# Improving the reliability and availability of a marine diesel generator using RCM on a tanker

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## ABSTRACT

The Reliability Centered Maintenance (RCM) implementation is proposed on a marine diesel generator to improve its reliability and operational availability. This equipment is critical to ensuring the safety and continuity of onboard operations, where uninterrupted power supply is essential. This applied, descriptive, and analytical study with a quantitative approach, is based on the technical and statistical evaluation of key indicators such as MTBF, MTTR, RPN, and availability. By applying RCM, the most critical failure modes (RPN > 150) were identified, including inadequate crankshaft lubrication (RPN = 192) and overheating (RPN = 180), allowing maintenance resources to be focused on functions with the greatest operational and safety implications. The projected results indicate a 150% increase in MTBF (from 192 to 480 hours) and a 41.7% reduction in MTTR (from 12 to 7 hours), resulting in an improvement in availability from 94.1% to 98.6%. These findings establish a technical benchmark for maintenance strategies in maritime-industrial environments.

## KEYWORDS

*Reliability centered maintenance (RCM), Marine diesel generator, Operational Availability, FMECA matrix, NTP 679, AMFE, Risk Priority Number (RPN).*

## INTRODUCTION

Reliability Centered Maintenance (RCM) emerged in the late 1960s as a response to growing demands for safety and availability in the aviation industry, where traditional preventive maintenance schemes proved ineffective in managing the increasing complexity of equipment [1]. Its development established a systematic approach focused not on the indiscriminate preservation of components, but on ensuring that systems fulfill their critical functions within a defined operating context [2]. Among its main strengths are the ability to identify specific failure modes, analyze causes and evaluate consequences from technical, operational and economic perspectives [3], [4], [5], [6]. This makes RCM a framework that prioritizes maintenance resources and efforts according to the criticality of the equipment, avoiding both unnecessary overhauls and exposure to risks associated with unexpected failures.

It is worth noting that RCM has proven highly effective in sectors such as aviation [7], power generation [8], the petroleum industry [9]and heavy manufacturing [10], where it has contributed to increasing asset reliability, optimizing mean time between failures (MTBF), reducing mean time to repair (MTTR) and improving operational availability. In the maritime sector, its application is particularly relevant due to the operating conditions of vessels, which combine demanding environments, logistical constraints and high costs associated with unplanned stops [11].

In maritime operations, particularly on tankers, the reliability of auxiliary systems is critical to ensuring the safety, efficiency, and continuity of essential onboard activities. Among these systems, the diesel generator set plays a central role by providing continuous power to navigation, control, pumping, lighting, and emergency systems [11]. The loss of this power supply can have serious operational and environmental consequences. There are documented cases on oil tankers where sudden generator failures resulted in the loss of auxiliary propulsion and communications, forcing the suspension of loading and unloading maneuvers in hazardous conditions [12]. In some cases, these failures led to threats of spills, contractual penalties, logistical delays, and high costs associated with unplanned repairs [13], [14], [15]. These events clearly demonstrate that the management of marine generators cannot be viewed solely as a technical issue, but rather as a strategic factor for the safety and sustainability of shipping operations.

Despite the crucial importance of these assets, maintenance practices in the maritime sector have traditionally been based on corrective or preventive schemes with fixed intervals [16]. However, the increasing complexity of systems and the pressure of regulatory requirements have revealed that these approaches are insufficient to guarantee reliable availability in real-life navigation scenarios. In response, more advanced maintenance methodologies have emerged, including Reliability-Centered Maintenance (RCM), which systematically assesses equipment functions, failure modes, causes, and consequences to establish more effective intervention strategies.[17] [18]While RCM has been successfully applied in sectors such as aviation, energy, and process industries, the existing literature shows limited applications in marine generator sets. Most studies in the naval field focus on propulsion engines, turbines, or compressors, revealing a knowledge gap specifically related to the reliability analysis of marine power generators, despite their indispensable role in the operational safety of tanker vessels.[19] [20] [21].

Furthermore, most research adopts theoretical models that do not always reflect the operational constraints of tankers, such as the limited availability of spare parts during voyage, dependence on scheduled port inspections, and the need to minimize unplanned stops. This lack of research addressing the specific operational reality of marine generators highlights the need for approaches that combine technical rigor with practical applicability, which forms the basis and justification of this study.

Starting from this research gap, this paper proposes the implementation of RCM in a marine diesel engine serving as the main electrical generator of a tanker vessel, with the aim of improving its reliability and operational availability. The innovation of this work lies in three main contributions. First, it contextualizes the methodology in an environment with restricted access to spare parts and technical personnel during navigation, which requires a differentiated approach compared to other industries. Second, it develops a comprehensive analysis covering the generator's main subsystems: fuel, lubrication, cooling, exhaust, electronic control, starting, and electrical generation; identifying specific failure modes and proposing tailored preventive and predictive maintenance tasks. Third, it designs a technical-economic model based on criticality, condition, and risk, offering a replicable approach for other critical onboard systems such as pumps, compressors, and switchboards.

### Justification

The research is justified by the need to optimize marine diesel engine maintenance, especially in tankers, where reliability and operational availability are crucial for safety, energy efficiency, and reduced operating costs. Although Reliability-Centered Maintenance (RCM) has proven effective in sectors such as aeronautics and oil and gas, its application in the maritime sector remains limited and fragmented. The evidence reviewed reveals gaps in the integration of real operating data, in the adaptation of methodological frameworks to marine environments, and in the consideration of organizational factors that determine the success of implementation.

Therefore, it is essential to develop an applied approach that can strengthen the reliability of marine diesel generators through the use of RCM, simulations, and optimization tools.

## Research objective

The study is structured around Failure Modes, Effects and Criticality Analysis (FMEA), with the objective of prioritizing failures according to their severity, frequency and detectability, thus generating a specific maintenance plan. This strategy is expected to optimize key technical indicators such as Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR) and operational availability, contributing to both efficiency improvements and risk reduction in maritime operations. Furthermore, this research supports the development of a more advanced technical culture in maritime asset management, aligned with international standards such as ISO 55000[22] and the International Maritime Organization guidelines, thus strengthening its academic and practical relevance.

## Literature review

First, recent literature consolidates FMEA/FMECA as a prioritization axis and RPN as a practical criticality metric. Furthermore, it underscores the need to adapt the taxonomy to the operational context and ensure the traceability of decisions [22].

Next, the reviews focused on marine machinery confirm a transition from time-based plans to condition-based schemes and, progressively, toward predictive and prescriptive maintenance with onboard instrumentation and analytics. Although PMS and TBM remain in use due to regulatory requirements and long-standing practices, their combination with RCM and RBM enhances safety and availability by aligning tasks with risk and function [23]. Consequently, decision-making requires reliable data, interoperability with CMMS, and fleet-level technical-economic evaluation.

In addition, integrated decision-making frameworks are emerging that combine traditional tools with probabilistic inference and optimization. On the one hand, the integration of DFTA + FMECA + BBN allows for estimating availability by subsystem and establishing differentiated policies for generator sets based on performance and environment. On the other hand, the RCM → FMEA/FTA/ [24]Markov → Genetic Algorithms flow generates more cost-effective maintenance plans than fixed preventive maintenance, as it incorporates degradation and failure dependencies [25]. Thus, the technical decision is no longer uniform and prioritizes interventions proportional to criticality.

Meanwhile, applications in critical marine diesel engine subsystems demonstrate a direct impact on safety and efficiency. In the main engine turbocharging, a study using K-Sim/ Wärtsilä RT-Flex operational simulation and FTA and RBD analysis quantified the effects of malfunctions and derived intervention windows that support CBM and PdM tactics. [26]. In common rail injection, a bench-validated 1D physical model reproduced typical faults, strengthened FMEA, and enabled reliability assessment from degradation trajectories in the absence of field data [27]. Furthermore, enhancing a fault database with RCM/FMECA and 1D simulation reduced redundant symptoms, introduced operational thresholds, and paved the way for the transition to CBM/IVHMS diagnostics. Finally, in the face of inaccurate expert judgments, two prioritization procedures called MOORA-RPN and geometric mean-RPN, when applied to [28]a marine engine fuel [29]oil system, provided robust rankings with lower complexity than fuzzy alternatives.

At the same time, industry evidence underscores that the technical effectiveness of RCM depends on organizational constraints. A study in the oil and gas industry identified fifteen critical success factors in the pre-implementation stage. These include leadership, technical capabilities, data quality, a culture of improvement, integration with CMMS and PHM, and change management. Prioritizing these factors reduces the risk of failure and improves program sustainability, while also promoting improvements in MTBF, MTTR, and availability [30].

Additionally, the comparison between marine and industrial diesel engines highlights environmental and load differences that impact the reliability of thermal equipment. The use of seawater and dynamic profiles increase corrosion and fouling in the marine environment. As a result, specific maintenance strategies, appropriate materials, and stricter monitoring are required [31]. This observation reinforces the role of RCM in adjusting tasks and thresholds to operational contexts with logistical constraints.

Finally, the working paper on the tanker diesel generator converges with the literature by prioritizing critical modes with high RPN and proposing a plan with a predominance of predictive and preventive tasks. Internal evidence points to projected improvements in MTBF, MTTR, and availability following the implementation of RCM and data-driven strategies. This result is consistent with studies reporting reliability increases in diesel-electric systems and with proposals for maintenance optimization in engines undergoing degradation [2]. In summary, the reviewed corpus validates RCM as an effective framework for increasing availability and safety in marine systems. Recent advances add degradation models, Bayesian inference, and optimization, while the success of implementation depends equally on organizational preparedness and data support [32].

## METHODOLOGY

This study is classified as applied research, as it seeks to solve a specific technical problem related to the reliability and availability of critical equipment onboard a tanker . It is also classified as descriptive and analytical, as it involves both the collection of one year of technical data and the analysis of failure modes and their impact on the operating performance of the generating system. Furthermore, it is considered quantitative in approach, as it is based on the numerical analysis of technical indicators (MTBF, MTTR, RPN, availability) and the use of statistical tools to evaluate the effectiveness of the proposed maintenance plan. A non-experimental cross-sectional design is used, where independent variables are not manipulated. Instead, the behavior of the equipment (engine-generator) is analyzed within its actual operation (failure history and operating conditions) to apply the RCM methodology.

The focus of this paper is on diesel power generation systems installed onboard operating tankers. This is represented by a marine diesel generator, selected for convenience, whose operation directly impacts the vessel's primary energy functions. The equipment selection is based on its high operational criticality, the availability of technical information, and access to maintenance and breakdown history. See Figure 1-2.

Figure 1. - Cumins NTA 855

Figure 2. - Cumins NTA 855

Data collection involved a combination of document review, direct experience-based observation, and condition monitoring to gain a comprehensive understanding of the marine diesel generator's architecture, functions, and operational behavior. Technical documents, such as manufacturer's manuals, assembly drawings, process diagrams, maintenance records, and regulatory standards, were analyzed to establish baseline operating parameters and safety criteria. Direct observation under normal conditions allowed for verification of maintenance routines, identification of wear or deterioration, and validation of documentary information.

These dates are managed using FMECA and RCM matrices, technical standards, and monitoring tools, with an analysis focused on criticality assessment (RPN), performance indicators (MTBF, MTTR, availability), failure trends, and maintenance task prioritization. Figure 1 below summarizes the methodological process.

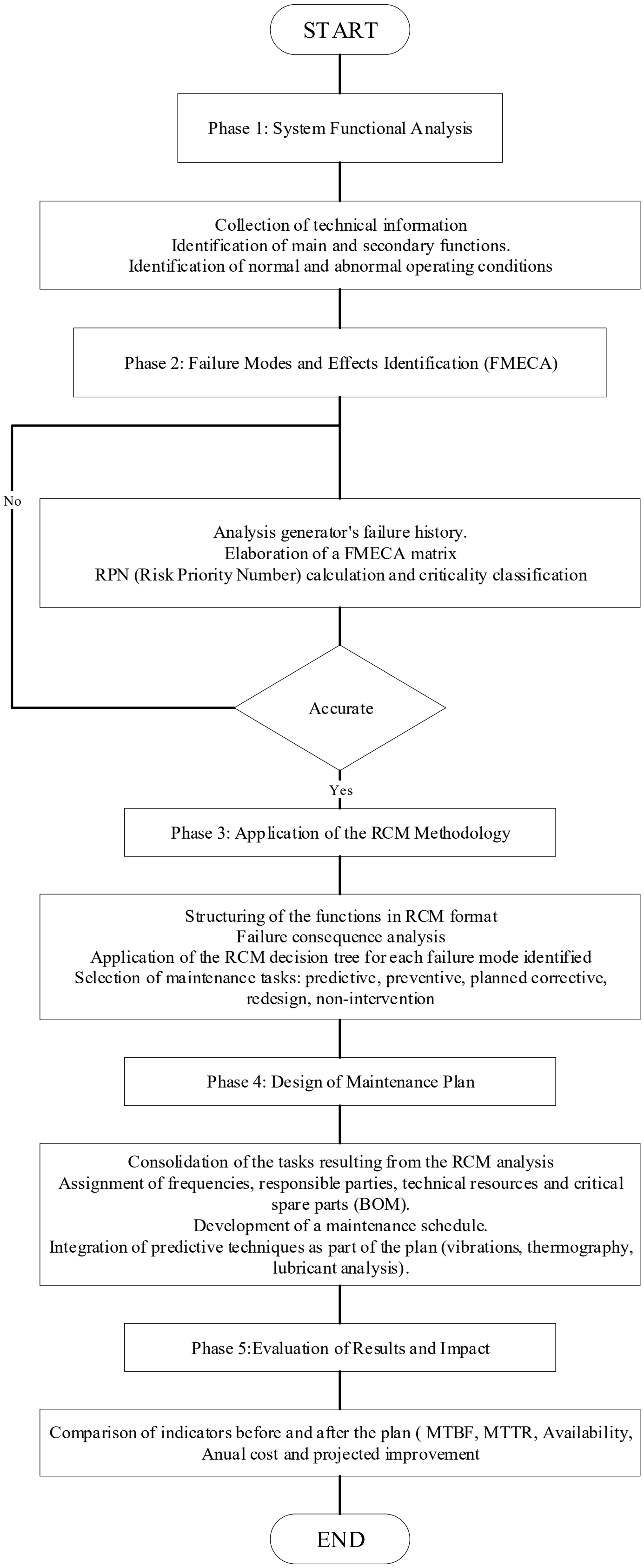

**Figure 3.** - Five-phase methodological process

## RESULTS

This chapter presents the results derived from the application of the RCM methodology to the marine diesel generating system, integrating the technical data obtained during the operational evaluation with the FMECA analysis. The critical equipment functions, the most representative failure modes, and their effect on the tanker's reliability and operational availability are identified. The results demonstrate how the systematic application of RCM optimizes maintenance management, prioritizes resources toward the highest-impact components, and contributes to improving energy continuity on board. This provides a solid technical basis for validating the proposed model in demanding naval environments.

### Functional analysis of marine diesel generators

As a result of the functional analysis phase, the primary and secondary functions of the generator system were identified. The primary functions include generating stable electrical power at 440 V/60 Hz to power the vessel's critical systems, maintaining continuous operation under variable load, and activating backup systems in emergency situations. Secondary functions include thermal regulation, the autonomous lubrication system, and synchronization with other generators. This identification allowed for the establishment of the system's physical and operational limits, as well as the identification of the systems, subsystems, and components of the element under study.

Table 1. - Diesel generator system, subsystem and components

| System | Subsystem | Main components |
|---|---|---|
| Marine diesel generator | Fuel system | Service tank, feed pumps, fuel filters, injectors, pipes, valves. |
| | Lubrication system | Lubrication pump, oil filters, oil heat exchanger, crankcase, distribution lines. |
| | Cooling system | Seawater pump, freshwater pump, heat exchanger, radiator, thermostats, pipes. |
| | Generation system | Alternator, rotor, stator, automatic voltage regulator (AVR), brushes, slip rings. |
| | Control system | Control panel, pressure sensors, CO2, temperature, switches, protection relays, PLC or electronic module. |
| | Starting system | Electric or pneumatic starter motor, batteries, starting air valves, compressor. |
| | Thermal Regulation System | Thermostats, control valves, fans, radiator. |
| | Backup and synchronization system | Automatic transfer switch (ATS), couplers, synchronization systems with other generators. |

### Identification of critical activities of the generating system

Eight key functional activities associated with the marine diesel generator were identified, grouped into their respective subsystems. These activities represent operational functions necessary to ensure the continuous and reliable supply of electrical power to the tanker. The functional classification was validated through direct observation and technical review.

The FMECA matrix is used to store information related to the most representative failure modes, their root causes, their effects and the criticality assessment by calculating the Risk Priority Number (RPN = S × O × D). In total, 15 failure modes were identified, grouped by subsystem (fuel, lubrication, cooling, generation, control and start-up). Of these, eight representative activities were selected with the objective of evaluating the criticality of each failure mode by analyzing the RPN . Table 2. - list below.

Table 2.- Summary of results

| Activity | Failure modes | Result | S | Cause | O | Controls | D | RPN | Behavior | S | O | D | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Starting the engine generator | Starter solenoid failure | The generator does not start | 7 | Sulfation of electrical contact | 5 | Periodic check of the starting system | 4 | 140 | Cleaning and protecting contacts; installing a solenoid status sensor | 6 | 4 | 2 | 48 |

| Activity | Failure modes | Result | S | Cause | O | Controls | D | RPN | Behavior | S | O | D | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Speed regulation | Frequency oscillation | Output voltage instability; Low frequency alarm; Equipment shutdown due to voltage fluctuations and current spikes | 8 | Incorrect governor adjustment | 4 | Governor check before each execution | 5 | 160 | Governor calibration with digital tools; monthly frequency analysis | 3 | 2 | 5 | 30 |
| Engine cooling | Overheating | High temperature shutdown | 9 | Blockage in the heat exchanger | 5 | Engine temperature monitoring | 4 | 180 | Internal cleaning of the heat exchanger and verification of water flow | 10 | 1 | 2 | 20 |
| Crankshaft lubrication | Low oil pressure | Bearing damage | 8 | Leaks or low level | 6 | Visual check of oil level and pressure | 4 | 192 | Install pressure sensor with alarm connected to the control panel | 5 | 1 | 2 | 10 |
| Fuel supply | Air in the injection line | Loss of power | 7 | Clogged fuel filter | 3 | Scheduled fuel filter change | 5 | 105 | Replacement by operating hours or measured pressure differential | 6 | 4 | 2 | 48 |
| Power generation | Loss of voltage | Charging system failure | 9 | Alternator damage | 3 | Checking alternator terminals and clamps | 4 | 108 | Thermographic analysis and functional testing under load | 3 | 2 | 5 | 30 |
| Electrical temperature control | Temperature sensor error | False alarms or system trips | 6 | Damaged sensor or incorrect calibration | 5 | Sensor test during power-up | 5 | 150 | Sensor replacement every 12 months; calibration every six months with reference equipment | 6 | 2 | 3 | 36 |
| Exhaust system | Excess exhaust pressure | Structural damage or gas reflux | 8 | Obstruction in the muffler | 4 | Exhaust cleaning during major | 4 | 128 | Semi-annual technical audit; installation | 5 | 3 | 2 | 30 |

| Activity | Failure modes | Result | S | Cause | O | Controls | D | RPN | Behavior | S | O | D | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | maintenance | | | of pressure relief valve or backpressure sensor | | | | |
| RPN > 150 | CRITICAL | | | | | | | | | | | | |
| RPN 100-150 | MODERATE | | | | | | | | | | | | |
| RPN <100 | LOWEST PRIORITY | | | | | | | | | | | | |

Note: Failure modes with an RPN greater than 150 were classified as critical and subject to immediate interventions within the proposed maintenance plan, as mentioned in NTP 679 standard. [33]This document establishes the characteristics to determine the values or magnitude of each criterion: Severity, Occurrence and Detectability.

The FMECA analysis identified the most critical failure modes in the marine diesel generator. The results showed that the crankshaft lubrication system had the highest RPN value (192), followed by the engine cooling system (180), speed control (160), and the temperature sensor (150). These results highlight the subsystems directly related to the operational safety and service continuity of the equipment.

Based on this prioritization, the matrix facilitated the definition of the most effective maintenance tasks for each failure mode. Predictive monitoring of oil pressure, temperature, and vibrations was implemented for critical components, while scheduled preventive maintenance was recommended for periodic sensor inspections, cooling system cleaning, and verification of electrical connections. Together, these measures guide resource allocation toward the functions with the greatest impact on generator reliability and availability.

## RCM decision tree and maintenance plan

By applying the RCM
decision tree to the identified failure modes, a reliability-focused maintenance plan was designed, prioritizing tasks based on criticality, consequences, and technical feasibility.

Table 3.- Tasks - Maintenance Plan

| Task type | Number of tasks | Percentage |
|---|---|---|
| Predictive maintenance (PdM) | 7 | 47% |
| Preventive maintenance | 5 | 33% |
| Planned corrective | 2 | 13% |
| Redesign or improvement | 1 | 7% |

Predictive maintenance (PdM) includes periodic vibration monitoring, oil analysis, thermography of electrical connections, and checking the condition of the coolant. Preventive tasks include filter inspection, cooling system cleaning, and functional testing of the starting system.

Operational consequences. The combined FMECA and RCM analysis revealed that critical failures in the marine diesel generator have a direct and significant impact on the tanker's operational continuity, particularly by compromising the performance of systems dependent on a stable and reliable electrical supply. Failures in critical subsystems, such as crankshaft lubrication (RPN = 192), can result in a complete generator shutdown, resulting in disruption of loading and unloading pumps, navigation equipment, lighting, and communication systems, thus paralyzing hydrocarbon transfer operations and exposing the vessel to safety, environmental, and economic risks. Furthermore, generator malfunctions can impact power availability by disrupting synchronization with auxiliary generators, forcing them to operate under emergency conditions with reduced capacity. This situation not only increases the likelihood of cascading failures in other vessel systems but also generates operational inefficiencies and increased fuel consumption, ultimately impairing the reliability and safety of maritime operations.

Economic consequences. Analysis of the costs associated with critical marine diesel generator failures demonstrated that their impact goes beyond the immediate technical consequences, generating direct and indirect economic losses for tanker operations. Direct costs include unplanned repairs, such as bearing replacement due to insufficient oil pressure, which can reach approximately USD 15.000, as well as fines imposed for delays in port operations, estimated between USD 5.000 and USD 10.000 per day of disruption. Indirect costs, although less tangible, represent an even greater long-term risk: recurring failures and unscheduled shutdowns can result in the loss of commercial contracts due to missed delivery deadlines, in addition to operational inefficiencies such as increased fuel consumption under partial failure conditions. For example, frequency oscillations associated with speed regulation failures (RPN = 160). These findings reinforce the strategic importance of adopting structured, reliability-based maintenance methodologies, not only to safeguard operational safety, but also to mitigate financial risks and preserve the competitiveness of shipping operations.

Consequences for safety and the environment. The analysis also highlighted the human and environmental risks associated with critical marine diesel generator failures, reinforcing their importance beyond the technical and economic dimensions. From a safety perspective, exhaust system failures (RPN = 128) can lead to the accumulation of toxic gases in the engine room, exposing crew members to the risk of poisoning and serious health risks. Likewise, alternator malfunctions (RPN = 108) can generate electrical surges capable of damaging sensitive equipment, thus increasing the likelihood of fires on board. In environmental terms, abrupt generator shutdowns pose a serious risk during cargo transfer operations: overheating failures (RPN = 180) can disrupt pump operation, potentially causing oil spills with immediate ecological and economic repercussions. Furthermore, incomplete combustion resulting from fuel injection failures (RPN = 105) generates excessive air emissions, contributing to air pollution and non-compliance with international environmental standards. These findings demonstrate that reliability-centered maintenance is not only a technical necessity but also a fundamental strategy for safeguarding human life and minimizing the ecological footprint of tanker operations.

Impact on technical maintenance indicators. One of the critical phases in implementing the RCM methodology is the objective measurement of its impact on the technical performance of the analyzed asset. To this end, three key maintenance management indicators were evaluated: MTBF, MTTR, and operational availability. The data are presented below. These parameters allow quantifying the reliability and operational capacity of the diesel electric generating system before and after implementing the technical proposal. The impact of the proposal on the generating system's technical indicators was evaluated by comparing the current situation (based on historical data) with the projected scenario after implementing the RCM plan.Table 4.- Maintenance work orders

| No. | Opening date | Closing date | Equipment code | Type of maintenance. | Brief description | State |
|---|---|---|---|---|---|---|
| VM-13933 | 04/05/2023 | 01/04/2024 | G-301 | Corrective | Manufacture six copper rings for the connection between the turbocharger outlet and the exhaust elbow according to specifications | Finished |
| VM-13936 | 05/20/2024 | 06/20/2024 | M-301 | Corrective | Replacing the main engine thrust bearings | Finished |
| VM-13937 | 05/14/2023 | – | M-302 | Corrective | Replace three thermometers in the reducer (ordered with samples) | Earring |
| VM-13984 | 09/28/2023 | 02/15/2024 | S-009 | Corrective | Replace the alarm float on the cascade tank and daily fuel tanks | Finished |
| VM-13995 | 12/07/2023 | 01/17/2024 | G-302 | Corrective | Inspection of the master pack of the three alternators for malfunction | Finished |
| VM-13986 | 08/16/2023 | 01/06/2024 | P-306 | Corrective | Repair of the exhaust elbow between the turbocharger outlet and the expansion joint | Finished |
| VM-13991 | 08/21/2023 | 05/08/2024 | P-217 | Corrective | Manufacturing of a new coupling for the feed freshwater transfer pump | Finished |
| VM-14019 | 02/10/2023 | – | S-021 | Corrective | Removal of the oil-saturated cement floor layer and | Earring |

| No. | Opening date | Closing date | Equipment code | Type of maintenance. | Brief description | State |
|---|---|---|---|---|---|---|
| | | | | | placement of a new cement layer in the crane pump area | |

**Numerical calculations**

The implementation of RCM allowed for an increase in the mean time between failures (MTBF) and a reduction in the mean time to repair (MTTR), thereby improving the operational availability of the equipment (see Table 4 above). The calculation of the operational reliability and efficiency assessment indicators for the marine generator set is presented below. Five failures were detected during the diagnostic phase in the generator's last three months of operation, with a total estimated operating time of 960 hours (8 hours per day × 5 days × 12 weeks). This results in a current MTBF of 192 hours:

$$MTBF = \frac{690}{5} = 192\ h \tag{1}$$

Following the implementation of the RCM maintenance plan, the number of failures is projected to decrease to two per quarter by eliminating recurring causes through specific predictive and preventive tasks. Therefore:

$$MTBF = \frac{960}{2} = 480\ h \tag{2}$$

According to the vessel's technical records, the repairs carried out during the last quarter accumulated a total time of 60 hours (average of 12 hours per failure × 5 failures):

$$MTBF = \frac{60}{5} = 12\ h \tag{3}$$

With the RCM proposal, which includes early detection, reduced diagnostic time, and availability of critical spare parts (defined by criticality in the FMECA), it is estimated that the total repair time will be reduced to 14 hours for two failures:

$$Projected\ MTTR = \frac{14}{2} = 7\ h \tag{4}$$

Availability. Availability indicates the probability that equipment will be operational when required; it measures the efficiency of the maintenance team. A lower MTTR indicates greater repair efficiency. Availability is the percentage of time that a piece of equipment or system is operational and available for use. It reflects the equipment's ability to be operational when needed. High availability indicates greater reliability:

$$Current\ AVAILABILITY\ = \frac{192 * 100}{192 + 12} = 94.1\% \tag{5}$$

$$Projected\ AVAILABILITY\ = \frac{480 * 100}{480 + 7} = 98.6\% \tag{6}$$

The following table 5 presents the summary of the indicators calculated above.

Table 5. - Summary of improvement in indicators %

| Indicator | Present value | Projected value | Improvement (%) |
|---|---|---|---|
| MTBF (hours) | 320 | 460 | +43.75% |
| MTTR (hours) | 12 | 7 | -41.7% |
| Operational availability (%) | 96.4% | 98.5% | +2.1 points |
| Failures per quarter | 5 | 2 | -60% |

## DISCUSSION

Analysis of the marine diesel generator using FMECA and RCM identified eight critical functional activities within the system, encompassing the fuel, lubrication, cooling, generation, control, and starting subsystems. Prioritization of failure modes, particularly those with RPN values above 150, such as crankshaft lubrication (RPN = 192) and engine cooling (RPN = 180), highlights the most influential subsystems in maintaining operational continuity. These findings are consistent with studies by[34] [35], who emphasized that, in marine and industrial environments, lubrication and thermal management systems consistently present the greatest risk and require specific preventive interventions. Our results reinforce the need for targeted maintenance strategies rather than generic programs.

Predictive maintenance measures, such as oil pressure, temperature, and vibration monitoring, were recommended for high-priority components, while scheduled preventative tasks addressed sensor inspections and cooling system cleaning. The distribution of tasks (47% predictive maintenance, 33% preventative maintenance, 13% planned corrective maintenance, and 7% redesign) reflects a structured approach, consistent with the recommendations of [ [36], [37], [38]manufacturer name], who reported that predictive monitoring on diesel generator systems significantly improves MTBF and operational reliability, particularly under high-load marine conditions. The comparison indicates that the integration of predictive and preventative measures provides measurable improvements in reliability indicators, compared to conventional maintenance practices.

The operational consequences of critical failures were particularly significant for systems dependent on continuous electrical supply. For example, crankshaft lubrication failures can lead to complete generator shutdowns, halting hydrocarbon transfer operations and affecting navigation and communication systems. These findings are supported by the work of [ [39], [40], [41]system name - missing context], who noted that generator failures on tankers often lead to cascading operational disruptions, reinforcing the importance of reliability-focused interventions to mitigate operational and safety risks. Furthermore, generator malfunctions compromise synchronization with auxiliary generators, forcing reduced capacity operation and increasing the likelihood of energy bottlenecks and inefficiencies.

The economic implications extend beyond direct repair costs. Unplanned repairs, such as bearing replacements due to low oil pressure (≈USD 15,000) and port fines (USD 5,000–10,000/day), underscore the financial exposure of tanker operations. Indirect costs, including lost contracts and fuel inefficiencies during partial failures, further amplify the economic risks. Similar patterns were observed in the study [42], [43], which found that critical diesel generator failures can increase operating costs by up to 40% in ocean shipping due to unscheduled downtime and non-compliance penalties. These parallels reinforce the conclusion that structured reliability-based maintenance directly contributes to both cost mitigation and operational resilience [44].

Safety and environmental risks were also confirmed. Exhaust system failures (RPN = 128) can lead to the buildup of toxic gases, while alternator malfunctions (RPN = 108) increase the likelihood of electrical hazards and fires. Overheating incidents (RPN = 180) pose environmental threats, including potential oil spills during cargo operations. These findings are consistent with IMO reports.[45] [46], [47], which documented similar risks arising from generator malfunctions on tankers, highlighting RCM as a crucial strategy not only for operational reliability, but also for crew safety and environmental protection [48]. Integrating predictive monitoring can prevent such incidents by detecting abnormal parameters early.

Finally, technical indicators demonstrate quantifiable improvements following the RCM plan. MTBF increased from 192 to 480 hours (+150%), MTTR decreased from 12 to 7 hours (-41.7%), and operational availability increased from 94.1% to 98.6%. These improvements reflect the results of marine reliability studies, such as those by Jardine et al. (2006), where reliability-centered maintenance led to MTBF increases of between 120% and 160% and MTTR reductions of up to 45% in similar diesel-electric systems. [49], [50], [51]Together, these results confirm that the application of RCM and predictive strategies improves generator reliability, reduces downtime, optimizes resource allocation, and mitigates operational, economic, and environmental risks in tanker operations.

## Conclusions

The implementation of Reliability Centered Maintenance (RCM) on the marine diesel generator set allowed the identification of the most critical failure modes, such as crankshaft lubrication (RPN = 192) and the cooling system (RPN = 180), and the establishment of predictive and preventive maintenance tasks focused on the subsystems with the greatest operational impact. The result is a significant increase in MTBF from 192 to 480 hours, a reduction in MTTR from 12 to 7 hours, and an improvement in operational availability from 94.1% to 98.6%, demonstrating the effectiveness of a maintenance strategy based on criticality and resource prioritization.

A thorough analysis of the operational, economic, safety, and environmental consequences showed that critical generator failures directly affect the vessel's operational continuity, generate substantial costs for unforeseen repairs and port fines, and pose risks to the crew and the environment. The application of RCM not only optimizes key technical indicators but also serves as a strategic tool for risk mitigation, ensuring operational safety, energy efficiency, and compliance with international standards in maritime transport operations.

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