooling water pump overhaul	18000 hours	Intrusive maintenance. Disassemble pump and replace worn out parts
Thermostatic element replacement	36000 hours	Intrusive maintenance. Replace thermostatic element

One out of the nine maintenance jobs in Table 1, “Visual inspection of level of tank”, can be performed remotely, as there is already an LT water tank level indicator installed in the system in the case study. One other job, “ME LT FW Stand-by Pump Routine”, can be partly completed as it is assumed that pumps can be started and stopped, and the pressure can be monitored remotely. All remaining tasks require human interaction to complete in the present design of the system. The intervals for all tasks except one are of one month or more and should be possible to carry out in port for the majority of ships. For the one task with an interval of one week, “Cooling System Test”, a more detailed evaluation should be done, but online monitoring of the cooling water quality may be possible. It is also possible, again based on a detailed evaluation, that the task interval can be extended without significant consequences.

Data on how many man-hours each job takes to complete is also recorded in the Lauritzen Kosan data. The total for the all the jobs done on the LT water system is 59.6 hours in total for the four vessels during a 6-month period. This translates to only 2.5 hours of maintenance work per vessel per month on average for the LT system, which should be possible to undertake during port stays. It must be remembered that the maintenance on the LT cooling water system is only a very small part of the total maintenance tasks required onboard the vessel.

It is assumed that the maintenance tasks and intervals listed here are similar to the level of maintenance done for the equipment units in the OREDA data [27]. The effect of the existing maintenance tasks in Table 1 on reliability is thus already included in the risk assessment using OREDA failure rate data. ABS [14] explains that for Failure Modes with the risk level "unacceptable", maintenance alone is typically not enough to reduce the risk to an acceptable level. Additional preventive maintenance tasks or reduced maintenance intervals are therefore not sufficient, and a change in the system design is thus needed to achieve an acceptable risk level.

4.6 Step - 7 Default Actions

For Failure Modes with unacceptable risk levels and where preventive measures are not sufficient to reduce the risk levels to an acceptable level, design changes need to be applied, and the risk level is evaluated again under the new conditions. If the design change does not reduce the risk level sufficiently, further design changes are applied in an iterative manner until an acceptable risk level is achieved.

4.7 Results of the case study

Maintenance tasks and intervals, which are normally the most important end result of an RCM analysis, do not differ much between UMS and CS in this case study. The salient results of the amended RCM method are found in the differences in the risk levels between manned and unmanned operation, which can be found in Figure 4. Therefore, this section focuses on the risk levels, as well as the design changes which are proposed to reduce the risk for the unmanned cargo ships to acceptable levels.

Figure 4 shows the detailed results of the analysis of the ME lube oil cooler. The detailed results of the other two analysed equipment units; the ME LT circulating pumps and the thermostatic regulation valve, can be found in Figure A.1 in the Appendix. A summary of the risk levels for all three equipment units analysed in this case study can be seen in Figure 5.

4.7.1 The results of the analysis of the ME lube oil cooler

Figure 4 shows the consequence severity, probability value, and the resulting risk level for each Failure Mode of the ME lube oil cooler. It also shows whether a Failure Mode is "critical", meaning that it will cause immediate loss of the equipment unit function, or if it is "degraded", meaning that it will result in reduced output of equipment function.

In Scenario 1: Preventive maintenance only, the consequences, probabilities, and resulting risk levels are the same for manned, UMS Short and UMS Long, and are therefore only shown once. In Scenario 2 and Scenario 3, the consequences, probabilities, and resulting risk levels vary greatly between manned and UMS Short and UMS Long, as seen in Figure 4 and they are therefore shown separately.

Figure 4 shows that the ME lube oil cooler has ten Failure Modes, each of which can cause degraded or a critical Functional Failure of the equipment unit. In Scenario 1: Preventive maintenance only, nine out of ten Failure Modes have a consequence severity "4, critical" and a probability of "2, remote" or "3, occasional", resulting in a high risk. There are four degraded Failure Modes, three of which are able to cause complete long-term loss of propulsion in Scenario 1: Preventive maintenance only. These three degraded Failure Modes are related to leakages. If a leakage from the ME lube oil cooler is left unattended, the system will eventually be drained of LT water or ME lube oil, causing loss of cooling or lubrication, resulting in ME shutdown. An internal leakage, if left unattended, can also result in severe damage to the engine and shutdown due to loss of lubrication. Detection of these leakages may be possible using camera surveillance or remote oil analysing systems. However, the possibilities for stopping or minimizing the leakages on a UMS at sea, even if detected, would be very limited.

In Scenario 2: Preventive and corrective maintenance, there are major differences between manned and unmanned operations. For manned operation, the risk levels of all the failures modes are reduced to medium or low. For UMS Short, there are still six modes with an unacceptable risk level of high and eight for UMS Long. The two additional Failure Modes with risk level high in the UMS Long situation compared to the UMS Short come from the matter of the degraded Failure Modes related to leakages. On long voyages, a non-critical leakage has a longer time to drain the system of oil or water, eventually causing complete loss of the equipment function.

A design change in the form of redundancy of heat exchangers is proposed to reduce the risk level for unmanned operation. Applying the first design change still leaves one Failure Mode with risk level high. For the Failure Mode "Internal Leakage", the damage occurs once LT water has mixed with the ME lube oil and it is not enough to stop the leakage only. As long as there is a substantial amount of water in the lube oil, damage will continue to develop for the engine bearings. Hence, to avoid water contamination of the ME lube oil in the heat exchanger a higher pressure is normally maintained on the ME lube oil than on the LT water. When the engine is not running, however, there will not be any lube oil pressure, but the LT water will still have a static pressure and a pressure from the circulation pump. Because the "Internal Leakage" of LT water into the ME lube oil can only occur during operation of the ME, the failure rate from the OREDA handbook [27] cannot be used directly. However, the Failure Mode "Internal Leakage" is still assumed to have an unacceptable risk level since it has a consequence severity of "4, critical". For the risk level to be reduced to medium, the probability of failure would have to decrease from "3, occasional" to "1, improbable" which is not assessed to be realistic for this Failure Mode.

It may be possible to detect an internal leak using remote oil analysis equipment but the possibilities for removing the water from the oil or replacing the oil remotely on a UMS at sea will be very limited. To eliminate or at least greatly reduce the possibility of internal leakage, it is proposed to use double-wall heat exchangers which have a void space between the process and utility medium. A leak of either cooling water or lube oil will run into the void space instead of contaminating the other medium, thus also enabling easier failure detection. The OREDA handbook [27] does not contain failure rate data specifically for double-wall heat exchangers. It is assumed that the probability of the Failure Modes related to external leakages is unaffected by this design change but that the probability of the Failure Mode "Internal Leakage" will be reduced to "1, improbable". The introduction of double-wall heat exchangers reduces the final Failure Mode risk level to medium.

Failure Mode		Scenario 1: Preventive maintenance only			Scenario 2: Preventive and corrective maintenance								
					Manned			UMS Short			UMS Long		
		C	P	R	C	P	R	C	P	R	C	P	R
Insufficient heat transfer	Critical	4	2	**H**	3	2	**M**	4	2	**H**	4	2	**H**
External leakage - process medium	Critical	4	3	**H**	3	3	**M**	4	3	**H**	4	3	**H**
External leakage - utility medium	Critical	4	3	**H**	3	3	**M**	4	3	**H**	4	3	**H**
Internal leakage	Critical	4	3	**H**	3	3	**M**	4	3	**H**	4	3	**H**
External leakage - process medium	Degraded	4	3	**H**	1	3	**L**	1	3	**L**	4	3	**H**
External leakage - utility medium	Degraded	4	3	**H**	1	3	**L**	1	3	**L**	4	3	**H**
Internal leakage	Degraded	4	3	**H**	1	3	**L**	1	3	**L**	1	3	**L**
Plugged/Chocked	Critical	4	3	**H**	3	3	**M**	4	3	**H**	4	3	**H**
Structural deficiency	Critical	4	3	**H**	3	3	**M**	4	3	**H**	4	3	**H**
Structural deficiency	Degraded	2	3	**M**	1	3	**L**	2	3	**M**	2	3	**M**

Failure Mode		Scenario 3.1: System redesign *Redundancy of heat exchangers*									Scenario 3.2: System redesign *Redundancy of heat exchangers & Double-wall heat exchangers*								
		Manned			UMS Short			UMS Long			Manned			UMS Short			UMS Long		
		C	P	R	C	P	R	C	P	R	C	P	R	C	P	R	C	P	R
Insufficient heat transfer	Critical	2	2	**M**	2	2	**M**	2	2	**M**	2	2	**M**	2	2	**M**	2	2	**M**
External leakage - process medium	Critical	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**
External leakage - utility medium	Critical	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**
Internal leakage	Critical	3	3	**M**	4	3	**H**	4	3	**H**	3	1	**M**	4	1	**M**	4	1	**M**
External leakage - process medium	Degraded	1	3	**L**	2	3	**M**	2	3	**M**	1	3	**L**	2	3	**M**	2	3	**M**
External leakage - utility medium	Degraded	1	3	**L**	2	3	**M**	2	3	**M**	1	3	**L**	2	3	**M**	2	3	**M**
Internal leakage	Degraded	1	3	**L**	2	3	**M**	2	3	**M**	1	3	**L**	2	3	**M**	2	3	**M**
Plugged/Chocked	Critical	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**
Structural deficiency	Critical	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**	2	3	**M**
Structural deficiency	Degraded	1	3	**L**	2	3	**M**	2	3	**M**	1	3	**L**	2	3	**M**	2	3	**M**

C = Consequence *L = Low*
P = Probability *M = Medium*
R = Risk *H = High*

Figure 4 Risk assessment of Heat Exchanger.

4.7.2 General results for all three equipment units

Figure 5 shows the risk assessments for manned, UMS Short and UMS Long for all three equipment units. The values in the table are percentages of Failure Modes with low, medium and high risk levels respectively, out of the total number of Failure Modes for that equipment unit. The ME lube oil cooler, for example, has ten Failure Modes in total. For "UMS Long" in Scenario 2: Preventive and corrective maintenance, the ME lube oil cooler has one Failure Mode with risk level low and one with risk level medium, equalling 10 per cent each. The last eight Failure Modes have risk level high, making up the remaining 80 per cent.

		Pumps			Lube oil cool.			Reg. Valve		
		Low	Medium	High	Low	Medium	High	Low	Medium	High
Manned	Scenario 1: Preventive maintenance only	73	13	13	0	10	90	33	17	50
	Scenario 2: Preventive and corrective maintenance	**80**	**20**	**0**	**40**	**60**	**0**	**50**	**50**	**0**
	Scenario 3: System redesign	93	7	0	40	60	0	100	0	0
UMS Short	Scenario 1: Preventive maintenance only	73	13	13	0	10	90	33	17	50
	Scenario 2: Preventive and corrective maintenance	**80**	**13**	**7**	**30**	**10**	**60**	**50**	**17**	**33**
	Scenario 3: System redesign	93	7	0	0	100	0	100	0	0
UMS Long	Scenario 1: Preventive maintenance only	73	7	20	0	10	90	33	17	50
	Scenario 2: Preventive and corrective maintenance	**80**	**7**	**13**	**10**	**10**	**80**	**50**	**17**	**33**
	Scenario 3: System redesign	93	7	0	0	100	0	100	0	0

Figure 5 Summary of risk levels for all three analysed equipment units. Numbers in pct. of total failure modes

The summary of the risk levels in Figure 5 shows the same general results as seen as in the detailed analysis of the ME lube oil cooler in Figure 4. There is almost no difference in the risk level between manned and unmanned operation in Scenario 1: Preventive maintenance only. However, in Scenario 2: Preventive and corrective maintenance, there are major differences. While preventive and corrective maintenance is sufficient to reduce the risk level to low or medium for all three equipment units during manned operation, it is not enough to achieve an acceptable risk level for any of the three equipment units for unmanned operation. For the thermostatic valve, redundancy of the entire equipment unit is proposed. For the ME LT FW circulating pumps, an additional redundant pump is proposed. These design changes will reduce the risk levels to medium and low. The detailed analysis of the ME LT FW circulating pumps and the thermostatic valve can be seen in the Appendix. If the same design changes are applied to the manned situation as the unmanned situations, the risk levels will be as low or lower for manned operation than for unmanned operation.

5 Discussion

In this section the results of the paper are discussed. The section is divided into four topics: in section 5.1 the RCM method and amendments are discussed. Conventionally manned cargo ships vs. unmanned cargo ships are discussed in section 5.2 and in section 5.3 uncertainty is considered. Lastly, the discussion of maintenance of unmanned cargo ships in the future is presented in section 5.4.

5.1 The RCM method and amendments

RCM is used in many industries, each of which have their specific characteristics and challenges regarding maintenance and reliability of machinery. Each industry will typically adapt the specific application of the method to suit their specific challenges. The amendments to the RCM method proposed in this paper are designed for use for the analysis of unmanned commercial cargo ships. What sets UMS apart from other industries is the operational constraint of not being able to access the machinery systems for repair of failures and performing maintenance for long periods at a time while at the same time not being able to power down the vessel without huge economic and safety-related consequences. This constraint also sets UMS apart from a CS that may otherwise be constructed in a similar manner. The proposed amendments to the RCM method focus on this difference in operational situations.

The amendment proposed in this paper to Step 4 - Failure Effects ensures that the long-term effects of the operation of a failed or partially failed system is considered when corrective maintenance actions cannot be performed in the timely manner otherwise assumed in the RCM method. In the amendments to Step 5 - Failure Consequences it is ensured that the intended voyage length is specifically considered. The voyage length will influence the probability of failure in multiple equipment units in systems with redundancy as detailed in section 3.1.3 and in the Appendix. The voyage length chosen for the long unmanned voyage in the case study is fourteen days which is typical for transatlantic or transpacific passages. Many cargo ships have bunker capacity for much longer voyages and some cargo ships regularly do uninterrupted sea passages of three or four weeks. The method can be used for any voyage length and the amendments will ensure that the effects which the longer voyage will have on reliability is considered.

5.2 CONVENTIONALLY MANNED CARGO SHIPS VS. UNMANNED CARGO SHIPS

The application of the amended RCM method to the case study shows that the main differences between manned and unmanned operation lie in the effect of corrective maintenance actions. For manned operation, corrective maintenance actions are able to reduce the risk level to an acceptable level for all Failure Modes for all equipment units. For the unmanned cargo ship, however, there are several Failure Modes with a risk level of high after the inclusion of the effect of corrective maintenance across all three equipment units.

Corrective maintenance tasks may be effective on UMS, but the main challenge is the severely restricted possibility of employing corrective maintenance actions. Most corrective maintenance actions rely on manual intervention at sea, which is not possible on UMS. If only preventive maintenance actions are possible, there are many Failure Modes with high risk levels for both manned and unmanned operation. For the ME lube oil cooler, eight out of ten Failure Modes have the potential to cause complete loss of propulsion and have a probability of failure in the category "4, probable". If only preventive maintenance actions can be utilised, and if these only influence probability and not the consequences of a failure mode, the probability of failure has to be reduced by several orders of magnitude to result in an acceptable risk level.

In the case study, it was assessed that additional maintenance tasks beyond those described in Table 1 would not be sufficient to reduce the risk levels of any equipment unit from high to medium or low. This is perhaps a crude assessment, but there is a limit to how much impact maintenance can have on reliability. Maintenance can contribute to maintaining the level of reliability designed and built into the system, but the level of reliability can never be higher than that inherently provided in the system design [28] unless modifications to the design are implemented.

In the case study only the consequences of failures to the propulsion of the vessel is considered, as explained in section 4.1.3. Failures of the LT water system analysed in the case study was evaluated to be unlikely to cause direct harm to human life, environment and equipment. In the analysis of other systems this will not be the case, but the amended RCM method can be used for the evaluation of these other type of consequences as well. It is further defined in the case study that a failure of the ship propulsion only has operational consequences, which is a limited assumption. Depending on the operational setting a failure of propulsion could further result in collisions with other ships or structures, groundings or foundering of the vessel. This could result in material damages, loss or danger to human life and environmental harm, all with potentially severe financial consequences as an outcome. Unmanned operation would certainly affect the magnitude of these consequences. Exactly how is still very uncertain and it is outside the scope of this paper to make a quantitative evaluation of this. Some reflection can be made on the topic, however.

In a collision, allision, grounding or foundering following a loss of propulsion, the consequences for human life could, because there are no people on board during sea passage, be expected to be less on a UMS, at least initially. Except in the case of the complete disappearance of the vessel in deep water, however, the ship would need to be salvaged which would most likely require human interaction. Without an onboard crew, mitigating the consequences of accidents would be more difficult [36] resulting in more severe environmental and material damages. The frequency at which marine accidents occur may decrease, however, due to an expected reduction in human errors during operation [36]. Human error which is an important contributing factor in many maritime accidents, will not disappear with unmanned operation [37, 38], but its nature may change. For the specific case study in this paper unmanned operation may not have a significant impact on human errors related to maintenance, since maintenance must still be carried out manually by repair personnel in port. Unmanned operation will, however, have a large impact on the ability to carry out corrective maintenance during operation.

5.3 Uncertainty

The analysis in the current paper shows that it is problematic to use existing machinery systems on UMS due to poor reliability and the severely restricted possibilities for performing corrective maintenance during unmanned operation. It must be remembered, however, that the analysed system was designed for manned operation and that it may not be suitable for unmanned operation, because it is not designed for this.

The OREDA database [27] shows that the ME lube oil cooler has high failure rates across the different Failure Modes. For this specific equipment unit, it seems very unlikely that preventive maintenance will be able to sufficiently reduce the probability of failure to achieve an acceptable risk level. For the pumps, and also for the regulation valve to some degree, it is possible that preventive maintenance tasks may be sufficient to achieve acceptable risk if slightly more reliable pumps and valves are available. It must be remembered, however, that the two pumps and one valve in the analysis are only three equipment units in a system with at least eight other units that each have the capacity to cause total failure of the system. Also, the system is only one of several systems that each have the capacity for causing a complete loss of propulsion, such as the fuel oil or lubrication oil system.

OREDA is the most comprehensive resource available for the reliability of offshore systems and is assessed to also be the most applicable database available for marine systems as explained in section 2.3, but there are important limitaitons to be considered. Only data on hardware failures is collected in the database. Human error might have been the undelying cause of some hardware failures included in the database. Also, human intervention might have prevented failures not included in the database, as well. The failure rate in OREDA is assumed to be constant over the lifetime of equipment units. Even though random failures dominate the failure distribution of many equipment units [28], this is a simplification. For the main part of the failure events in the OREDA database the beginning and end life of equipment units, which typically have a higher than average probaility of failures, is not included. Failures which happen outside the boundary of the equipment unit specified in the OREDA handbook, but which still affects the output of the unit, is not included. This could be failures to drive or control units. The failure rate estimates presented in the OREDA handbook must be considered to be a minimum over the entire life cycle of the equipment unit [27] and the risk assessments based on these are likely to be non-conservative.

The limitations of the reliability data from OREDA is acknowledged but the accuracy of results presented in the case study is evaluated to be within acceptable margins. For unmanned operation of cargo ships, however, the case study should not be seen as an analysis of a proposed unmanned system. Rather it should be seen as an indication of the shortcomings of using existing machinery systems, designed for manned operation, on UMS. An unmanned system, based on the findings in this paper, would need more redundancy, more remote operation capabilities, and more actuators and sensors. This, in turn, would create a more complex system with more sources of potential failures. On the other hand, the analysis in the paper is performed using failure rate data from the OREDA database [27] which is collected from existing systems designed for manned operation with all the assumptions that this entails.

Reliability of machinery is always a concern in the design of a system, but it must also be balanced with cost. The OREDA handbook presents data collected from real systems which may not have the highest achievable reliability. It may not have been technically feasible to invest in higher quality equipment to improve reliability or to install advanced condition monitoring equipment to detect potential failures on the assumption that corrective maintenance actions could be taken to reduce the risk to an acceptable level when a failure occurred. On a UMS where the same corrective maintenance actions cannot be performed and where the consequence of a failure might therefore be different, it may be cost effective to invest in advanced condition monitoring systems or equipment with higher inherent reliability.

5.4 Maintenance of unmanned cargo ships in the future

Failure detection does not prevent failures, it only detects failures or potential failures. When used correctly, condition monitoring can minimise collateral damage to equipment, reduce the need for unplanned operation stops and avoid unnecessary maintenance [39], but it does not eliminate the need for maintenance.

Unmanned operation may tip the business case in favour of more condition monitoring. The reason for this, however, is not because condition monitoring would be easier or cheaper on a UMS than on CS, but because the costs of failure may be higher. The introduction of UMS might necessitate increased use of condition monitoring, but it does not enable it – as such. Continuously measured failure indicators, as described in section 2.2.4, could easily be transmitted to a shore control centre and some operational check may be carried out remotely. Many condition monitoring techniques, however, rely on human presence, handheld equipment and/or partial disassembly of equipment units, such as thermography or electrical resistance testing, not to mention inspections by human sensory inputs. There are no condition monitoring methods that can be used on a UMS which cannot also be used on a CS, but there are many that are used on a CS which cannot be used on a UMS.

With advances in maritime data communication and sensor technology, as well as an increasing focus on maintenance as an instrument for operational and performance optimization, the breakeven point for when condition-based and predictive maintenance is cost effective may change in the future.

6 Conclusion

In this study, amendments to the RCM method for assessing reliability challenges and maintenance needs of unmanned ships are proposed. The applicability of the conventional RCM method for use on unmanned cargo ships is examined and the differences and similarities with respect to maintenance between conventionally manned and unmanned cargo ships are analysed. The analysis shows that the RCM method is generally well suited for maintenance management and the investigation of reliability issues for unmanned operation, but there are also limitations. Many corrective maintenance tasks are implicitly included in the operational scenario and the effect of these corrective maintenance tasks is not as visible as the preventive maintenance tasks explicitly resulting from the RCM analysis. A more structured way of assessing the effects of corrective maintenance tasks is therefore proposed in this paper. A method is also proposed for assessing the impact from long unmanned voyages on the development of failures in systems with redundancy before the system can be accessed and repaired.

The amended RCM method is tested on a case study of a real machinery system, i.e., the Main Engine (ME) Low Temperature (LT) Fresh Water (FW) cooling water system. For the case study, no major differences were found in the proposed preventive maintenance tasks between manned and unmanned operation. On manned cargo vessels, preventive maintenance work is currently performed both while the vessel is at sea and in port, but in the unmanned scenario in this paper, all maintenance work must be done in port. This was found to be realistic for the proposed preventive maintenance during port calls, both with regard to the number of work hours required and the maintenance task intervals if the operational pattern of the unmanned cargo ship is similar to that of a typical manned vessel of this type. The analyses in this paper, however, do not indicate whether it will be possible to perform all the needed maintenance while the vessel is in port without interfering with the normal operation of the cargo ship, as the maintenance tasks proposed for the analysed machinery system are only a very small part of the total maintenance work burden.

Major differences in the possibilities for performing corrective maintenance between manned and unmanned operation were found, because corrective maintenance chiefly depends on the ability of the onboard crew to make physical repairs. Without humans present on the unmanned cargo ship at sea, the possibilities for performing corrective maintenance are severely restricted, which has a major impact on the consequences of failures. To achieve an acceptable risk level on unmanned cargo ships, increased redundancy in some form is found to be necessary for all the analysed equipment units.

Design changes that reduce the risk level to an acceptable level are proposed. The risk is found to be manageable with design changes to the unmanned cargo ship for the analysed system but is not found to be lower for unmanned operation than for manned operation in any scenario. The main difference between manned and unmanned operation regarding reliability is found to be the greatly differing possibilities for corrective maintenance actions. This presents a major challenge to the unmanned operation of commercial cargo ships.

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APPENDIX

Figure A.1 in this appendix shows the details of the risk assessment of the ME LT FW circulating pumps and thermostatic regulation valve which are not displayed in detail in the main text. The details of the results of specific failure modes are explained.

	Failure Mode		Scenario 1: Preventive maintenance only			Scenario 2: Preventive and corrective maintenance									Scenario 3: System redesign *Redundancy equipment unit*								
						Manned			UMS Short			UMS Long			Manned			UMS Short			UMS Long		
			C	P	R	C	P	R	C	P	R	C	P	R	C	P	R	C	P	R	C	P	R
ME LT circulating pumps	Spurious stop	Critical	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	External leakage - process medium	Critical	1	4	M	1	4	M	1	4	M	1	4	M	1	4	M	1	4	M	1	4	M
	External leakage - process medium *	Degraded	4	3	**H**	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	External leakage - utility medium	Critical	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	External leakage - utility medium	Degraded	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Internal leakage	Critical	1	2	L	1	2	L	1	2	L	1	2	L	1	2	L	1	2	L	1	2	L
	Internal leakage	Degraded	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Plugged/Choked	Critical	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Plugged/Choked	Degraded	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Breakdown	Critical	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Structural deficiency	Critical	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Structural deficiency	Degraded	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Low output	Degraded	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L	1	3	L
	Critical failure + fail to start on demand †		4	2	**H**	3	2	M	4	2	**H**	4	2	**H**	1	2	L	1	2	L	1	2	L
	Two independent failures ‡		4	2	**H**	3	1	M	4	1	M	4	2	**H**	1	1	L	1	1	L	1	2	L
Thermostatic regulation valve	Fail to regulate	Critical	4	1	M	3	1	M	4	1	M	4	1	M	1	1	L	1	1	L	1	1	L
	Fail to regulate	Degraded	2	1	L	2	1	L	2	1	L	2	1	L	1	1	L	1	1	L	1	1	L
	Spurious operation	Critical	4	2	**H**	3	2	M	4	2	**H**	4	2	**H**	1	2	L	1	2	L	1	2	L
	Spurious operation	Degraded	2	1	L	2	1	L	2	1	L	2	1	L	1	1	L	1	1	L	1	1	L
	External leakage - process medium	Critical	4	2	**H**	3	2	M	4	2	**H**	4	2	**H**	1	2	L	1	2	L	1	2	L
	External leakage - process medium	Degraded	4	2	**H**	1	2	L	1	2	L	1	2	L	1	2	L	1	2	L	1	2	L

C = Consequence
P = Probability
R = Risk

L = Low
M = Medium
H = High

Figure A.1 Risk assessment of ME LT circulating pumps and thermostatic regulation valve

* The ME LT circulating pumps are fitted with an auto-start function which will activate the stand-by pump if the outlet pressure of the operating pump decreases below a predefined setpoint. A critical leakage of process medium from the operating pump, in this case LT cooling water, will activate this function with little or no disruption to the LT cooling water flow. A degraded leakage of process medium may not create a pressure drop large enough to activate the auto-start function. If the degraded leakage remains undetected for

long enough, the LT water will drain from the system and cause disruption to the LT cooling water flow, resulting in shutdown of the propulsion.

† The auto-start function of the ME LT circulating pumps relies on the stand-by pump to take over when the operating pump fails. However, sometimes the stand-by pump will fail to start on demand, which may have severe consequences in a system with only two pumps. The OREDA handbook includes information on the rate at which equipment units fail to start on demand. Equation A.1 calculates the rate at which a failure mode is experienced and where the stand-by unit will subsequently fail to start on demand.

$$\lambda_{Total} = \lambda_{Critical\,failure} \cdot \lambda_{Fail\,to\,start\,on\,demand} \tag{A.1}$$

The failure rate of the Failure Mode *"Critical failure + fail to start on demand"* is calculated as the rate at which any of the critical failure modes of the ME LT circulating pumps will occur and where the stand-by pump subsequently fails to start on demand.

‡When there is redundancy of equipment units, as is the case with the ME LT circulating pumps, the risk level is initially assessed using the probability and consequence of one equipment unit failing and the redundant unit(s) being able to take over the function of the failed unit. In redundant systems, there is also the possibility of failure of all the redundant units within a specified time period, which will typically have severe consequences. For many equipment units, such as the ME lube oil cooler and the thermostatic regulation valves, the probability of multiple units failing within the duration of a typical sea passage of a ship is so insignificant that this possibility can be ignored. For the ME LT FW circulating pumps, however, the probability of experiencing failures of multiple equipment units is a real possibility. This should especially be considered for long unmanned voyages, where there is little possibility of repairing a failed unit at sea.

Equation A.2 calculates the reliability of a system with redundancy in the equipment units with *k* units over the time period t, where one is running at a time while the others are in stand-by, and where λ is the failure rate. The equipment units have identical failure rates and there are no failures in the stand-by mode.

$$R(t) = e^{-\lambda \cdot t} \cdot \sum_{i=0}^{k-1} \frac{(\lambda \cdot t)^i}{i!} \tag{A.2}$$

Time period t is 1 day for UMS Short and for manned operation and 14 days for UMS Long.

Equation A.3 calculates the probability of experiencing a failure of multiple units over the course of one year of continuous operation of voyages with duration t.

$$F_t(t) = 1 - R(t)^{\frac{365}{t}} \tag{A.3}$$

For small values of λ, $\lambda \approx F_t$.

The failure rate of the Failure Mode "*Two independent failures*" is calculated as the rate at which both ME LT circulating pumps will experience any of the critical Failure Modes of this equipment unit type over a year of continuous operation of voyages with duration t.