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# Naval maintenance. From corrective maintenance to condition monitoring and IoT. Future trends set by latest IMO amendments and autonomous ships.

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**Abstract**. The maintenance of an equipment represents the totality of the actions undertaken for the maintenance or restoration of its functions to fulfill the role for which it was designed. These actions have evolved due to technological progress and each industry has contributed to its improvement, creating maintenance policies and strategies that are widely applicable in all areas. The maritime industry has experienced a transformation of maintenance strategies similar to the manufacturing industry, from reactive to preventive and, recently, to proactive.
The current paper highlights the role of maintenance in the shipping industry and the need for some of the maintenance strategies to be adapted to meet the last requirements in terms of pollution and operation of autonomous ships. Also, are presented the evolution, role and need for change of maintenance management in the shipping industry according to the latest IMO amendments. Some of the less applied maintenance strategies in the shipping industry, but which have proved useful in other areas, such as Reliability Centered Maintenance, Self-Maintenance and IoT Maintenance, are discussed with emphasis on adaptability and implementation on board ships.
**Keywords**: ship maintenance, IMO amendments, autonomous ship, RBI, RCM, IoT based maintenance

## 1. Introduction

The shipping industry is one of the main elements of international trade. According to the latest reports in the field, about 85% of international trade occurs on the sea and river routes around the globe, one of the reasons being the low price compared to the volume of goods transported.

To support the accelerated growth of international trade, ships have experienced significant technological improvements, to increase transport capacity, increase operational safety, but also to reduce the risk of pollution of the marine environment. Currently about 20.1% of container vessels and 31.2% of tankers have a GT> 60,000 [1].

In addition to the transport of goods, ships and maritime constructions are used for resource exploitation activities (oil and gas, fishing), military missions, support activities (tugs, pushers, dredging) or research.

Usually the life of a ship exceeds 25 years of operation. Maintaining operational status involves the allocation of resources for regular maintenance of main systems and equipment but also reconversion/refurbishment to align with the new standards imposed by international law. Statistics show that 58% of the total number of ships are over 15 years of operation, the largest share being ships of small and medium transport capacity, below 25 000 GT about 61%.

Competitiveness, reducing costs in this area but also by increasing the operating time of ships influence the maintenance policies that can be applied for ships. Over time, maintenance has advanced from reactive to preventive and proactive or advanced, defined by Trojan and Marcal (2017) - Monitoring, Maintenance engineering, RCM, TPM [2]. In the maritime field, maintenance can be classified into three broad categories: time-based maintenance (TBM), condition-based maintenance (CBM) and run-to-failure (RTF).

As the degree of automation and technological complexity of the ship is increasing, the maintenance activities become a challenge for the company's management and on-board operating personnel. For these reasons, failures and faults of the ship's systems can lead to accidents and safety problems of the personnel (maintenance accidents and safety problems). According to the study "*The causes of maritime accidents in the period 2002–2016*" conducted by a team of researchers at Cardiff University it is observed that inadequate or inefficient maintenance was the main cause in 12.1% of cases (84 accidents) [3].

The ship's systems and equipment are maintained after periods/cycles/hours of operation, without checking actual condition of the components or the entire system. Here, the periods of operation and the volume of repair work are dictated by the manufacturer's specifications and require the allocation of significant resources for maintenance planning, related work, spare parts stock, the degree of operation of the ship. Due to the redundant feature of the equipment on board, the operation of the ship will not be affected for low complexity work (maintenance, overhaul, testing).

This paper is organized as fallow: Section 1 is an introduction to the thematic where is highlighted the necessity for a different maintenance strategy for onboard systems after a short discussion on current maintenance practices. In the second section article study RCM, IoT and self-maintenance as better approaches to reduce potential failure and improve the reliability of ships and its equipment.

For understanding the scope and direction for failure detection and risk evaluation for onboard systems, key-findings of ten research articles were discussed in the last section. The authors introduced a model design for integrating the maintenance strategy discussed. With the aim of improving maintenance performance and reduce costs, maintenance strategy will change perspective and moving forward toward a "predict-and-prevent" maintenance using tools and methods to prognose the defect at an early state and restore equipment condition after normal wear in operation.

The proposed framework provides a theoretical means for understanding how performance data, the history of failure events, risk assessment, IoT infrastructure and machine learning will improve reliability of onboard systems.

## 2. Maintenance of naval vessels

### *2.1. Current maintenance practice*

Three types of maintenance are being used in the maritime sector for equipment application (figure 1): corrective, preventive and predictive (also known as condition-based maintenance).

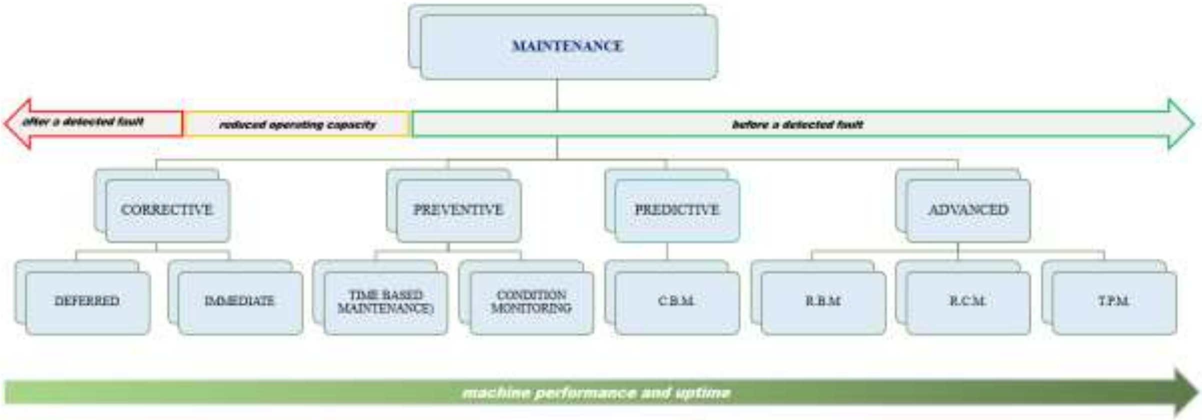


Figure 1. Type of maintenance (adapted from EN 13306 and [2])

Corrective maintenance (run-to-failure, breakdown, reactive) allows a failure to develop before action is taken. In most of the cases, no repair is possible and the damaged component (equipment) is replaced by a new one. To execute repair, a large spare-parts inventory is required onboard the ship [4].

This method of maintenance is, at first, low cost, because it can be performed using few resources and low maintenance infrastructure (tools, technologies and expertise). The cost rises when the failure may lead to high equipment downtime and risk of secondary faults that will affect multiple components or entire ship operation. Also, maintenance-related activities are not planned in advance with consequences for the safety of personnel and mission. In terms of reliability of the equipment the MTBF will be much lower than preventive or proactive maintenance.

However, this type of maintenance is still-applied onboard to not expensive and non-critical equipment or where redundancies are well implemented for uninterrupted system (ship) operation. To overcome the disadvantages a large spare-parts inventory is required and crew onboard is caring out maintenance tasks to restore the equipment to a proper condition during ship operation. According to IACS corrective maintenance procedure consist of location and isolation of failure, establishing the cause and propose a solution to rectify the fault.

Preventive maintenance deals with scheduled inspection (time base maintenance), which are performer to replace or repair equipment at a fixed frequency, usually following manufacturer recommendations and offers many benefits compared to reactive strategy. However, preventive maintenance also has multiple shortcomings regarding cost and planned downtime. Because maintenance tasks like, lubrication, adjustments, replacement is conducted as a precaution, irrespective of the actual condition of the equipment it can be considered a resource consuming maintenance practice. Also, repeated process for replacing components will result in over-maintenance with no improvement on service life, reliability, or lower risk of failure for an asset.

Corrective and preventive maintenance are still present in the maritime industry even if the ship maintenance is about 10%-15% of direct operating cost. Take into consideration all of the above an optimized maintenance program will focus on extended equipment lifespan, optimize downtime, reduce cost and improve safety. This type of maintenance is usually classified as predictive and offers a more innovative method of maintenance planning and execution.

Predictive maintenance involves the use of condition data and machine learning technique to evaluate the system also statistical algorithms to predict a failure [5]. At first requires a higher cost for implementing condition monitoring and training personnel (installation, operate, collect and evaluate condition data) but considering the benefits over an extended period becomes more economical than periodic maintenance. Most important is that an accurate evaluation of equipment condition is a perquisite for better maintenance planning and reduce human errors.

*2.2 Reason for moving forward toward a "predict-and-prevent maintenance"*

Ships are the backbone of world trade and the volume of goods transported is expected to at least double in size by 2030 with a corresponding increase in the world merchant fleet [6].

This will lead to a substantial increase in maritime traffic and the risk of maritime accidents and incident at sea could be higher in the future, if we consider that nowadays the cause for 80%-90% of maritime accidents are due to human error [7, 8].

Recently, various research projects analyze challenges and proposed solutions regarding operational concept and new technologies for maritime autonomous ships. International Maritime Organization also conducts a regulatory scoping exercise to develop a framework, including objectives, methodology, instruments, type and size of ships, different types and concepts of autonomy, automation, operations and manning to be considered [9].

To eliminate human errors, increase productivity and efficiency shipping industry has implemented different grade of automation onboard ships. Lloyd's Register define autonomy levels (AL) from AL1 to AL6, as a fully autonomous ship with no access required during voyage (figure 2).


Figure 2. Autonomy level (AL) for ship design and operation [10]

Beside necessary regulation amendments that will need to be issued, ship design, construction and operation will change the shape of future vessel. Some changes identified through a literature review are related to: [11]

- redesign of hull structure, deckhouse and machinery spaces;
- new propulsion system: electric, hydrogen, fuel cell;
- sensor development to ensure autonomous function for different systems;
- remote operation capabilities;
- reliable (safe) communication system and cybersecurity;
- improve equipment redundancy;
- remote monitoring, maintenance and inspection;
- decision support technology for emergency response situation;

Maritime industry as all other transport industries, is in a continuous state of digital transformation and with strong cooperation of all stakeholders - ship designers, classification societies, equipment manufacturers and shipping companies in a narrow timeframe the fully autonomous ships will be a reality. [12]

Over the last decade, with the increase in international trade, the IMO has issued new amendments to reduce air pollution due to fuel consumption. According to a study on the effect of sulfur oxide (SOx) content in exhaust gases in coastal areas, setting new limits on sulfur content five years earlier may help reduce the content of air pollutants by 77%. Thus, from 2020 onward, the maximum sulfur content of the fuel used on board ships should be reduced from 3.5% (the maximum value set in 2012) to 0.5% and 0.1%, respectively, in SECA (Sulfur Emission Control Areas) [13].

On short-term ships must meet the challenging goals posed by IMO to reduce the overall emission, improve the use of energy, consider renewable sources of energy and focused on increasing safety and reliability for the safe efficient and clean transport.

Besides the equipment manufacturer recommendations decision for servicing the equipment onboard depends on a sensor-driven management system that provides continuous monitoring for the main parameters (pressure, temperature, flow, speed, current, voltage) and alarm system when the values exceeds the limits. When an alarm is activated a certain level of degradation is installed and in most of the cases it's already too late to prevent the failure.

Therefore, ship maintenance, as other industries, must change perspective and move forward toward a "predict-and-prevent" maintenance using tools and methods to prognose the defect at an early state for better logistical scheduling and maintenance [14].

## 3. Overview of advanced maintenance strategy

As stated above, one of the most important factors for safety and seaworthiness of a ship is the proper maintenance of the equipment and system. Analyzing figure 2, from the third autonomy level reduces human presence onboard will affect conventional maintenance management activities (failure detection, stand by selection, isolating fault, repairs, spare parts, testing and operation of equipment).

Research conducted particulars in maritime industry develop methods for solving this maintenance problems. The article study RCM, IoT and self-maintenance approaches to reduce potential failure and improve the reliability of ship and its equipment.

The scholarly or academic databases used for this article include articles from ScienceDirect, Web of Science, and ResearchGate. The search was conducted based on keywords "ship maintenance", "RCM", "RBI" (risk-based inspection), "IoT" and "self-maintenance" in different combinations. The documents are limited to the recent time parameters 2010 to 2020, subject from engineering and energy, in English. Most of the results were in the area of reliability and risk-based inspection, IoT and IoT maintenance with few articles recently. Some articles with topic self-maintenance were published before 2010 and few after, most of them are cited at section 3.3.

### *3.1 Reliability-centered maintenance*

Reliability-centered maintenance (RCM) was first introduced in a report published by US Department of Defense in 1978. At the beginning RCM was developed in the aviation industry with positive results and the method was standardized. Soon after different industries adapt the RCM and became well known in the field of maintenance.

RCM is used in many industries, each of which have their specific characteristics and challenges regarding maintenance and reliability of equipment. Each industry will adapt the specific application of the method to suit their specific requirements [15]. It is a method to determine which maintenance method will be best for a particular piece of equipment that is selected for RCM analysis.

In maritime industry reliability-centered maintenance can be useful due to different reasons. First, this method is adaptable to many types of system and can provide technical maintenance information throughout the equipment life cycle (number of failure and repairs, downtime, repair time, condition of equipment). If this information is processed and properly analyzed the equipment reliability will increase and maintenance activities would become more efficient at a lower cost. Alternatively, RCM is a dynamic method and new information related to equipment condition will keep the maintenance program updated.

RCM is an optimal mix of known maintenance policies - reactive, time based, condition-based and proactive and its application brings benefits such as increased equipment reliability at a low maintenance cost and a positive impact on productivity. A simple RCM implementation process consists of three main steps: equipment selection, analysis, outcome and feedback. A more detailed succession of stages is described in figure 3 [18].

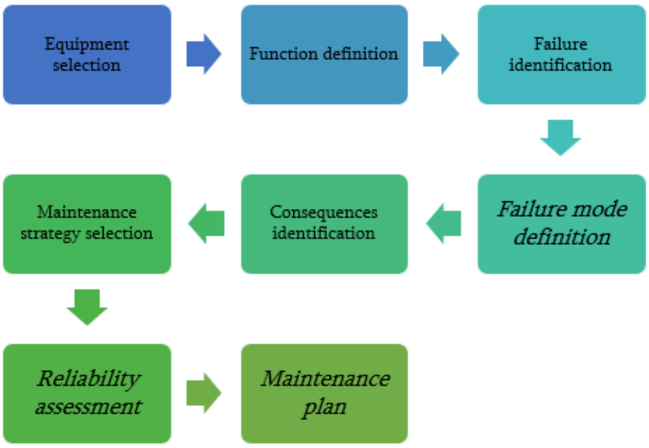


Figure 3. RCM methodology [18]

For a better understanding of the process in table 1, the process is detailed starting with the selection of equipment, data collection, identification of defects and consequences for the analysis of the reliability of the system to plan maintenance work [16 - 21].

Table 1.

| **Phase** | **Description** | **Characteristic** | **Done by** | **Question** |
|---|---|---|---|---|
| Selecting equipment and collecting relevant data | Select asset, process, system that needed deep analyze regarding severity, cost and other requirements | Collecting operational and maintenance data | Operators, experienced technicians, RCM teams, experts | What is the most important equipment? |
| Define system functions (block diagram) | How system works so that it can be handled accordingly | Define components contained in the system and how they operate. Essential to know the function of selected equipment to apply best maintenance strategy. | | What is the function of this equipment? |
| Failure mode definition | Identify all the ways in which selected equipment and system can fail. | It involves identifying all the events, which are reasonably likely to cause each failure state | | How can it fail?<br>Does it matter if it fails? |
| Identify root causes | Identify main causes of such failures so that failures can be removed permanently | Root causes are the main reason for the occurrence of such failures. It's necessary to identify main causes of failure, so that one can identify and implement effective solutions and maintenance strategies to eliminate failure permanently | | What happens if it fails?<br>What could cause it to fail? |
| Consequences of failure | The effects of each failure mode are considered. Failure can have a greater impact on the system. | Necessary to determine criticality of failure before its occurrence. Various techniques can be used to identify the effect of failure as given below: failure mode and effect analysis (FMEA), hazard and operability studies (HAZOPS), fault tree analysis (FTA), Risk-based inspection (RBI) | Software, RCM teams, experts | What is the impact of the failure?<br>In what way does each failure matter?<br>What are the consequences of each failure? |

| Phase | Description | Characteristic | Done by | Question |
|---|---|---|---|---|
| Maintenance strategy selection/determine preventive tasks | Represents the only way to preserve the failure of the equipment. It must be cost-effective, reliable, and technically feasible | Choosing the maintenance strategy based on the operational context, such as time-based, condition-based, or run to failure. | Maintenance management, RCM teams, experts | Which is the best way to diminish to a satisfactory degree, the consequence of the failure? |
| Identify alternatives | In case of maintenance tasks are not effective an alternative must be found | If maintenance tasks are incapable of preserving the reliability and function of equipment, RCM teams may have to replace or redesign the unit. | Maintenance management, RCM teams, experts | What must be done if a suitable proactive task cannot be found? |
| Create maintenance plan implement and review | Base on reliability assessment maintenance tasks will be programed. | RCM is a process that requires continuous improvement and maintenance. Therefore, after implementing maintenance strategy, one to review and check it regularly and should main continuous improvement. It should be reviewed regularly so that new updates can be implemented. | Maintenance management User, maintenance personal engineer | Is this program efficient? Can it be improved? |

However, this type of maintenance has some drawbacks, one is related to personnel working onboard ships, in particular their knowledge about risk assessment and the general perception that an extensive amount of information will make the task of maintenance more difficult to execute [22].

Also, failure detection does not prevent failures, it only detects potential failures. When used correctly, condition monitoring can lower the risk of damage to equipment, reduce the need for unplanned actions and avoid unnecessary maintenance, but it does not eliminate the need for maintenance.

### *3.2. Internet of Things based maintenance*

The organization that relies heavily on data will rapidly adopt cloud computing infrastructure. These architectures have the advantages of various computing and data storage resources, including the Internet of Things (IoT).

Recently, the Internet of Things has received increased attention and now it actively shapes industrial and commercial environment. Machine-to-machine (M2M), a technology that allow machines to communicate with each other, set the foundation on which IoT improved by adding the third element: data. Each solution improves business performance through a remote connectivity power collection of data but M2M technology usually use data for local point application. IoT is a technology of system integration and can be defined as the intelligent connectivity of smart devices that can sense and interact with the environment around them getting real-time information and feedback.

It started as a vision in which the internet extends in real life and everyday objects [23]. At the beginning the concept of connecting equipment to internet was implemented for home appliances, such refrigerators, air condition unit, control devices for lighting and heating by using mobile or private networks. Nowadays, IoT evolved to a smart industry where manufacturers, retailers and consumers from various domain like production, facility management, transport, health, oil and gas can use the data for increase production, employee safety and reduce expenses [24]. Because of its flexibility this technology has an almost unlimited potential to be useful in a wide variety of application and environments.

Application of IoT concept in maintenance is at the beginning and few studies address this topic [25–27]. The main reason to apply IoT concept in maintenance is related to predictive techniques for monitoring assets. Sensors embedded in equipment check for abnormal condition and after a proper evaluation the system notifies operating personal when safe operation limits are breached or even trigger work orders when a part replacement is required. In the manufacturing industry, it started with collecting performance data from different equipment using IoT platform and creating a cloud based predictive maintenance system for improving factory upkeep [25].

For a predictive maintenance strategy to work effectively, maintenance is conducted only after evaluating the actual condition of equipment, thus reducing maintenance cost. Actual condition can be assessed based on the "symptoms" it manifests during operation: vibration, noise, temperature, pressure, current as is represented in figure 4.

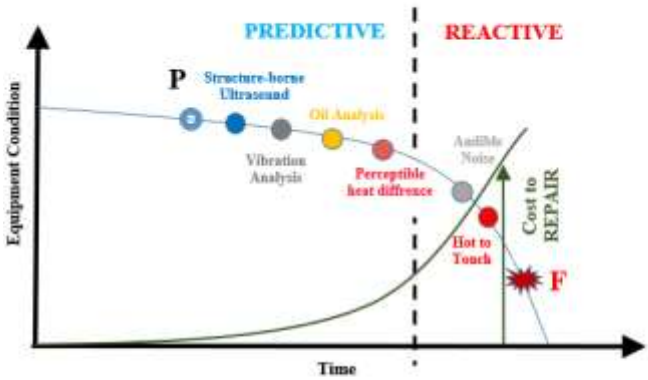


Figure 4. P-F curve for bearing failure in a production system

Sensors are designed to capture row data which are converted and transfer for further analysis on cloud computing. For better understanding of the process and to prevent early failures different sensors are embedded. An IoT predictive maintenance program relies heavily on the central system that stores the information collected (figure 5) [27].


Figure 5. IoT implementation in manufacturing industry [27]

Processing of predictive maintenance algorithms can be done on the three layers of cloud computing, based on criticality, redundancy and availability of the equipment. Cloud computing and IoT are often talked about in conjunction because the two technologies support each other, in fact IoT relies on different cloud services to store and analyze device data and metrics or enable automation. Figure 6 presents the main characteristics, difference between layers and how information is processed in cloud computing.

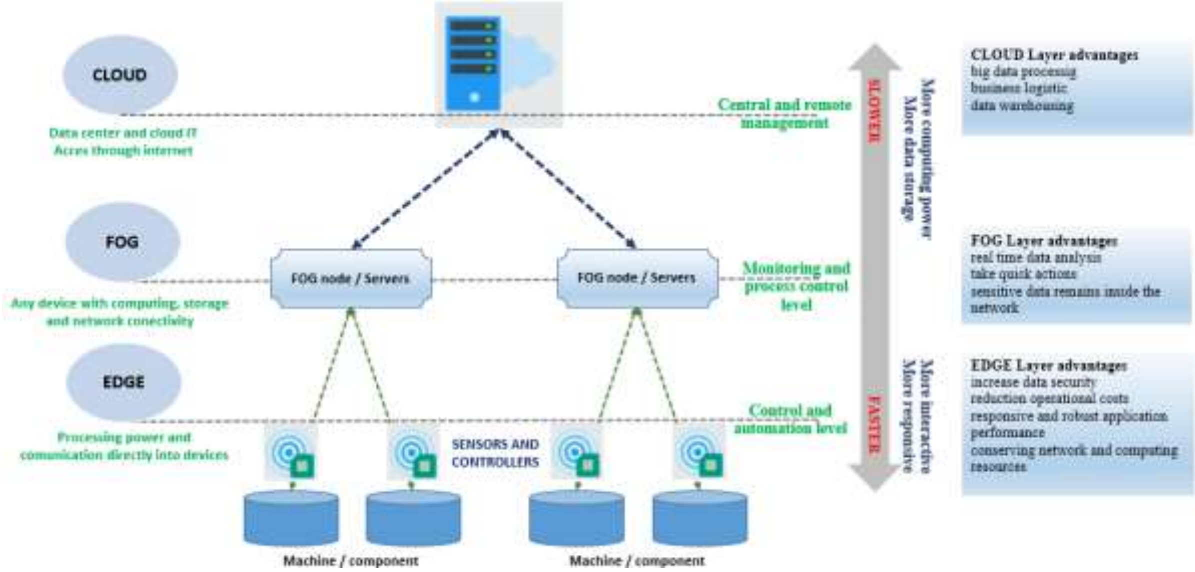


Figure 6. Industrial IoT data processing layer stack [27]

Discussion on IoT maintenance, infrastructure, communication and detail about how information is processed will be continued in section 4.

### *3.3 Self-maintenance*

Self-maintenance is a new system methodology that is based on the concept of functional maintenance introduced by Umeda et al., 1995 [28]. Functional maintenance recovers the requested function of a machine after a fault or a certain level of degradation has occurred by trading off function. It is a more flexible strategy than physical maintenance (traditional repair) that recovers initial physical state of machine by replacing faulty components.

Another system approach for this concept is proposed by Lee et all (2011) witch discus the self-maintaining ability of equipment by adding the self-service trigger function. An equipment with this function will be able to self-monitor, self-diagnose, and self-trigger the service request with detailed and clear maintenance requirements. The maintenance task is still conducted by maintenance personnel, but the "no gap integration of machine, maintenance schedule, dispatch system and inventory management system will minimize maintenance costs to the greatest extent and raise customer satisfaction to the highest level" [29].

Self-maintenance can be useful in sites difficult to access, such as offshore wind turbines or autonomous ships, where equipment function without human supervision. A self-maintenance machine should monitor and diagnose itself by adding "intelligence" to the machine. Therefore, a self-maintenance machine should have some capabilities for monitoring, fault detection, diagnose, repairing planning and executing, self-learning and improvement, besides its required main functions. To achieve above capabilities Singh et all, 2014 propose an architecture for the self-maintenance machine, as presented in figure 7 [30].

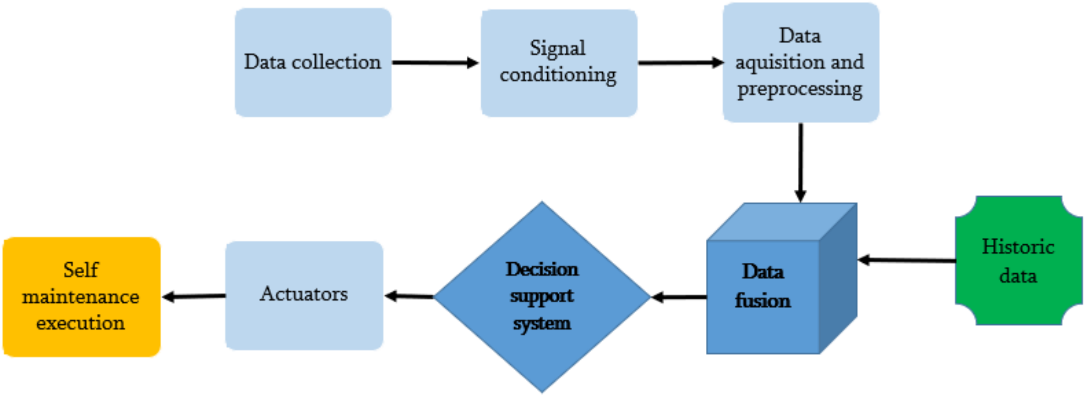


Figure 7. Architecture of self-maintenance system [30]

A practical application of this strategy was introduced by Umeda who designs a self-repairing copier that was capable of adjusting parameters in case of fault to recover part of its requested function and have the possibility of "functional redundancy" to use potential functions in different ways from the original design.

The implementation of self-maintenance machines will reduce the sudden, unscheduled visits of service engineers at the equipment location and, in the case of fault, the equipment will continue to function on low performance by reconfiguration of behavior to maintain the most important function while sacrificing the other.

## 4. Application for ship maintenance

The data acquisition system is the key requirement for predict-and-prevent maintenance. Al three maintenance method use information for assessing equipment condition, executing maintenance tasks or improve work efficiency at a lower cost than conventional maintenance strategy.

Each step from collecting row data to evaluating and building algorithms is important for a proper maintenance decision. Good data acquisition system will lead to correct and rapid identification of failure and scheduling a complete repair to restore equipment function.

When we talk about unmanned ships, self-maintenance will be implemented onboard because it does not involve the human factor in repair activities, allowing machines to execute maintenance tasks after evaluating actual condition of the equipment and still maintain its function. For this approach to be effective is necessary to identify which machine/piece of equipment need to be monitored and why.

Reliability center maintenance has tools and means to identify faults or problems that, when eliminated or resolved, increase the overall production of certain equipment, as well as lower maintenance costs. Recently, various studies and research articles discussed failure identification and risk assessment in maintenance activities from maritime industry. Understanding the scope, benefits and direction of these studies will be useful for adoption and implementation of condition monitoring systems to assess and reduce the potential risk of failure for conventional or autonomous ships. Some techniques used for risk assessment, extracted from ten research articles published between 2010 and 2020 for onboard system and equipment, requirements and further direction are presented in the **Appendix**.

Take into consideration all the facts presented in previous sections for practical implementation of a predictive maintenance program, using the benefits from RCM, IoT and self-maintenance it is necessary to plan and execute some activities by following the framework presented in figure 8.

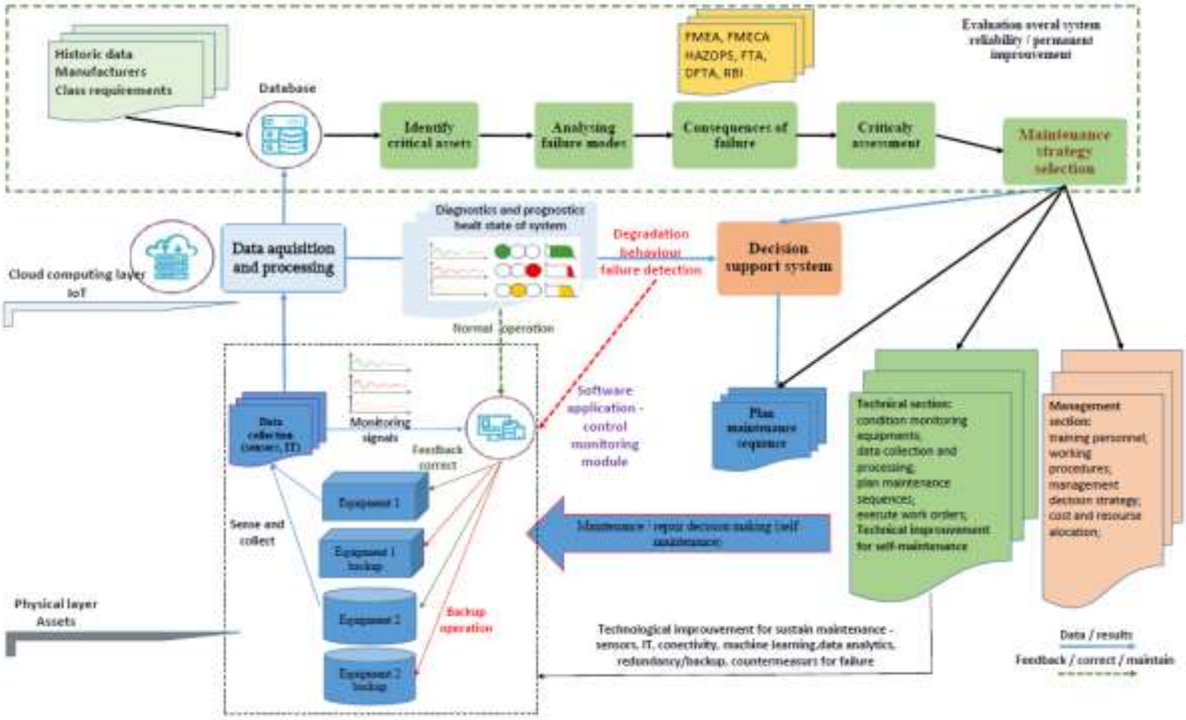

Figure 8. Overall framework for maintenance strategies discussed in the article

The linking element for all activities is represented by a database where information from various sources is stored for further use. One side is represented by stakeholders (such as equipment manufacturers, suppliers, class authorities) who set guidelines regarding repair and preventive maintenance task and historical data of equipment (maintenance and monitored condition data) for reliability analysis.

Relevant data are used for equipment selection, analysis of failure mode, root cause and consequences. From studies presented in **Appendix**, various methods to determine the effect of failure can be used, such as: failure mode and effect analysis (FMEA), Failure mode, effects, and criticality analysis (FMECA), hazard and operability studies (HAZOPS), fault tree analysis (FTA), dynamic fault tree analysis (DFTA), Risk-based inspection (RBI).

For the last step of RCM implementation, the most appropriate maintenance strategy, that is technically and economically feasible, is determined for each failure:

- condition-based maintenance - to detect the onset of the failure mode;
- time (usage) based preventive maintenance - to reduce the risk of failure using this method;
- corrective maintenance - for failure modes that were not identified as being critical.

For failure modes that do not have satisfactory condition-based maintenance or preventive maintenance options, should be considered a redesign of the system to eliminate or reduce the failure mode. Because corrective maintenance depends on the ability of onboard crew to execute repairs in a short time frame for an autonomous ship this method will not be a solution. To reduce the risk to an acceptable level some form of redundancy will be implemented onboard [40].

To implement maintenance tasks accordingly some management and technical aspects will need to be considered. Technological improvement is needed to sustain IoT based maintenance - sensors, IT infrastructure, connectivity, machine learning, data analytics, redundancy/backup, countermeasures for failure.

Each piece of equipment is part of a system, which is designed to fulfill a specific function onboard and a redundancy level is requested. An IoT application is divided in five layers [41]:

- sensing layer - gathers data from equipment/environment and interacts with it using sensors and actuators;
- network layer - connects lower level and send data to storage layer;
- storage layer - stores sensor data, aggregations, and other types of data;
- learning layers - perform data analytics for knowledge discovery;
- the application layer - provides the interface to the IoT system by providing lower layer access and control.

Condition monitoring is the process of “monitoring a set of parameters of condition in a system to identify a significant change that indicates a developing fault” [32]. Analysis of measured data represents a pre-processing step that validates sensor output and extract value for diagnostics and prognostics. If a deviation is detected, the system will send an alert signal for an operator/control system to take action.

In case of anomaly detection, or deviation detection control monitoring module will activate response action for starting backup equipment (part of the equipment) to preserve normal operation of the system and, considering level of deviation and the criticality of the system, to ensure

- reduce load, adjusting values of equipment parameters for restoring normal operation;
- activate “functional redundancy” to restore some of the function, at the lowest level, to use equipment as backup;
- reduce load on equipment and prepare shut down;
- safety shut down of equipment.

Also, for a backup communication system or in case of emergency (safety situation) it is necessary that on-board level (EDGE layer) information and monitoring signal to be analyzed in real-time. Smoke, vapors, short circuit or fire will be considered “safety triggers” and emergency response actions should be considered.

In conclusion predictive maintenance relies on condition-monitoring equipment to evaluate an asset’s performance in real-time. Using condition-based diagnostics with predictive formulas and with benefits from the Internet of Things, predictive maintenance creates an accurate tool for collecting and analyzing equipment data. These data allow for proper identification of events that need or will need more attention for preventing failure development.

## 5. Conclusion

The primary purpose of this paper is to specify the need for a different maintenance strategy for onboard system facing development of autonomous ships and new amendments to protect maritime environment.

Second, for understanding the scope and direction for failure detection and risk evaluation for onboard systems, key-findings of ten research articles were discussed.

Research conducted particulars in maritime industry develop methods for solving this maintenance problems. After a short discussion on current maintenance practices, article study RCM, IoT and self-maintenance as better approaches to reduce potential failure and improve the reliability of ships and its equipment.

The authors introduced a model design for integrating the maintenance strategy discussed in section 3. With the aim of improving maintenance performance and reduce costs, maintenance strategy should change perspective and moving forward toward a “predict-and-prevent” maintenance using tools and methods to prognose the defect at an early state and restore equipment condition after normal wear in operation.

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**Appendix**

| Reference/year | Maintenance strategy | Topic | Requirements/findings | KEY- FINDINGS |
|---|---|---|---|---|
| 31, 2011 | RCM, RBI | Study of an innovative ship maintenance strategy based on criticality and reliability assessment | Review current maintenance standards and procedures and propose a framework for reliability and criticality-based maintenance for ship systems.<br>A novel approach of FTA applied onboard a diving support vessel (DSV) using dynamic gates for a more precise representation and to describe and solve the problems for complex structure, like | Evaluate system components, observe their influence on ship reliability and give a solution for later improvements. |
| 32, 2012 | RCM | New strategy in maintenance - Reliability and Criticality based Maintenance (RCBM) | Highlight the need for a novel maintenance strategy.<br>Propose framework for optimum maintenance approach for a ship based on system reliability and criticality analysis (the innovative RCBM maritime maintenance strategy.<br>This strategy brings the equipment to a good functional state within the operational limits rather to restore it to perfect operational state.<br>Present the use of Dynamic Fault Tree Analysis (DFTA) for the main system of a diving support vessel. | The proposed RCBM strategy has the capability and flexibility to adapt the application for an entire system as well for the sub-systems.<br>RCBM strategy could enable real-time decision support actions if it will be applied with a web-based solution for collecting and evaluating maintenance data. |
| 33, 2014 | RCM, RBM | Novel approach regarding risk priority number (RPN)<br>Study on the application of Failure Mode Effect and Analysis (FMEA) for marine machinery systems | Evaluate the existing risk analysis techniques for marine machinery systems – FMEA.<br>Propose a hybrid risk prioritization methodology for calculating the risk priority number (RPN) using AVRPN (Averaging RPN) and AVTOPSIS (Averaging TOPSIS). | Either method proposed can be suitable for use in the prioritization of marine machinery systems when dealing with data that may be imprecise.<br>These methods use averages without resorting to specialized software or programing concepts. |
| 34, 2016 | CBM, RCBM | INCASS project – an innovative solution to ship inspection by integrating robotic automatic platform for on-line or on-demand ship inspection activities | In the presence of the latest literature review of HCA (Hull Condition Assessment), CBM, and condition monitoring techniques.<br>Propose a framework for developing INCAS platform (Inspection Capabilities for Enhanced Ship Safety) consists of soft tools for assessment of risk and reliability for structural and machinery of ships (SRA and MRA) and a central database. | Introduce the innovative solution for ship inspection and maintenance, regarding ship structure and machinery.<br>Analysis of failure prediction for ship systems and machinery. |

| Reference/year | Maintenance strategy | Topic | Requirements/findings | KEY- FINDINGS |
|---|---|---|---|---|
| 35, 2017 | MP-FMEA | Study on maintenance progress failure mode effect analysis (MP-FMEA) for ship equipment | MP-FMEA is an analysis method, which can find failure mode with high risk and to reduce or eliminate the risk of failure through improvement approach like corrective action in maintenance procedures.<br>Propose a method for calculation of RPN (risk priority number), which is defined as system, operation, personnel and maintenance resources | The proposed method of MP-FMEA give a proper classification of failure effects in the maintenance operations and is a useful tool for detecting faults in maintenance operation. |
| 36, 2017 | FTA, FMA | The improvement of the sea water cooling system in terms of reliability for application onboard autonomous ships. | The approach of the study is based on the visit of 115 ships equipped with similar machinery for collecting relevant data about cooling arrangement, planned maintenance system, engine log books.<br>Propose o solution to improve reliability and availability for sea water cooling system onboard autonomous ships.<br>Identification of the week loops of the system proposes using FTA and FMEA. | The proposed design for SW central cooling system demonstrate a high reliability and can operate safely on a ship without human intervention for an interval of 500 h.<br>Improvements can be done during operation by implementing CBM onboard the ship. |
| 37, 2018 | RBM | Study on risk-based maintenance scheduling with application to naval vessel | Review and evaluate the existing maintenance-scheduling approaches in terms of cost and vessel availability.<br>Propose a five-step framework for RBM-scheduling implementation onboard ships: establishment, application design, system design and validation, design acceptance, integration.<br>The proposed framework requires continuous improvement as a cyclic process comprising risk assessment, maintenance scheduling and quantification elements. | Sufficient resources are required from the organization in maritime industry or navy to collect data and develop suitable risk assessment and maintenance scheduling for the application of RBM.<br>An RBM properly developed for naval application is expected to deliver maximum availability and reduce overall maintenance costs. |
| 38, 2020 | Predictive maintenance | Reevaluate the maintenance for onboard systems facing new IMO sulfur amendments. | Present the new IMO regulation for maritime fuels and evaluate repair and maintenance procedures that are currently used for system onboard ships.<br>Propose predictive maintenance policy to prevent engine component degradation and machinery failure, two of the problems arise from using fuels with verry low sulfur content. | Predictive maintenance should become mandatory for decreasing possible failure risk, component degradation and overall maintenance costs arising from using a new type of fuel for marine engines. |

| Reference/year | Maintenance strategy | Topic | Requirements/findings | KEY- FINDINGS |
|---|---|---|---|---|
| 39, 2020 | Predictive Maintenance | Predictive maintenance approach using machine learning as opposed to sensor technology | Propose a predictive maintenance conceptual framework via machine learning.<br>The case study for ballast pump without sensor technology.<br>Creating a warning software tool using data collected from five parameters of the system to optimize the maintenance of dock pumps. | The predictive maintenance system is based on the continuous input of real-time operating data of the dock pump.<br>Need for high-quality machinery-operating data is required since the tool is sensitive due to the set control limits.<br>It is recommended that an investigation on the behavior of the physical parameters on the tool to be conducted. |
| 40, 2021 | RCM | RCM for assessing maintenance needs and reliability issues on unmanned cargo ships | Review current RCM methodology.<br>The study discovers some limitations regarding unmanned ships: corrective actions or partially fail state operation for a limited time will not be adopted; for failure development it is necessary to consider the length of the voyages.<br>The proposed amendments are verified for the main engine fresh water-cooling system. | To reduce risks to an acceptable level on unmanned cargo ships, increased redundancy in some form is found to be necessary.<br>The risk is found to be manageable with design changes to the unmanned cargo ship for the analyzed system. |