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Ship Maintenance in the Digital Age Focus on Predictive Systems

Abstract

Modern ships are complex technical units composed of various systems and subsystems, including the ship management system, safety and protective systems for the ship and crew, propulsion system, hull structure, power supply and distribution system, cargo handling system, and accommodation systems for crew and passengers. All these systems are interconnected and collectively contribute to the ship's purpose, primarily achieved through comprehensive maintenance. Increasingly rigorous international regulations regarding ship and crew safety, as well as environmental protection, encourage shipowners to emphasize regular, proactive, and predictive maintenance of ship systems to ensure uninterrupted operations without delays. Advancements in modern technology have transformed approaches to ship maintenance by leveraging developments in the ICT sector, including analytical methods and AI models like machine learning and deep learning, which have revolutionized maintenance practices. This paper, in addition to exploring conventional maintenance methods, investigates key components of predictive maintenance, discusses challenges such as transparency and ethical implications, and analyzes the latest trends in AI-based predictive maintenance—from sensors and data collection to data processing algorithms and decision-making modules.

Keywords: maintenance, reliability, ship systems, predictive maintenance

1. Introduction

Any maintenance system consists of its components and connections between them, which ensure the complete upkeep of specific types and categories of technical systems throughout their lifecycle. The primary characteristics of a maintenance system include conceptual (maintenance policies, comprehensiveness), organizational (processes, process management: levels, authorities, planning, supervision, information, etc.) and technological aspects. Maintenance technology encompasses all preventive and corrective maintenance operations, through which a particular type of technical system is maintained effectively over its useful lifespan. The choice of maintenance policy depends on the fundamental maintenance approach selected, which can be categorized as reactive maintenance, scheduled periodic maintenance (preventive), based on time or operational resources, or reliability-centered maintenance.

This paper outlines various maintenance approaches and explains the lifecycle management system established during the design and construction phases of a ship. All ships share a common classification of systems essential to their operation. The analysis focuses on maintenance specificities in light of the general purpose of the ship, to which all ship subsystems are subordinated. The purpose of this paper is to consolidate, in one place, the types of modern ships and their distinctive characteristics, highlighting the importance of preventive, proactive, and predictive maintenance.

A specific research goal is the use of artificial intelligence (AI) as a key tool in modern predictive maintenance systems due to its ability to process large volumes of data, identify causative factors, and make accurate, timely decisions. AI leverages various machine learning (ML) and deep learning (DL) techniques to model system behavior and enable prediction-based maintenance, thereby enhancing equipment reliability and efficiency.

2. Terotechnology in the Function of Ship System Maintenance

The classical theory of ship maintenance systems supports two types of maintenance: preventive and corrective (Waeyenbergh & Pintelon, 2002). Corrective maintenance is performed when a component operates under a “run-to-failure” condition, implying that the consequences and cost of this failure are deemed acceptable and manageable, at least compared to the costs of preventive maintenance. Thus, it is typically applied to inexpensive and non-critical components, avoiding the opportunity cost of downtime and productivity loss.

Preventive maintenance, on the other hand, is conducted before component failure to enhance the safety, quality, and availability of the system by detecting, systematically inspecting, and preventing incipient failures (Wang, 2002). Preventive maintenance methodologies have been developed since the 1970s, with the Ministry of Industry Committee introducing the Terotechnology model to balance maintenance costs and profitability. Belak and Čičin-Šain (Razvoj koncepta terotehnologije, 2005) describe terotechnology as “a combination of management, finance, engineering, construction, and other disciplines applied to a company’s physical assets with a focus on cost-effectiveness throughout their useful life.” Although terotechnology can be defined in various ways depending on perspective, it universally emphasizes synergy among technical and scientific disciplines involved in maintenance processes, aimed at maximizing utility.

In today's modern world, terotechnology is one of the most important technologies. As the term itself suggests (derived from the Greek word "tirein," meaning to care for or supervise), it involves preservation or maintenance technology, essential for preventing ship system failures, extending their operational lifespan, and addressing failures in the most effective way (Lovrić, J., 1989). For a ship, a highly complex and expensive entity for transporting cargo and passengers, maintenance plays a crucial role in its lifecycle and economic utility. Terotechnology seeks to optimize maintenance costs through design and planning, aiming to achieve a maintenance approach where the sum of direct (intervention costs) and indirect (downtime costs) expenses is minimized. This enables shipowners to offer competitive freight rates by lowering operational costs, thereby enhancing market competitiveness and profitability while meeting regulatory safety and seaworthiness requirements set by authorities and ensuring economic viability.

A shipowner develops maintenance policies by prioritizing minimal environmental impact, operational cost efficiency, and asset preservation by extending ship's economic utility, and maximizing her resale value. A sound policy increases the ship's profitability, which is also influenced by factors like the ship's age, operating conditions, and historical maintenance practices (Mohović, Ivče, & Zorović, 2007).

Maintenance on ships is performed through:

- ◊ Fault repair tasks,
- ◊ Following equipment manufacturer recommendations for specific ship systems,
- ◊ Established maintenance practices to control or slow deterioration,
- ◊ Meeting the requirements of classification societies and other organizations that inspect and supervise ships.

After an inspection, classification societies or other authorized organizations acting on behalf of the state issue certificates affirming that the ship is adequately maintained with regard to safety and seaworthiness.

3. Ship System Maintenance

The following classification is organized from the perspective of utilizing the ship according to its primary function, with the understanding that a passenger ship may include additional systems beyond those listed here, as this pertains to a typical cargo ship. This classification aids in managing the ship as a complex, mobile technical unit, recognizing that different ship components uniquely affect overall functionality and therefore require distinct maintenance practices. Maintenance also includes regular inspections by authorized inspectors, who evaluate not only the physical readiness of systems but also the crew's handling and operational proficiency with those systems.

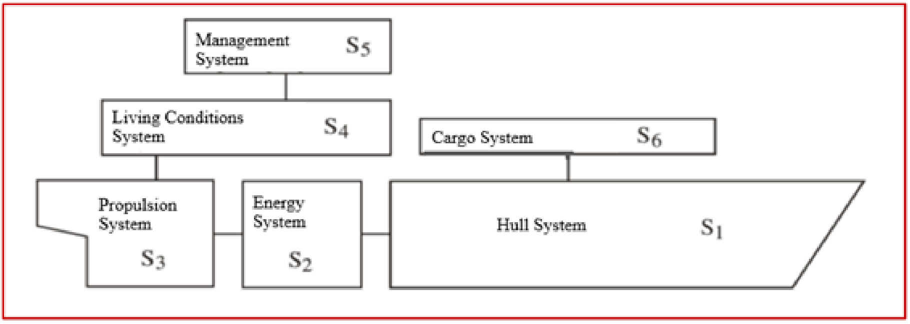


Figure 1 - Ship Systems
Source: Lovrić, J.: Osnove brodske terotehnologije. Dubrovnik, 1989.

Viewed through the exploitation of the ship and analysis of individual systems, the ship can be divided into the following primary macrosystems (Čovo, 2007):

- □ **Ship Management System** - The ship management system is operated from the command bridge, which is the central point for ship control. Although the size of the devices on the bridge has significantly decreased over the past 20–30 years, their functions have remained consistent, evolving alongside advancements in technology. These devices include communication, propulsion control, steering, and navigation equipment. Communication devices are regulated by the Global Maritime Distress and Safety System (GMDSS). Authorized crew members maintain these communication devices preventively, following specific instructions outlined in each device's manual. Every check of the system's functionality is recorded in the radio log, and a physical check may also be noted in the general maintenance log if required by the shipowner. Navigation equipment includes ECDIS (Electronic Chart Display and Information System), ARPA (Automatic Radar Plotting Aid), positioning devices, and other essential instruments on the command bridge.
- □ **Safety and Protection System for the Ship and Crew** - This system is regulated by the SOLAS (Safety of Life at Sea) Convention and can be divided into the following components (Zec, 2001):
  - **Firefighting Equipment** - Essential for preventing and managing onboard fires, including fire extinguishers, hoses, and detection systems.
  - **Evacuation and Rescue Equipment** - Equipment for abandoning ship and ensuring crew and passenger safety in emergencies, such as lifeboats, life rafts, and personal flotation devices.
  - **Emergency Power Supply and Distribution System** - A dedicated electrical power system to provide necessary power during emergency situations, ensuring critical systems remain operational.

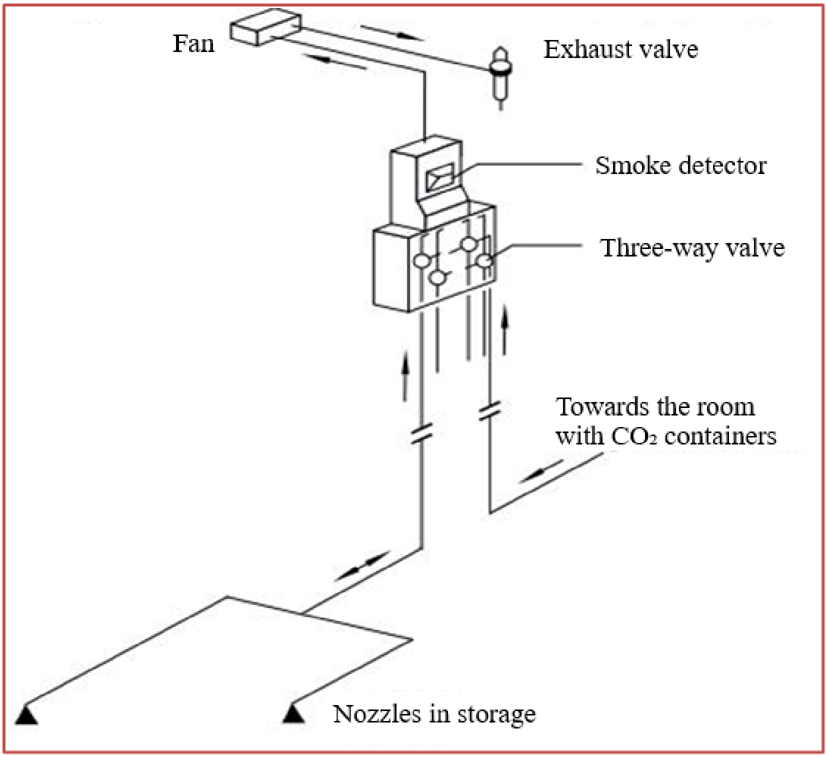


Figure 2 - Example of a Firefighting System
Source: Dr.sc.Damir Zec:Sigurnost na moru, Pomorski fakultet u Rijeci, Rijeka, 2001

- ☐ **Propulsion System** - The main component of this system is the propulsion engine, which can vary in number and type depending on the ship's purpose and requirements, thus necessitating varied maintenance practices. The propulsion engine is connected to the power transmission system, fuel and lubricant supply and preparation devices, and thrusters, which can be bow or stern thrusters. Maintenance of mechanical components includes monitoring system parameters, lubrication, cleaning, and component replacement. Both planned and corrective maintenance are employed in this system, as some components significantly impact ship operation, while others have less impact and can be run to failure if replacement parts are readily available.
- ☐ **Hull System** - The hull serves as the supporting structure for all other systems. Its thickness and strength are thoroughly inspected during overhauls by classification societies, as these aspects directly affect the ship's safety and the safety of those onboard. While the crew has limited maintenance capabilities for the hull during

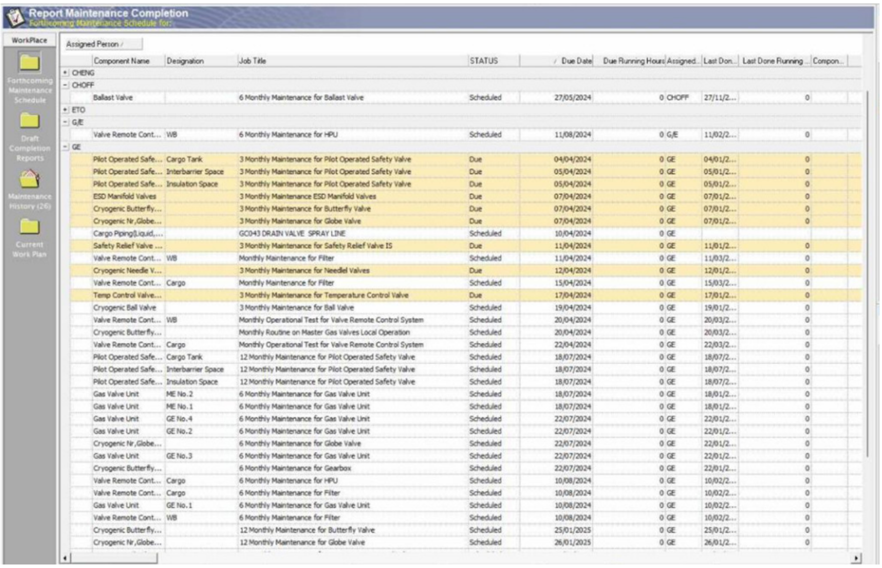
voyages, they may maintain corrosion protection systems if the ship is equipped with impressed current systems. Additionally, the crew can protect the deck and interior hull sections from corrosion through protective coatings.

- **Power Supply and Distribution System** - Indirectly connected to the propulsion system, it includes devices for generating and distributing electricity, as well as systems for compressed air, hydraulics, and water and steam. This connection is indirect because the power system components are essential for starting and operating the propulsion engine. Maintenance is conducted preventively, similarly to the propulsion system, due to its impact on both ship utilization and safety.
- **Cargo Handling System** - This system varies by ship type and cargo type. For instance, two general cargo ships may differ if one has its own cranes for cargo handling while the other does not. One may operate in regions without port facilities for cargo transfer, necessitating additional investment in handling equipment, while the other may not.
- **Crew and Passenger Accommodation System** - This encompasses all equipment and spaces that support onboard living conditions, including galleys for food preparation, food storage areas, ventilation and air conditioning, and sanitary facilities. Preventive maintenance is essential to ensure normal living conditions, which are critical for the ship's operation, as it cannot serve its purpose without a fully functional crew.

3.1. Cargo System Maintenance

The **Cargo System** varies from one ship to another depending on the type of cargo it transports and the cargo specialization, as analyzed in more detail below (Radica, 2009):

- **Maintenance Specifics for Liquefied Gas Carriers** - Ships transporting liquefied gases, which can be carried in three ways—sub-cooled, compressed, or through a combination of pressure and temperature—require specialized maintenance. Among the most notable types are natural gas derived from wells (LNG - Liquefied Natural Gas) and petroleum gas obtained through oil refining (LPG - Liquefied Petroleum Gas). These ships are highly sensitive in terms of maintenance and have a high potential for accidents, which can occur rapidly. Due to the demanding nature of these vessels, their maintenance systems are digitalized, utilizing Planned Maintenance System (PMS) software that assigns daily tasks detailing what needs maintenance and how it should be performed (Sumner, 2015). An example task list can be seen in *Figure 2*.



	Component Name	Designation	Job Title	STATUS	Due Date	Due Running Hours	Assigned...	Last Don...	Last Done Running ...	Compon...
+ CHENG										
− CHOFF										
	Ballast Valve		6 Monthly Maintenance for Ballast Valve	Scheduled	27/05/2024	0	CHOFF	27/11/2...	0	
+ ETO										
− G/E										
	Valve Remote Cont...	WB	6 Monthly Maintenance for HPU	Scheduled	11/08/2024	0	G/E	11/02/2...	0	
− GE										
	Pilot Operated Safe...	Cargo Tank	3 Monthly Maintenance for Pilot Operated Safety Valve	Due	04/04/2024	0	GE	04/01/2...	0	
	Pilot Operated Safe...	Interbarrier Space	3 Monthly Maintenance for Pilot Operated Safety Valve	Due	05/04/2024	0	GE	05/01/2...	0	
	Pilot Operated Safe...	Insulation Space	3 Monthly Maintenance for Pilot Operated Safety Valve	Due	05/04/2024	0	GE	05/01/2...	0	
	ESD Manifold Valves		3 Monthly Maintenance ESD Manifold Valves	Due	07/04/2024	0	GE	07/01/2...	0	
	Cryogenic Butterfly...		3 Monthly Maintenance for Butterfly Valve	Due	07/04/2024	0	GE	07/01/2...	0	
	Cryogenic Nr,Globe...		3 Monthly Maintenance for Globe Valve	Due	07/04/2024	0	GE	07/01/2...	0	
	Cargo Piping(Liquid,...		GC043 DRAIN VALVE SPRAY LINE	Scheduled	10/04/2024	0	GE			
	Safety Relief Valve ...		3 Monthly Maintenance for Safety Relief Valve IS	Due	11/04/2024	0	GE	11/01/2...	0	
	Valve Remote Cont...	WB	Monthly Maintenance for Filter	Scheduled	11/04/2024	0	GE	11/03/2...	0	
	Cryogenic Needle V...		3 Monthly Maintenance for Needlel Valves	Due	12/04/2024	0	GE	12/01/2...	0	
	Valve Remote Cont...	Cargo	Monthly Maintenance for Filter	Scheduled	15/04/2024	0	GE	15/03/2...	0	
	Temp Control Valve...		3 Monthly Maintenance for Temperature Control Valve	Due	17/04/2024	0	GE	17/01/2...	0	
	Cryogenic Ball Valve		3 Monthly Maintenance for Ball Valve	Scheduled	19/04/2024	0	GE	19/01/2...	0	
	Valve Remote Cont...	WB	Monthly Operational Test for Valve Remote Control System	Scheduled	20/04/2024	0	GE	20/03/2...	0	
	Cryogenic Butterfly...		Monthly Routine on Master Gas Valves Local Operation	Scheduled	20/04/2024	0	GE	20/03/2...	0	
	Valve Remote Cont...	Cargo	Monthly Operational Test for Valve Remote Control System	Scheduled	22/04/2024	0	GE	22/03/2...	0	
	Pilot Operated Safe...	Cargo Tank	12 Monthly Maintenance for Pilot Operated Safety Valve	Scheduled	18/07/2024	0	GE	18/07/2...	0	
	Pilot Operated Safe...	Interbarrier Space	12 Monthly Maintenance for Pilot Operated Safety Valve	Scheduled	18/07/2024	0	GE	18/07/2...	0	
	Pilot Operated Safe...	Insulation Space	12 Monthly Maintenance for Pilot Operated Safety Valve	Scheduled	18/07/2024	0	GE	18/07/2...	0	
	Gas Valve Unit	ME No.2	6 Monthly Maintenance for Gas Valve Unit	Scheduled	18/07/2024	0	GE	18/01/2...	0	
	Gas Valve Unit	ME No.1	6 Monthly Maintenance for Gas Valve Unit	Scheduled	18/07/2024	0	GE	18/01/2...	0	
	Gas Valve Unit	GE No.4	6 Monthly Maintenance for Gas Valve Unit	Scheduled	22/07/2024	0	GE	22/01/2...	0	
	Gas Valve Unit	GE No.2	6 Monthly Maintenance for Gas Valve Unit	Scheduled	22/07/2024	0	GE	22/01/2...	0	
	Cryogenic Nr,Globe...		6 Monthly Maintenance for Globe Valve	Scheduled	22/07/2024	0	GE	22/01/2...	0	
	Gas Valve Unit	GE No.3	6 Monthly Maintenance for Gas Valve Unit	Scheduled	22/07/2024	0	GE	22/01/2...	0	
	Cryogenic Butterfly...		6 Monthly Maintenance for Gearbox	Scheduled	22/07/2024	0	GE	22/01/2...	0	
	Valve Remote Cont...	Cargo	6 Monthly Maintenance for HPU	Scheduled	10/08/2024	0	GE	10/02/2...	0	
	Valve Remote Cont...	Cargo	6 Monthly Maintenance for Filter	Scheduled	10/08/2024	0	GE	10/02/2...	0	
	Gas Valve Unit	GE No.1	6 Monthly Maintenance for Gas Valve Unit	Scheduled	10/08/2024	0	GE	10/02/2...	0	
	Valve Remote Cont...	WB	6 Monthly Maintenance for Filter	Scheduled	10/08/2024	0	GE	10/02/2...	0	
	Cryogenic Butterfly...		12 Monthly Maintenance for Butterfly Valve	Scheduled	25/01/2025	0	GE	25/01/2...	0	
	Cryogenic Nr,Globe...		12 Monthly Maintenance for Globe Valve	Scheduled	26/01/2025	0	GE	26/01/2...	0	

Figure 3. Task List in PMS Software
Source: Author

- □ **Maintenance Specifics for Crude Oil and Oil Product Tankers** - The cargo system on tankers transporting crude oil and oil products includes:
  - **Pipelines** for inert gas, cargo heating, tank cleaning, and cargo operations,
  - **Manifolds** or connectors, typically located midship on both port and starboard sides, but may also be at the bow or stern,
  - **Vents and P/V Valves** for pressure and vacuum control,
  - **Tank Cleaning Equipment, Level Sensors, and Atmospheric Composition Sensors** within tanks,
  - **Coatings for Cargo Tanks** on ships carrying oil products,
  - **Cargo Discharge Pumps.**

Cargo operation pipelines (for loading or unloading) on oil tankers can undergo pressure testing to determine the maximum pressure they can withstand, especially in the event of hydraulic shock; this information, along with the testing date, is marked on the pipeline. Similar to liquefied gas carriers, oil tankers require adherence to strict maintenance protocols, operational procedures, and parameter monitoring (such as pump RPM, discharge rates, inert gas production, and pressure/vacuum limits of P/V valves) to avoid significant environmental pollution and preserve the ship's economic lifespan (Rudan, 2010).

- □ **Maintenance Specifics for Bulk Cargo Carriers** - Bulk carriers, which evolved from general cargo ships, share several similarities with them. However, there are key differences: general cargo ships are typically up to 100 meters in length with a DWT of around 10,000 tons, whereas bulk carriers can be as long as 360 meters with a DWT of up to 400,000 tons. Maintenance on bulk carriers is primarily preventive, involving thorough inspections and repairs of cargo holds and equipment before each cargo loading. The condition of cargo holds for specific cargo types and safe voyage execution is governed by the IMSBC (International Maritime Solid Bulk Cargo) Code, which includes five cleanliness standards applied based on cargo and shipper requirements.

Planned maintenance and pre-loading inspections should cover the hold frames and critical structural elements, access structures (ladders), the bilge system, hatch openings and covers, lighting, coating conditions, pipes within holds, and fixed firefighting systems. Structural inspections include external checks for dents that may compromise safety and for corrosion, which can weaken the structure or react with certain cargoes. Proper coatings are applied to protect structural integrity according to the cargo type, and any damage is repaired as necessary (Mohović Đ. , 2010).

□ **Maintenance Specifics for Container Ships** - The cargo system on container ships includes cargo holds divided into bays, guides for stacking containers in columns, electrical outlets for powering refrigerated containers, vents for bay ventilation, equipment for securing containers, a bow shield to protect containers on the bow from wave impact, and an anti-heeling system. The electrical outlets for refrigerated containers, which transport perishable goods requiring controlled temperatures, are maintained by ship electricians following both their technical expertise and the manufacturer’s instructions. For more complex repairs, shore-based service support is called.

□ **Maintenance Specifics for General Cargo Ships** - The International Organization for Standardization (ISO) provides a standard, “ISO 4309:2017 - Cranes - Wire Ropes (Care and Maintenance, Inspection, and Discard),” which sets forth:

- General principles for wire rope care,
- Maintenance, inspection, and replacement criteria for ropes,
- Guidelines for storage, handling, and installation of wire ropes.

The cranes and other cargo-handling equipment are governed by the International Labour Organization (ILO) Convention 152, which mandates that a logbook be kept onboard for records of equipment inspections and defines a testing process conducted every five years and annually by an inspector from the relevant ship classification society. All equipment inspections, whether routine, general, or thorough, must be documented (Ivče, 2015).

□ **Maintenance Specifics for Passenger Ships** - International standards are highly stringent when it comes to the safety of human lives at sea, whether on cargo or passenger vessels. One requirement is the maintenance of lifesaving appliances and associated equipment. While the crew partially handles maintenance onboard, a certified technician from the manufacturer performs comprehensive checks annually and every five years during dry docking. According to SOLAS "Chapter IV - Lifesaving Appliances and Arrangements," "Regulation 36 - Instructions for Maintenance Onboard" (IMO, 2024):

□ maintenance instructions must be clear, preferably illustrated, and include:
  - A checklist for inspection,
  - Maintenance and repair instructions,
  - A schedule for periodic maintenance,
  - A lubrication chart with recommended lubricants,
  - A list of replaceable parts,
  - A source list for spare parts,
  - Records of inspections and maintenance.

Inspections, as specified in SOLAS "Regulation 20 - Operational Readiness, Maintenance, and Inspections" (IMO, 2024): include:

□ **Weekly inspections** (visual checks of lifeboats and life rafts to confirm readiness for use, checking hooks and release gear, starting the lifeboat engines for at least three minutes at ambient temperature to ensure operational readiness, and testing the general alarm),

□ **Monthly inspections** (moving all lifeboats out of their stowed positions without personnel onboard, weather permitting, and lowering them into the water every three months; all lifesaving appliances are inspected using a checklist).

These inspections are conducted by the crew as much as possible, following the manufacturer's instructions, while certified technicians perform thorough inspections at least once a year. This includes inspecting life rafts, life jackets, the Marine Evacuation System (MES), and potentially repairing some equipment on board and some in shore-based workshops. Weekly and monthly inspections may also involve checking the lubrication of release equipment and other necessary equipment. The convention establishes minimum periodic inspection requirements, further supplemented by the Life-Saving Appliances (LSA) Code, which prescribes standardized tests across all equipment to ensure readiness. Most equipment testing is conducted onshore.

4. Predictive Maintenance of Ship Systems Using Artificial Intelligence (AI)

Predictive Maintenance (PdM) is an approach that applies advanced analytics to data collected from multiple sensors to predict when a system is likely to fail, organizing maintenance tasks accordingly to optimize maintenance intervals, reduce downtime, and increase system reliability. PdM has experienced substantial growth and advancements. Recently, low-cost sensors and new real-time condition monitoring systems have been effectively used to generate large datasets. These developments, alongside expert algorithms and specialized human expertise, have driven significant progress in predictive maintenance. Current efforts are focused on developing new multivariate statistical models and expert algorithms to improve prediction accuracy and reduce operational costs (Ucar, Karakose, & Kırımça, 2024).

Achieving autonomy in the next steps of robotic systems is now feasible thanks to sophisticated algorithms, AI-based models, and expert systems. Moreover, the potential of AI-driven PdM continues to expand, further enhancing the scope and effectiveness of predictive maintenance.

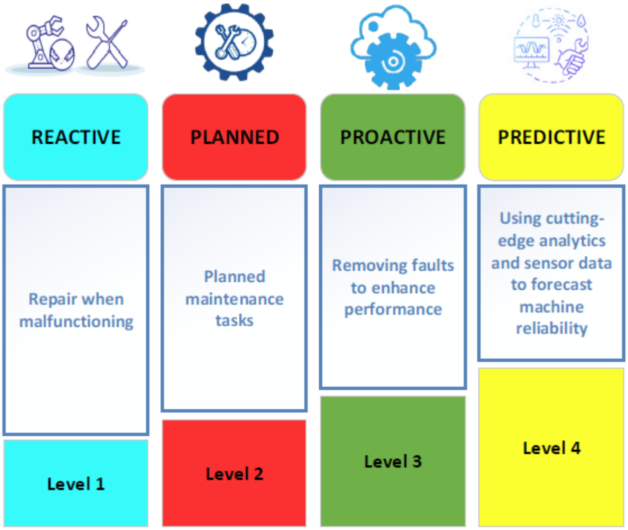


Figure 4. Different Levels of System Maintenance.
Source: Ucar, Karakose, & Kırımça; Artificial Intelligence for Predictive Maintenance Applications: Key Components, Trustworthiness, and Future Trends, 2024.

AI-based learning systems that simulate the condition of industrial processes or their components (e.g., maritime vessels) solely by using available measurement data associated with a specific state (or class) are becoming increasingly prevalent in maintenance engineering (Konieczny & Stojek, 2021). Traditional maintenance strategies (corrective and preventive) have proven ineffective in meeting the safety and efficiency standards demanded by modern industry.

4.1. Key Components of AI-Based Predictive Maintenance

AI-based predictive maintenance (PdM) can be fundamentally broken down into six distinct components: data preprocessing, AI algorithms, decision-making modules, communication and integration, and user interface and reporting, as illustrated in the following figure.

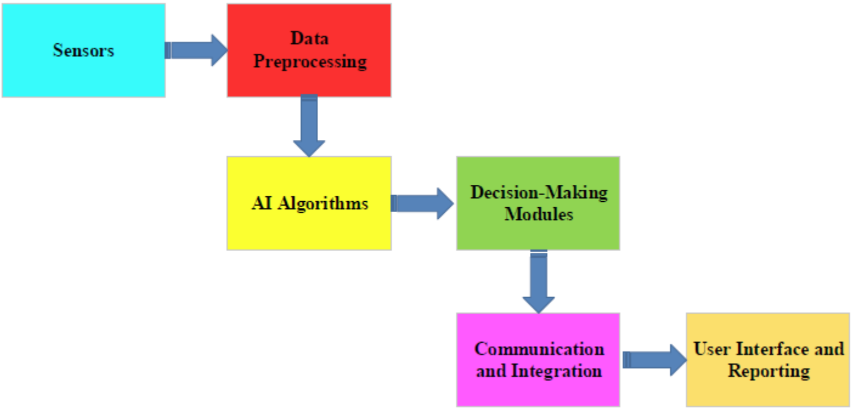


Figure 5. Key Components of an AI-Based PdM System
Source: Ucar, Karakose, & Kırımça; Artificial Intelligence for Predictive Maintenance Applications: Key Components, Trustworthiness, and Future Trends, 2024.

1. **Sensors**: Sensors serve as the primary data collectors in the PdM system. These specialized devices are strategically positioned on equipment and machinery to continuously monitor various parameters such as temperature, pressure, and vibrations. Sensor data provide real-time insights into equipment condition, forming the basis for predictive maintenance analysis.
2. **Data Preprocessing**: Raw sensor data often contain noise and inconsistencies. Data preprocessing is the initial step in preparing this data for analysis, including data cleaning, normalization, and handling missing values. High-quality data are essential for accurate PdM modeling.
3. **AI Algorithms**: AI algorithms, including machine learning and deep learning techniques, form the brain of the PdM system. They analyze data to identify critical features related to potential failures, learning from historical data to predict equipment failures, anomalies, and remaining useful life (RUL).
4. **Decision-Making Modules**: The insights and predictions generated by AI algorithms are processed by decision-making modules, which determine when maintenance actions are needed. These modules recommend preventive or corrective maintenance tasks, schedule maintenance, and trigger alerts to maintenance teams when necessary.
5. **Communication and Integration**: This component ensures that insights generated by the PdM system effectively translate into actionable steps. It involves interaction with various stakeholders, including maintenance staff and management, and integrates with business systems like ERP and asset management software to align predictive maintenance with broader organizational goals.

6. **User Interface and Reporting**: To make insights accessible to maintenance staff and decision-makers, user interfaces and reporting tools are essential. These tools help users understand complex data patterns and make informed decisions by providing data visualizations, dashboards, and reporting capabilities. Data visualization tools and dashboards convey insights and forecast information to maintenance teams and decision-makers, facilitating the understanding of complex data patterns and supporting informed decision-making.

Three additional data-related units have been integrated with advanced AI methods to achieve resilient, reliable, secure, and highly stable results in AI-based PdM within complex and dynamic environments (Simion, Postolache, Fleacă, & Fleacă, 2024):

7. **Sensor Data and Internet of Things (IoT) Integration**: IoT and sensor technology integration is vital in advancing autonomy for PdM tasks. IoT sensors are strategically installed on equipment and machinery to monitor their condition continuously in real time.
8. **Data Integration**: Data integration combines information from various sources, including historical maintenance records, real-time sensor data, external factors (e.g., weather), and production schedules. This holistic view of equipment health enhances decision-making.
9. **Digital Twins**: Digital twins create virtual replicas of physical assets, enabling real-time simulation and monitoring. AI systems oversee these digital twins to identify operational anomalies and recommend optimal maintenance strategies before any adverse impact occurs on physical equipment.
10. **Edge and Cloud Computing**: Edge computing brings data processing closer to the source through IoT sensors, enabling real-time analysis and reducing latency. Cloud computing manages and stores large volumes of data, supporting historical analysis and long-term trend tracking.

4.2. Challenges and Limitations of AI in Predictive Maintenance

Despite the significant potential of artificial intelligence (AI) in predictive maintenance, various challenges and limitations must be overcome to make these systems fully effective. This section examines the key challenges facing AI technology applications, including system transparency, AI model explainability, ethical issues, data protection, and technical and operational challenges (Stanton, Munir, Ikram, & El-Bakry, 2023).

4.2.1. Transparency and Explainability of AI Systems

One of the main challenges in applying AI to predictive maintenance is the issue of transparency and explainability. Many AI models, especially those based on deep learning, operate as “black boxes,” meaning that while they can make highly accurate predictions, it is often difficult to explain how and why they reach certain conclusions (Balasubramaniam , Kauppinen, & Rannisto, 2023).

For many industries, particularly those requiring high safety standards like aviation, energy, or healthcare, the explainability of AI models is essential for building trust in the system. In predictive maintenance, it is important for engineers and managers to understand why an AI system recommends certain actions, such as part replacement or repair. If the system makes decisions without explanation, it becomes challenging to verify its accuracy and ensure that the recommended actions will not lead to additional issues.

To address this challenge, the concept of Explainable AI (XAI) is increasingly utilized, designed to improve the explainability of AI model decisions. XAI enables users to understand the processes behind AI predictions and decisions, providing insights into how models reach their conclusions. Techniques include data visualization, expert feedback, and detailed model explanations. The application of XAI is particularly critical in maintenance contexts, where precise decisions affecting equipment safety and reliability are required (Ali, Abuhmed, El-Sappagh, & Muhammad, 2023).

4.2.2. Ethical Issues and Data Privacy

The use of AI in industry raises several ethical issues, especially concerning data privacy and its impact on jobs. A key challenge faced by AI-based PdM systems is the question of data collection and usage. Since these systems rely on large volumes of data collected through sensors, concerns arise over the privacy and security of these data (SIIA, 2017).

Data collected in industrial settings may contain sensitive information about operational processes, making it susceptible to misuse or unauthorized access. Ensuring the security of this data is critical to maintaining trust in AI-based PdM systems. Techniques such as data encryption, security protocols, and the application of blockchain technology can help protect data and ensure its reliability and integrity (IEEE SA, 2024)

Furthermore, AI systems can have an impact on employment. Automating maintenance processes may reduce the need for human intervention, potentially leading to job losses in specific sectors. While AI-based PdM offers substantial benefits in terms of efficiency and cost reduction, it is essential to strike a balance between technological progress and job preservation. Experts agree that policies promoting workforce reskilling and skill adaptation are needed to enable workers to participate in AI system oversight and management (Ucar, Karakose, & Kırımça, 2024)

4.2.3. Technical Limitations and Operational Challenges

Another challenge in implementing AI-based predictive maintenance lies in the technical limitations and complexity of industrial systems. The quality of AI system predictions heavily depends on the quality of the data collected. Incomplete, imprecise, or irregularly timed data can lead AI models to make inaccurate or untimely decisions.

Collecting high-quality data in many industrial environments can be difficult due to technical sensor limitations or harsh working conditions. For example, environments with high vibration levels, extreme temperatures, or aggressive chemical conditions can result in inaccurate or damaged sensor data, reducing prediction quality (Lu, 2022)

Additionally, different industries have specific maintenance requirements, meaning that AI models must be adapted to the unique conditions of each system. Models that work well in the automotive industry may not be effective in aviation or the maritime sector. The need to adapt and train models for different scenarios and environments poses a significant technical challenge for implementing AI-based PdM systems.

4.2.4. Integration of AI Systems with Existing Systems

A key operational challenge in implementing AI-based predictive maintenance is integrating these systems with existing industrial processes and infrastructure. Many industries already use ERP (Enterprise Resource Planning) systems, CMMS (Computerized Maintenance Management Systems), and other data management systems. To provide maximum value, AI systems must seamlessly integrate with these existing solutions.

Integration can be complex due to varying technologies, legacy systems, or a lack of interoperability across platforms. AI-based PdM systems must be designed to easily connect with other systems, enabling seamless data exchange and maintenance process automation. Without successful integration, the benefits of AI may be limited, and systems may continue to rely on manual processes and interventions (applsci-14-00898-v2).

4.3. Application in the Maritime Transport Industry

The maritime industry faces unique maintenance challenges due to the complexity of ship systems and extreme operational conditions, such as high humidity, salt exposure, and elevated temperatures. Traditional ship maintenance has often been reactive, leading to costly repairs and downtime in the middle of voyages. However, applying AI-based predictive maintenance in maritime transport has enabled significant improvements in ship efficiency and reliability.

A notable example of successful predictive maintenance application in the maritime industry is the maintenance of cooling systems on tankers. By using sensors to collect temperature and water flow data, AI models can analyze these data to identify patterns indicating potential cooling system issues. For instance, a study on a tanker's cooling system revealed that an AI model could predict a cooling pump failure several days in advance, allowing for timely intervention and part replacement before a serious problem occurred. (Simion, Postolache, Fleacă, & Fleacă, 2024)

Furthermore, predictive maintenance enables shipowners to reduce unnecessary maintenance costs. For example, a major European ship operator implemented an AI-based PdM system to optimize maintenance of propulsion systems across a fleet of 50 ships. Thanks to real-time data analysis, the company reduced unplanned downtime by 20% in the first year of system implementation (Simion, Postolache, Fleacă, & Fleacă, 2024)

These systems also enhance ship safety. Automated data analysis allows operators to quickly identify potential risks, such as engine or generator failures, which could lead to serious incidents at sea. Additionally, reducing manual inspections lowers the risk of human error, contributing to overall navigational safety.

5. Conclusion

Ship maintenance is planned through lifecycle management strategies during the design and construction phases, tailored for ships whose purpose may be cargo or passenger transport. Effective planning extends the operational lifespan of a ship by creating a structured maintenance system mandated by the ISM Code (International Safety Management Code). Ship system maintenance can be scheduled based on calendar time, operational hours, condition and performance, post-failure, or renewal. Components and systems that do not lead to significant economic or functional losses may be maintained post-failure or through renewal, whereas cargo handling and safety systems require maintenance based on operating hours and calendar time. The ship is divided into systems to simplify maintenance planning and assign responsibilities to the crew, as different systems require distinct maintenance approaches and schedules. This structured maintenance system facilitates efficient upkeep across various ship systems, with cargo handling as an exception that varies by ship type.

The application of artificial intelligence in predictive maintenance continues to evolve rapidly, offering industries new opportunities to optimize operations, reduce costs, and enhance equipment reliability. Technologies like digital twins, IoT, collaborative robots, and blockchain enable industries to achieve greater flexibility and efficiency in maintenance planning and execution.

Challenges such as transparency, data security, and system integration persist, but advancements in technologies like Explainable AI (XAI) and security measures like blockchain provide solutions to these issues. Emerging trends, including autonomous systems and collaborative robots, promise further improvements in predictive maintenance, allowing for increased automation and enhanced safety.

Given the ongoing technological progress, it is clear that AI-based predictive maintenance will play a crucial role in the future of many industries, bringing significant benefits to operational efficiency and safety.

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