

Enhancing the Reliability of Marine Main Diesel Engines A Review of Failure Modes, Maintenance Strategies, and Condition Monitoring

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Abstract— Marine main diesel engine failures remain one of the largest sources of operational risk and commercial loss in merchant shipping, with loss of propulsion consistently ranked as a top machinery casualty category and engine maintenance quality now an explicit criterion in commercial vetting regimes such as SIRE 2.0. However, existing reviews largely treat maintenance strategy selection as a generic engineering problem, without systematically linking specific failure-mode behavior to strategy assignment or consolidating condition monitoring techniques into a subsystem-specific, actionable guide; this leaves fleet operators without a unified decision tool connecting failure diagnosis, strategy selection, and monitoring technology. This review therefore aims to (1) identify the dominant failure modes and root causes of marine main diesel engines reported in the peer-reviewed literature, (2) systematize available maintenance strategies through an integrated Failure Mode and Effects Analysis-Reliability-Centered Maintenance (FMEA-RCM) decision framework that assigns each strategy to specific subsystems; and (3) map condition monitoring techniques onto main engine components to support the transition from time-based to condition-based maintenance (CBM). A narrative literature review methodology was employed, combining structured database searches (Scopus, Web of Science, Google Scholar) with backward citation tracking across 31 peer-reviewed journal articles, textbooks, international standards, and maritime authority casualty reports published between 1997 and 2025, synthesized thematically using the bathtub failure-rate model and FMEA-RCM decision logic as the integrating analytical framework. The review found that the fuel injection system, cylinder components, turbochargers, and the lubricating and cooling oil systems are the dominant contributors to main engine unreliability, with root causes concentrated in fuel and lubricant quality, thermal overload, and deferred maintenance rather than in inherent design deficiency. A hybrid maintenance architecture combining time-based tasks for age-related failure modes with CBM for randomly occurring, detectable degradation emerged as the most effective strategy, with lubricating oil analysis, thermodynamic performance monitoring, vibration analysis, and thermography constituting the principal CBM toolkit, and organizational integration into the planned maintenance system identified as the key remaining implementation barrier..

Keywords— marine main engine, reliability, failure mode, maintenance strategy, reliability-centered maintenance, condition monitoring, FMEA, CBM.

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I. INTRODUCTION

Marine machinery failures account for one of the largest categories of shipping casualties globally, with propulsion system failures particularly those involving the main diesel engine among the most safety-critical consequences for vessels in confined waters, heavy traffic, or adverse weather conditions [1,2]. Beyond safety, main engine unreliability imposes severe commercial penalties off-hire losses, emergency repair costs, charter-party claims, and adverse findings in port state control (PSC) inspections and commercial vetting regimes such as SIRE 2.0, where the quality of engine maintenance records is an explicit assessment criterion [3].

Maintenance engineering for marine propulsion systems has evolved significantly over the past three decades, progressing from purely corrective (run-to-failure) approaches through planned time-based preventive maintenance anchored in maker intervals and classification society survey cycles, toward condition-based and predictive maintenance enabled by onboard instrumentation and data analytics [4,5]. The theoretical framework underpinning this evolution is reliability-centered maintenance (RCM), which allocates the most appropriate maintenance strategy to each failure mode based on its consequences and the technical feasibility of detection or prevention [6,7]. While RCM originated in the aviation sector, its adaptation to ship machinery has been demonstrated across a substantial body of maritime engineering research [4,8,9].

The central problem motivating this review is the absence of a unified, subsystem-specific decision tool that connects three tasks fleet operators must currently perform separately diagnosing which main engine components are most likely to fail and why, selecting a maintenance strategy appropriate to each failure mode's behavior, and choosing a condition monitoring technique capable of detecting that failure mode before it escalates.

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Most existing reviews treat marine maintenance strategy selection as a generic engineering problem, without systematically linking specific main engine failure mode behavior (age-related versus random) to specific maintenance strategy assignments using an integrated FMEA–RCM decision framework. Furthermore, the mapping of condition monitoring techniques onto individual main engine subsystems in a form directly actionable for fleet operators has not been comprehensively consolidated, and recent advances in machine-learning-based prognostics and health management (PHM) have not yet been reconciled with the classical RCM decision logic that fleet maintenance departments still rely on in practice [26,27].

The novelty of this review lies in (1) providing an integrated FMEA–RCM decision matrix that explicitly links failure mode criticality and detectability to maintenance strategy selection across all major main engine subsystems, rather than treating strategy selection qualitatively; and (2) synthesizing the current state of condition monitoring techniques from established sensor-based methods to emerging machine-learning and PHM approaches into a subsystem-specific implementation guide that connects monitoring technology to the planned maintenance system workflow. This dual contribution distinguishes the present review from single-technique surveys and positions it as a practical bridge between reliability theory and shipboard maintenance decision-making.

This review consolidates the existing body of knowledge with three specific objectives (1) to identify the dominant failure modes of marine main diesel engines and their root causes; (2) to systematize available maintenance strategies and assign them to main engine subsystems through FMEA–RCM decision logic; and (3) to review condition monitoring techniques and their requirements for effective implementation. The review targets ship operators, technical superintendents, classification society surveyors, and researchers engaged in marine machinery reliability improvement.

The reliability of marine diesel engines has been studied from multiple perspectives. Early work by Mokashi et al. [4] established the applicability of RCM principles to ship machinery, demonstrating that the maintenance decision logic developed in aviation could be systematically applied to propulsion systems when failure consequence data were available. This foundational contribution was extended by Lazakis et al. [5], who demonstrated through a fleet-wide case study that holistic maintenance management integrating condition monitoring data into planned maintenance systems produced measurable improvements in machinery availability compared to conventional time-based approaches.

Failure mode characterization of main engine subsystems has been addressed by several empirical and analytical studies. Woodyard [13] provides the most comprehensive descriptive taxonomy of marine diesel failure modes, identifying the fuel injection system as consistently the highest-frequency failure subsystem across engine types and sizes, with injector fouling and pump wear as the dominant mechanisms. Cicek and

Celik [14] applied FMEA methodology specifically to crankcase explosion failure, demonstrating that consequence severity rather than failure frequency should drive maintenance priority for low-probability/high-consequence events a conclusion directly consistent with RCM decision logic as formalized by Moubray [6].

Condition-based maintenance for marine machinery has been reviewed by Lazakis et al. [9], who identified lubricating oil analysis and thermodynamic performance monitoring as the two most information-rich CBM techniques for main engine condition assessment, and emphasized the organizational gap between data acquisition and maintenance decision-making as the primary barrier to CBM implementation in ship operations. Emovon et al. [8] applied multi-criteria decision-making (MCDM) methodology to maintenance strategy selection for ship machinery, confirming that CBM is the dominant optimal strategy for critical, randomly-failing subsystems when condition indicators are available, while time-based maintenance remains appropriate for age-related failure modes.

The temporal behavior of marine engine failure modes has been studied through the lens of the bathtub reliability model (Rausand and Høyland [10]), which distinguishes three failure rate phases early failure (infant mortality), useful life (random failure), and wear-out. Jimenez et al. [15] applied predictive modeling to vessel machinery data, confirming that most shipboard machinery subsystems exhibit mixed failure behavior combining random failures during useful life with progressive wear-out at high running hours, which necessitates the hybrid maintenance architecture identified in this review. These collective contributions provide the analytical foundation upon which the present review builds its integrated FMEA–RCM framework.

A. Evolution of Marine Maintenance Strategies

Maintenance strategies in the maritime industry have evolved significantly over the past several decades in response to increasing demands for navigational safety, operational reliability, cost efficiency, and compliance with international maritime regulations. In the early stages of maritime maintenance practice, corrective maintenance was the predominant approach, in which maintenance activities were performed only after a component had failed. This strategy was considered relatively simple because it required neither systematic maintenance planning nor continuous condition monitoring. However, unexpected failures frequently resulted in propulsion loss, voyage delays, increased repair costs, and a higher risk of maritime accidents. Consequently, corrective maintenance is generally considered suitable only for non-critical components whose failures have limited operational and safety consequences.

As marine propulsion systems became increasingly complex, the maritime industry gradually shifted toward preventive maintenance, which is performed at predetermined time intervals or operating hours according to manufacturers' recommendations and classification society requirements. The primary

objective of preventive maintenance is to reduce the probability of equipment failure through scheduled inspections, component replacement, and periodic overhauls before the end of their expected service life. This strategy has proven effective for components that exhibit age-related degradation mechanisms, such as exhaust valves, piston rings, and cylinder liners. Nevertheless, preventive maintenance may lead to unnecessary maintenance activities because not all components deteriorate according to fixed maintenance intervals.

The introduction of Reliability-Centered Maintenance (RCM) represented a significant advancement in maintenance philosophy. Originally developed in the aviation industry and later adopted in the maritime sector, RCM differs fundamentally from preventive maintenance by selecting maintenance strategies based on failure characteristics, operational consequences, and the detectability of component degradation. Within the RCM framework, Failure Mode and Effects Analysis (FMEA) serves as the primary analytical tool for identifying potential failure modes, determining their root causes and consequences, assessing their criticality, and prioritizing maintenance actions. This systematic approach enables maintenance resources to be allocated more effectively while improving overall system reliability.

The rapid advancement of sensor technologies and onboard monitoring systems subsequently facilitated the implementation of Condition-Based Maintenance (CBM). Unlike time-based maintenance approaches, CBM determines maintenance requirements according to the actual condition of equipment. Various operational parameters, including lubricating oil condition, exhaust gas temperature, cylinder pressure, turbocharger vibration, and cooling water quality, are continuously monitored to evaluate machinery health. Maintenance activities are initiated only when monitored parameters indicate abnormal degradation or approach predefined alarm thresholds. Consequently, CBM reduces unnecessary maintenance while improving equipment availability and operational reliability.

More recently, maintenance management has progressed toward Predictive Maintenance (PdM), which integrates continuous sensor monitoring, historical operational data, trend analysis, machine learning algorithms, and Planned Maintenance Systems (PMS). Rather than merely detecting existing equipment degradation, predictive maintenance estimates the Remaining Useful Life (RUL) of critical components and predicts potential failures before they occur. This enables maintenance decisions to be scheduled proactively, thereby minimizing unplanned downtime and optimizing maintenance costs. Although challenges remain regarding data integration, sensor reliability, and implementation costs, predictive maintenance is widely recognized as the future direction of reliability management for modern merchant fleets.

Overall, the evolution of maintenance strategies demonstrates a clear transition from reactive maintenance toward increasingly proactive and data-driven maintenance philosophies. Corrective

maintenance addresses failures only after they occur, preventive maintenance seeks to prevent failures through scheduled interventions, Reliability-Centered Maintenance determines the most appropriate maintenance strategy based on failure characteristics, Condition-Based Maintenance relies on real-time equipment condition, and Predictive Maintenance employs advanced data analytics to forecast future failures. This progressive evolution provides the conceptual foundation for the integrated reliability management framework proposed in this review, which combines failure mode analysis, maintenance strategy selection, and condition monitoring techniques to enhance the operational reliability of marine main diesel engines.

B. Reliability Concepts in Marine Engineering

The concept of reliability constitutes the fundamental basis of maintenance engineering and asset management in the maritime industry. For merchant vessels, reliability extends beyond the ability of machinery to operate continuously; it directly influences navigational safety, operational efficiency, environmental compliance, and fleet availability. Since the marine main diesel engine functions as the primary propulsion system, its reliability is essential for ensuring uninterrupted voyage operations and minimizing the risk of propulsion failure. Consequently, reliability assessment has become one of the principal considerations in developing effective maintenance strategies for marine machinery.

1) Reliability

Reliability is generally defined as the probability that a system or component performs its intended function without failure under specified operating conditions for a given period of time. In marine engineering, reliability reflects the capability of propulsion machinery to operate safely and efficiently throughout its service interval while maintaining the required operational performance. Higher reliability reduces unexpected machinery breakdowns, minimizes operational disruptions, and improves vessel safety. Therefore, reliability has become one of the primary performance indicators in modern maintenance management and serves as the foundation for Reliability-Centered Maintenance (RCM).

2) Availability

Availability represents the proportion of time during which equipment remains capable of performing its intended function whenever required. Unlike reliability, which focuses solely on the occurrence of failure, availability also considers the duration of repair and restoration activities. In merchant vessel operations, high equipment availability is critical because propulsion system downtime may result in voyage delays, increased operating costs, contractual penalties, and reduced commercial performance. Consequently, maintenance planning should aim not only to improve reliability but also to maximize equipment availability through efficient inspection, repair, and spare parts management.

3) Maintainability

Maintainability describes the ease and speed with which failed equipment can be restored to its operational condition using established maintenance procedures and available resources. Components designed with good

maintainability require shorter repair times, fewer maintenance resources, and lower lifecycle costs. Within marine propulsion systems, maintainability is influenced by machinery accessibility, spare parts availability, crew competency, technical documentation, and maintenance planning. High maintainability contributes significantly to reducing Mean Time to Repair (MTTR), thereby improving overall system availability.

4) Failure Rate

Failure rate is one of the most widely used reliability indicators for evaluating machinery performance. It represents the frequency at which failures occur within a specified operating period. Marine diesel engine components exhibit different failure characteristics depending on their operating conditions, material degradation, maintenance quality, and environmental exposure. Critical components such as fuel injection systems, cylinder assemblies, turbochargers, and lubrication systems often experience relatively higher failure rates due to continuous mechanical and thermal loading. Understanding failure rate trends enables ship operators to prioritize maintenance activities and allocate maintenance resources more effectively.

5) Bathtub Curve

The Bathtub Curve is a classical reliability model describing the variation of failure rates throughout the service life of engineering equipment. The curve consists of three distinct phases: the infant mortality period, characterized by early failures resulting from manufacturing defects or installation errors; the useful life period, during which failures occur randomly at a relatively constant rate; and the wear-out period, where failure rates increase due to aging, fatigue, corrosion, and material degradation. Understanding the Bathtub Curve assists maintenance engineers in selecting appropriate maintenance strategies according to the dominant failure characteristics observed during each lifecycle stage.

6) P-F Interval

The Potential Failure to Functional Failure (P-F) Interval represents the period between the initial detection of equipment degradation and the occurrence of complete functional failure. This concept forms the theoretical foundation of Condition-Based Maintenance (CBM) and Predictive Maintenance (PdM). During the P-F interval, maintenance personnel have an opportunity to identify abnormal equipment conditions through techniques such as lubricating oil analysis, vibration monitoring, thermography, performance monitoring, and acoustic diagnostics before catastrophic failure occurs. The longer the P-F interval, the greater the opportunity to schedule maintenance proactively, thereby reducing unexpected downtime and maintenance costs.

Overall, reliability, availability, maintainability, failure rate, the Bathtub Curve, and the P-F Interval are closely interconnected concepts that collectively support the implementation of modern maintenance strategies. Reliability describes the probability of failure-free operation, availability measures operational readiness, maintainability determines repair efficiency, failure rate quantifies degradation trends, the Bathtub Curve explains lifecycle failure behavior, and the P-F Interval provides the basis for predictive maintenance decisions.

Together, these concepts establish the theoretical framework underpinning Reliability-Centered Maintenance and Condition-Based Maintenance, both of which are essential for improving the operational reliability of marine main diesel engines.

C. Reliability Assessment Approaches

Various analytical approaches have been developed to evaluate and improve the reliability of marine machinery systems. These approaches differ in their objectives, analytical principles, and applications, but collectively provide a systematic framework for identifying failures, determining their causes, selecting appropriate maintenance strategies, and improving operational reliability. In marine engineering, reliability assessment generally combines failure analysis, maintenance optimization, and condition monitoring to minimize unexpected failures while maximizing equipment availability and operational safety.

Reliability analysis forms the foundation of reliability engineering by evaluating the probability that a component or system will perform its intended function without failure over a specified operating period. Common reliability indicators include failure rate, mean time between failures (MTBF), mean time to repair (MTTR), reliability function, and availability. These indicators enable maintenance personnel to quantify equipment performance and identify critical systems requiring maintenance priority.

Condition-Based Maintenance (CBM) further enhances maintenance planning by continuously monitoring equipment health through measurable condition indicators. Techniques such as lubricating oil analysis, vibration monitoring, thermography, ultrasonic inspection, and performance monitoring enable maintenance decisions to be based on actual equipment condition rather than predetermined schedules. This approach reduces unexpected failures and extends component service life by detecting degradation before functional failure occurs.

Predictive Maintenance (PdM) represents the latest development in reliability assessment by integrating condition monitoring with advanced data analytics, artificial intelligence, and machine learning algorithms. Instead of merely identifying equipment degradation, PdM estimates the remaining useful life (RUL) of components and predicts future failures using historical operational data and real-time sensor information. As digitalization continues to expand across the maritime industry, predictive maintenance is increasingly recognized as an essential element of intelligent fleet management and smart shipping operations.

Overall, these reliability assessment approaches are complementary rather than independent. Reliability analysis provides performance measurement, FMEA and FTA identify failure mechanisms, RCM determines appropriate maintenance policies, while CBM and PdM optimize maintenance timing through equipment condition monitoring. The integration of these approaches establishes a comprehensive reliability management framework capable of improving the safety, availability, and operational efficiency of marine main diesel engines.

Recent literature has extended this foundation in two directions relevant to the present review's objectives. First, several 2021–2024 studies have advanced maintenance strategy selection methodology Animah and Shafiee [31] applied a hybrid AHP–PROMETHEE and cost-benefit framework to shipboard machinery strategy selection, while Tripathi and Hari Prasad [28] used genetic algorithms to optimize RCM-based maintenance intervals specifically for marine diesel engines, confirming that RCM decision logic remains an active and evolving research area rather than a settled methodology. Second, condition monitoring research has moved rapidly toward data-driven and machine-learning approaches Gharib and Kovács [26] reviewed prognostic and health management (PHM) methods for marine diesel engines and identified the integration of PHM processes into a single decision-support system as an open research gap; Zhang et al. [27] conducted a systematic review of PHM for marine systems and equipment spanning health condition monitoring through to maintenance strategy; Maione et al. [29] demonstrated a machine-learning framework for CBM of marine diesel engines using real case-study data; and Arslanoğlu [30] proposed a hybrid predictive maintenance approach combining RCM and CBM logic for main engine bearings. However, none of these studies systematically cross-references failure mode criticality and detectability against maintenance strategy assignment in a single subsystem-level decision matrix, nor do they reconcile emerging machine-learning-based PHM methods with the classical FMEA–RCM logic still used operationally by ship maintenance departments the specific gap this review addresses.

II. METHOD

The study employs a narrative literature review methodology with a structured synthesis approach. Relevant publications were identified through systematic searches of scholarly databases (Scopus, Web of Science, Google Scholar) using Boolean combinations of the primary keywords marine diesel engine, main engine reliability, failure mode and effects analysis, reliability-centered maintenance, condition-based maintenance, condition monitoring, and ship machinery. Searches were supplemented by backward citation tracking from key anchor references. The final corpus comprised 25 peer-reviewed journal articles and textbooks published between 1997 and 2023, international standards on condition monitoring practice [12], and maritime authority casualty statistics [1,2].

Extracted material was synthesized thematically across three domains corresponding to the review objectives (1) failure mode characterization and root cause analysis; (2) maintenance strategy selection logic; and (3) condition monitoring technique assessment. The analytical lens applied throughout was the failure rate function and its bathtub characteristic [10], which provides the theoretical basis for distinguishing age-related from random failure modes and therefore for selecting between time-based and condition-based maintenance strategies. FMEA was applied as the structured method for failure mode consequence

assessment, and RCM decision logic [6] was used to formalize strategy assignments. A qualitative FMEA matrix was constructed by synthesizing failure mode, consequence, and root cause data from the reviewed literature across seven primary main engine subsystems.

A. Review Design

This study adopted a narrative literature review design to synthesize existing knowledge regarding the reliability of marine main diesel engines. A narrative review was considered appropriate because the objective of this study was not to statistically aggregate quantitative findings, but to integrate engineering theories, maintenance philosophies, failure mechanisms, and condition monitoring practices reported across diverse literature sources. The reviewed publications consisted of peer-reviewed journal articles, engineering textbooks, international standards, technical guidelines, and industrial reports, each providing complementary perspectives on marine machinery reliability. Unlike systematic reviews or meta-analyses, which generally focus on homogeneous datasets and quantitative comparisons, a narrative review enables a comprehensive interpretation of heterogeneous evidence and facilitates the development of an integrated conceptual framework. Therefore, this approach is considered suitable for identifying dominant failure modes, comparing maintenance strategies based on Reliability-Centered Maintenance (RCM) principles, and evaluating the contribution of Condition-Based Maintenance (CBM) techniques toward improving the operational reliability of marine main diesel engines. The review was conducted by synthesizing the available literature into three principal themes, namely failure modes and root causes, maintenance strategy selection, and condition monitoring techniques, corresponding to the objectives of this study.

B. Literature Search Strategy

The literature search was conducted to identify publications relevant to the reliability management of marine main diesel engines. Several academic databases, including Scopus, Google Scholar, ScienceDirect, SpringerLink, and MDPI, were used to retrieve peer-reviewed journal articles, review papers, technical reports, engineering textbooks, and international standards. These sources were selected because they provide comprehensive and authoritative references in the fields of marine engineering, reliability engineering, maintenance management, and condition monitoring.

The literature search employed combinations of keywords related to the objectives of this review, including "marine main diesel engine", "marine diesel engine reliability", "maintenance strategy", "Reliability-Centered Maintenance (RCM)", "Condition-Based Maintenance (CBM)", "Failure Mode and Effects Analysis (FMEA)", "condition monitoring", "lubricating oil analysis", "vibration analysis", and "predictive maintenance". To improve the relevance of the search results, Boolean operators such as AND and OR were applied. For example, search strings included ("marine diesel engine" AND reliability), ("marine diesel engine"

AND maintenance), and ("condition monitoring" OR predictive maintenance) AND marine engine.

C. Study Selection

The retrieved literature was evaluated through a structured screening process to ensure its relevance to the objectives of this review. Publications were selected based on their contribution to the understanding of marine main diesel engine reliability, maintenance strategies, failure mechanisms, and condition monitoring technologies. Priority was given to peer-reviewed journal articles published in reputable international journals, complemented by engineering textbooks, international standards, technical guidelines, and industrial reports that provide well-established theoretical and practical foundations for marine machinery maintenance.

To ensure the quality and relevance of the reviewed literature, only publications written in English and directly related to marine main diesel engines were considered. The selected references primarily covered topics such as Reliability-Centered Maintenance (RCM), Failure Mode and Effects Analysis (FMEA), Condition-Based Maintenance (CBM), predictive maintenance, lubricating oil analysis, vibration analysis, and other condition monitoring techniques. Preference was also given to recent publications published between 2020 and 2025 to capture current technological developments, while several classical references were retained because they represent the fundamental theories of reliability engineering and maintenance management.

Publications were excluded when they focused on propulsion systems other than marine main diesel engines, discussed unrelated industrial applications, lacked sufficient technical information, or duplicated findings already represented in the selected literature. Conference abstracts, editorial articles, and non-technical publications were also excluded because they generally provide limited methodological and engineering detail. Through this screening process, the selected literature was considered sufficiently comprehensive to support the synthesis of failure modes, maintenance strategies, and condition monitoring techniques presented in this review.

D. Data Synthesis

The selected literature was synthesized using a thematic analysis approach to provide a comprehensive understanding of reliability management for marine main diesel engines. Following the screening process, the reviewed publications were systematically classified into three principal themes corresponding to the objectives of this study

- (1) failure modes and root causes,
- (2) maintenance strategies, and
- (3) condition monitoring techniques.

Within each theme, the literature was comparatively analyzed to identify the most frequently reported failure mechanisms, commonly adopted maintenance approaches, and the effectiveness of various monitoring technologies in improving engine reliability. In addition to summarizing previous findings, similarities, differences, and limitations among the reviewed studies

were critically evaluated to identify current research trends and remaining knowledge gaps. The synthesized findings were subsequently integrated to develop a comprehensive reliability management perspective by linking Failure Mode and Effects Analysis (FMEA), Reliability-Centered Maintenance (RCM), and Condition-Based Maintenance (CBM). This thematic synthesis provides the analytical foundation for discussing how failure analysis, maintenance strategy selection, and condition monitoring can collectively improve the operational reliability of marine main diesel engines.

III. RESULTS AND DISCUSSION

A. Dominant Failure Modes and Root Causes

Across the reviewed studies, main engine failures concentrate in a recurring set of subsystems. The fuel injection system injectors, fuel pumps, and high-pressure pipework is consistently reported as the highest-frequency failure subsystem, with degradation driven primarily by fuel quality (catalytic fines, water contamination, poor combustion properties) and manifesting as injector fouling, spray pattern deterioration, and pump wear. The direct consequences include combustion quality degradation, elevated thermal loading, and abnormal exhaust conditions [8,13]. Cylinder components liners, piston rings, and exhaust valves form the second major cluster, with failure mechanisms including abrasive and corrosive liner wear, ring breakage, scuffing, and valve burning, strongly governed by cylinder lubrication quality and combustion conditions [5,13].

Turbochargers contribute high-consequence failures ranging from compressor and turbine fouling to surging and rotor or bearing damage. The cooling water and lubricating oil systems function as systemic failure enablers cooling water treatment deficiencies produce corrosion, scaling, and thermal overload in heat exchangers and liner cooling bores; lubricating oil contamination or degradation propagates wear progressively through bearings, running gear, and cylinder components [4,9]. Crankcase-related failures, while comparatively infrequent, carry the most severe safety and commercial consequences, with crankcase explosion representing the limiting case [14]. Table 1 presents the integrated qualitative FMEA synthesis compiled from the reviewed literature.

Beyond identifying individual failure modes, the reviewed literature demonstrates that the interaction between failure mechanisms and their underlying root causes plays a decisive role in determining the overall reliability of marine main diesel engines. Similar failure modes may originate from different operational conditions, including inadequate maintenance practices, fuel contamination, improper lubrication, excessive thermal loading, and prolonged engine operation. This indicates that improving engine reliability requires more than simply replacing failed components; it requires systematic identification of failure causes and the implementation of maintenance strategies that address the mechanisms leading to component degradation. Consequently, understanding the relationship between

dominant failure modes and their root causes provides the analytical basis for applying Failure Mode and Effects Analysis (FMEA) and selecting appropriate

Reliability-Centered Maintenance (RCM) and Condition-Based Maintenance (CBM) strategies.

TABLE 1.

QUALITATIVE FMEA SYNTHESIS OF PRINCIPAL MARINE MAIN DIESEL ENGINE SUBSYSTEMS, COMPILED FROM REVIEWED LITERATURE [4,5,8,9,13,14].

Subsystem	Typical Failure Modes	Dominant Root Causes	Consequence	Suitable Strategy
Fuel injection system	Injector fouling, spray deterioration, pump wear	Fuel quality (cat-fines, water), abrasion	Poor combustion, thermal overload	Preventive + performance monitoring
Cylinder liner/rings	Abrasive/corrosive wear, scuffing, ring breakage	Cylinder lubrication, combustion condition	Loss of compression, high wear rates	Preventive + drain oil analysis
Exhaust valves	Valve burning, seat recession	Thermal load, fuel quality	Power loss, cylinder damage	Time-based preventive
Turbocharger	Fouling, surging, rotor/bearing damage	Deposits, unbalance, lubrication	Power limitation, consequential damage	CBM (vibration, performance)
Main/crankpin bearings	Wear, fatigue, wiping	Oil contamination, load, alignment	Crankshaft damage, crankcase explosion	CBM (oil analysis, temperature)
Cooling water system	Corrosion, scaling, pump failure	Water treatment deficiency	Thermal overload of components	Preventive + water quality monitoring
Lubricating oil system	Oil degradation, contamination, filter blockage	Water/fuel ingress, oxidation	Systemic wear propagation	CBM (lubricating oil analysis)

Overall, the reviewed literature indicates that failures associated with combustion-related subsystems occur more frequently than failures originating from structural engine components. Fuel injection equipment, cylinder assemblies, and lubrication systems consistently appear as the primary contributors to engine unreliability because their degradation directly affects combustion efficiency, thermal loading, and mechanical wear. These findings suggest that improving engine reliability requires maintenance strategies that prioritize critical subsystems based on failure characteristics and operational consequences rather than focusing solely on component replacement. Therefore, selecting appropriate maintenance strategies becomes essential for minimizing unexpected failures and enhancing the long-term reliability of marine main diesel engines.

B. Failure Rate Behavior and Maintenance Strategy Assignment

The temporal behavior of main engine failure modes follows the bathtub reliability characteristic [10]. Early failures cluster in the period immediately following overhauls and component installation, typically caused by assembly errors, incorrect clearances, or defective

spare parts a pattern that cautions against unnecessarily intrusive maintenance intervention. During the useful life period, failures occur essentially at random, driven by operating stressors (fuel and lubricant quality, load cycles) rather than component age, which fundamentally limits the effectiveness of time-based overhaul for these modes. In the wear-out period, age-related degradation mechanisms (liner wear, valve seat recession, bearing fatigue) dominate, and scheduled restoration or replacement regains effectiveness [6,10].

Figure 1 illustrates the bathtub curve and its implications for maintenance strategy selection. RCM decision logic [6] prescribes time-based preventive maintenance for age-related failure modes where a restoration interval can be determined; CBM for randomly-occurring failure modes where degradation is detectable with sufficient warning (the P-F interval); and run-to-failure where failure consequences are negligible. Applied to main engine subsystems, this logic produces the strategy assignments shown in Table 1 and Figure 2 CBM-dominant for bearings, turbochargers, and the lubricating oil system; time-based preventive for exhaust valves and injectors; hybrid approaches for cylinder liner/ring systems.

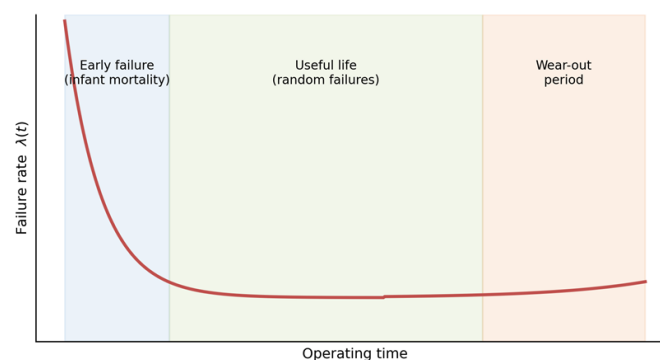


Figure 1. The bathtub reliability curve of failure rate over operating time, distinguishing early failure, useful life, and wear-out periods, and their implications for maintenance strategy selection (adapted from [10]).

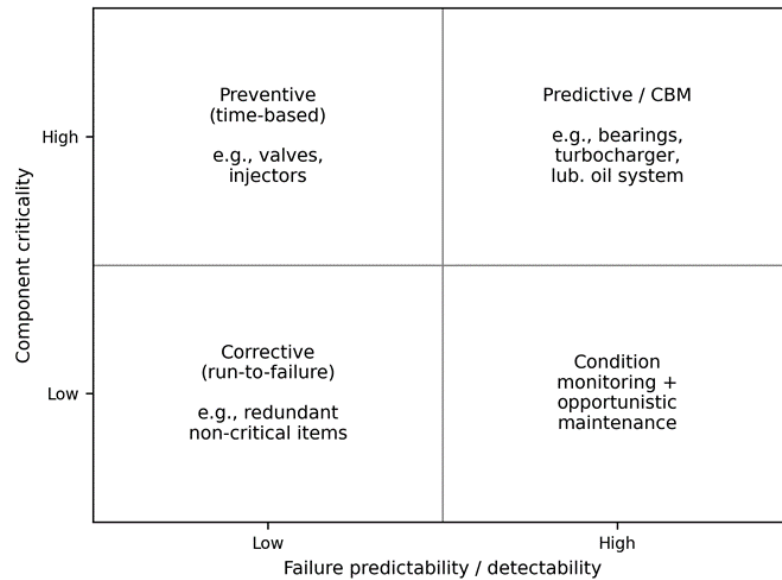


Figure 2. Maintenance strategy assignment matrix for marine main engine subsystems, based on failure consequence criticality and failure mode predictability/detectability (synthesized from [4,6,8]).

C. Condition Monitoring Techniques

Four families of condition monitoring techniques are established in marine main engine practice [5,12]. Lubricating oil analysis measuring viscosity, base number (BN), water and fuel dilution, insolubles, and wear metals by spectrometry provides the highest information density of any single monitoring technique for diesel machinery, yielding simultaneous insight into lubricant condition, contamination status, and wear state of lubricated components. On two-stroke engines, cylinder drain (scrape-down) oil analysis extends this capability to monitor cylinder lubrication effectiveness and liner wear independently. Thermodynamic performance monitoring comprising cylinder pressure indication, exhaust gas temperature trending, turbocharger speed and pressure ratio monitoring, and specific fuel consumption analysis detects combustion-related degradation including injector deterioration, piston blow-by, valve leakage, and turbocharger fouling at the subsystem level.

Vibration analysis targets rotating machinery elements, principally turbochargers and attached centrifugal pumps, enabling detection of developing unbalance, misalignment, and bearing defects prior to functional failure. Infrared thermography complements these techniques by revealing abnormal thermal patterns in exhaust systems, cylinder heads, turbocharger casings, and electrical equipment, and by detecting insulation degradation and cooling circuit anomalies. Effective CBM implementation requires that all monitoring measurements be acquired at defined intervals against established baselines, trended to distinguish normal scatter from degradation signals, and linked to pre-defined alarm thresholds and maintenance decision rules requirements formalized in ISO 17359 [12]. Critically, condition data must be integrated into the ship's planned maintenance system (PMS) so that monitoring findings directly generate work orders and spare parts requisitions rather than remaining as standalone records [5,15].

D. The Upstream Reliability Principle

The most significant cross-cutting finding of this review is that main engine reliability is governed primarily by factors upstream of the engine's mechanical components fuel quality management, lubricant condition control, and cooling water treatment appear as dominant root causes across virtually every major failure cluster identified in Section 4.1. This upstream reliability principle has a direct implication for maintenance program design maintenance programs that treat enabling systems (fuel system, lubricant system, cooling system) as first-class reliability items with their own condition monitoring parameters, acceptance criteria, and trend analysis consistently outperform programs that focus resources on mechanical component overhaul intervals [8,13]. Translated into operational practice, this finding supports prioritizing fuel quality testing at bunkering, lubricating oil analysis programs on defined intervals, and cooling water quality monitoring over periodic intrusive overhauls of fuel injectors and cylinder components in cases where operating condition data suggest no imminent degradation.

E. Consequence-Driven Strategy Economics

The economics of maintenance strategy selection in marine engineering are dominated by failure consequences rather than failure frequencies a principle that distinguishes RCM-based from interval-based maintenance planning [6]. This review confirms that low-frequency/high-consequence failure modes (bearing wipe progressing to crankcase explosion; turbocharger rotor failure) justify intensive and continuous monitoring investment even where base failure rates are low, because the cost of a single failure event dwarfs the entire lifecycle cost of the monitoring system [14]. Conversely, high-frequency/low-consequence failures of redundant auxiliaries are correctly managed by run-to-failure with adequate spares holding, avoiding

unnecessary maintenance cost and the early-failure risk introduced by intrusive intervention. The novelty of the FMEA–RCM matrix presented in Table 1 and Figure 2 is its explicit operationalization of this consequence-driven logic at the subsystem level, providing fleet operators with a directly actionable decision tool rather than a generic framework.

F. Organizational Integration as the Critical Implementation Gap

The principal barrier to CBM implementation identified across recent literature is not the availability of monitoring technology but its organizational integration into the maintenance decision workflow [5,9,15]. Modern vessels increasingly carry instrumentation capable of generating rich condition data streams, yet the value chain from measurement acquisition through trending, diagnosis, and maintenance work order generation is routinely disrupted by fragmented software environments, unclear responsibility boundaries between ship and shore technical teams, and the absence of systematic reliability data collection and feedback mechanisms. Classification societies have recognized this gap through machinery condition monitoring (MCM) class notations that permit survey scope reduction when certified condition monitoring programs are in place, providing a regulatory incentive for CBM adoption [5]. The practical implementation roadmap emerging from the literature is incremental and risk-stratified begin with lubricating oil analysis and performance monitoring on critical items (turbochargers, main bearings), integrate findings into the PMS, apply FMEA-based criticality ranking to expand the CBM scope systematically, and build the reliability database progressively to enable predictive analytics as data maturity grows [4,8,9].

G. Contribution Relative to Recent Machine-Learning-Based Reviews

The findings of this review carry a specific implication for how the field should reconcile classical reliability engineering with the recent surge of machine-learning-based PHM research. Gharib and Kovács [26] and Zhang et al. [27] both identify the fragmentation of PHM technical processes condition monitoring, fault diagnosis, health prognosis, and maintenance decision-making as the principal barrier to fleet-wide adoption, echoing the organizational integration gap identified in Section 5.3 of this review. Machine-learning approaches such as those of Maione et al. [29] demonstrate strong diagnostic and prognostic accuracy on case-study data, yet they typically optimize a single subsystem or failure signature in isolation rather than situating that subsystem within a fleet-wide, consequence-weighted maintenance strategy. The integrated FMEA–RCM matrix presented in Table 1 and Figure 2 is therefore not a competitor to machine-learning-based PHM but a complementary decision layer it determines which subsystems justify the investment in advanced condition monitoring or predictive analytics in the first place, based on failure consequence and detectability, before a specific monitoring technology is selected. This positions the

present review's novelty as methodologically prior to, rather than redundant with, the data-driven PHM literature providing the criticality and strategy-assignment logic that machine-learning implementations such as Tripathi and Hari Prasad's genetic-algorithm-optimized RCM model [28] and Arslanoğlu's hybrid predictive maintenance framework [30] both require as an input but do not themselves derive from first principles.

H. Limitations and Directions for Future Research

This review's principal limitation follows from its narrative character the synthesis is qualitative, the underlying studies span diverse engine types, ship types, flag states, and operational profiles, and publication bias toward positive CBM outcomes cannot be excluded. Quantitative meta-analysis of marine engine failure rate data remains constrained by the rarity of operators' reliability databases in the public domain. Future research priorities identified include (1) development of standardized, anonymized marine machinery failure reporting frameworks analogous to those operating in aviation to enable quantitative reliability modeling; (2) investigation of the impact of alternative fuels (LNG, methanol, ammonia, FAME blends) on failure mode distributions and maintenance strategy validity, as the energy transition alters the operating envelope of main diesel and dual-fuel engines; and (3) prospective evaluation of digital twin and machine learning-based predictive maintenance approaches against the established CBM baseline documented in this review.

IV. CONCLUSION

This review consolidated the literature on marine main diesel engine reliability management around three objectives, which are addressed in turn below.

Regarding dominant failure modes and root causes (Objective 1) the fuel injection system, cylinder components (liners, rings, exhaust valves), turbochargers, and the lubricating and cooling oil systems are the dominant contributors to main engine unreliability. Root causes are concentrated in fuel and lubricant quality, thermal loading, and maintenance quality rather than in inherent component design deficiencies. The upstream reliability principle that enabling system condition governs mechanical component reliability is the most operationally significant finding for maintenance program design.

Regarding maintenance strategy assignment (Objective 2) because main engine failure modes mix age-related and random behavior, no single strategy is universally optimal. The integrated FMEA–RCM decision framework identifies a hybrid architecture as the evidence-based solution time-based preventive maintenance for age-related, poorly-predictable failure modes (exhaust valves, injectors) CBM for randomly-occurring, well-detectable degradation on critical subsystems (bearings, turbochargers, lubricating oil system); and run-to-failure for low-consequence redundant items. This assignment is directly derivable from the FMEA–RCM matrix presented in Table 1 and Figure 2.

Regarding condition monitoring implementation (Objective 3) lubricating oil analysis, thermodynamic performance monitoring, vibration analysis, and infrared thermography constitute the established CBM toolkit for main engine components. The critical success factor is not technology availability but organizational integration condition data must be linked to maintenance decision rules and PMS work order generation, with clear ship–shore responsibility boundaries. The integration of condition monitoring data into classification society survey planning, enabled through MCM class notations, represents the principal regulatory lever for fleet-wide CBM adoption.

Taken together, these findings directly close the gap identified at the outset of this review fleet operators no longer need to treat failure diagnosis, maintenance strategy selection, and condition monitoring technique selection as three separate decisions. The integrated FMEA–RCM matrix (Table 1, Figure 2) provides the missing subsystem-level link between them, and its logic remains complementary to rather than superseded by the emerging machine-learning-based PHM methods reviewed in Section 5.4. Future work operationalizing this matrix within shipboard planned maintenance systems, and validating it against fleet-wide failure and maintenance-cost data, would confirm its practical value beyond the literature synthesis presented here.

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