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## CHAPTER 10

# Digital strategies for enhancing the efficiency of cargo ships maintenance

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### Abstract

This section is dedicated to the systematization of digital solutions in the field of ship maintenance, with a focus on enhancing the reliability of ship equipment, reducing costs, and improving operational performance. The analysis of previous studies and publications is used to identify potential challenges and demonstrate how the application of digital strategies can effectively address them. The section explores modern approaches to implementing digital strategies in the context of systematic maintenance of cargo vessels, outlines the main challenges related to the inefficiencies of traditional maintenance practices, and substantiates the necessity of adopting digital strategies to achieve sustainable shipping objectives.

The emphasis is placed on the integration of digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), digital twins, and Big Data to ensure the reliable operation of fleet technical systems. It is justified that the use of digital models not only enhances the safety and efficiency of maintenance processes but also enables significant reductions in fuel consumption through optimized engine load management, early fault detection, and predictive maintenance planning.

A digital strategy development approach is proposed, based on the principles of energy-efficient lifecycle management of ship systems. The potential of virtualized maintenance is analyzed as a means of minimizing resource consumption, human effort, and environmental impact. Examples are provided of digital platforms being implemented to monitor the technical condition of vessels in real time, which allows for increased flexibility in decision-making and reduced downtime. The section also discusses and substantiates optimal parameters for a ship maintenance system based on the use of digital strategies.

### Keywords

Digital strategies, energy efficiency, maintenance, cargo vessels, digital twins, artificial intelligence, condition monitoring, parameter optimization, maritime transport, ship systems.

## 10.1 Introduction

The issue of ensuring energy efficiency in maritime transport is directly linked to the technical condition of cargo vessels and the effectiveness of their maintenance systems. Given the continuous rise in fuel costs and increasing requirements for greenhouse gas emission reductions, traditional scheduled maintenance methods are becoming inadequate. These methods fail to account for the current condition indicators of onboard systems and do not enable effective responses to changes in technical or navigational contexts.

In contrast, digital technologies – particularly digital twin models, sensor-based monitoring systems, and artificial intelligence – enable the implementation of a new maintenance paradigm, where the priorities are predictiveness, adaptability, and energy efficiency. This approach reduces the risk of emergency stoppages, improves resource utilization, and minimizes vessels' idle time. The focus is not only on technical operability but also on minimizing energy losses caused by the misalignment of mechanical components and systems.

Modern merchant vessels play a crucial role in the global transportation system, enabling the movement of large volumes of cargo worldwide. This imposes high demands on the efficiency and reliability of shipboard equipment. Maintenance systems for cargo vessels are essential for ensuring their functional integrity and operational safety. However, several issues persist concerning the current state of ship maintenance systems. Specifically, the reliability and efficiency of technical maintenance are critical for optimizing operational costs and enhancing the overall performance of maritime transport. Well-defined maintenance system parameters can address these challenges and improve cargo vessel operations.

The operation of the cargo fleet under current conditions is characterized by a high degree of technological complexity, increasing energy costs, stricter environmental regulations, and the need to maintain competitiveness in the global shipping market. In this context, effective maintenance of ship systems is particularly relevant, as it helps reduce repair costs, ensures voyage safety, and lowers overall fuel consumption. Outdated maintenance approaches – focused on scheduled or breakdown-based repairs – do not reflect the actual technical condition of equipment and fail to meet required energy efficiency standards.

Within this framework, digital transformation serves as a key tool for modernizing cargo vessel maintenance systems. Digital technologies such as sensor networks, big data, predictive analytics, digital twin models, and artificial intelligence tools provide new opportunities for real-time technical condition monitoring, failure forecasting, and optimal maintenance planning. Especially important is the

implementation of strategies that integrate digitalization with the principles of energy-efficient shipping.

## **10.2 Development of digital strategies for improving the efficiency of maintenance systems for cargo vessels**

In the current context of maritime transport operations, where increasingly stringent requirements are imposed on reducing greenhouse gas emissions and enhancing the energy efficiency of shipping, there is a pressing need to optimize maintenance systems for cargo vessels. Effective management of a ship's technical condition directly affects not only its reliability and safety, but also its energy consumption during operation. This necessitates a comprehensive revision of traditional approaches to service maintenance, incorporating cutting-edge digital technologies that can minimize fuel losses, reduce unplanned downtime, and consequently improve carbon footprint metrics [1].

A wide range of factors – including unplanned breakdowns, idle time due to unexpected repairs, excess fuel consumption resulting from inefficient operation of onboard systems, and the absence of modern condition monitoring infrastructure – contribute not only to financial losses but also to a reduction in the vessel's overall energy efficiency. For instance, improper maintenance planning may result in increased hull resistance, higher auxiliary energy consumption, and decreased efficiency of propulsion systems.

Key challenges that require immediate attention include:

1. Predictability and downtime. The absence of digital early-warning tools leads to operational failures and downtime, which in turn causes elevated fuel consumption, especially in cases of engine restarts or course deviations.
2. Economic and fuel-related costs. Ineffective planning of repairs and maintenance leads to excessive use of resources, including fuel, and underutilization of equipment capacity, ultimately resulting in avoidable fuel expenditures.
3. Technical obsolescence. The use of outdated monitoring and control systems prevents early detection of anomalies in propulsion and power systems, increasing energy losses and reducing the overall operational efficiency of the vessel.
4. Safety and environmental concerns. Equipment failures pose threats not only to crew safety but also increase environmental risks through the release of harmful substances and non-compliance with fuel consumption standards.
5. Lack of systemic coordination. Insufficient integration of information flows between onboard systems and shore-based facilities leads to time and energy losses, as well as poor coordination in resource management, including energy use [2].

In light of these challenges, an effective maintenance system must serve not only as a service tool but also as a means of enhancing a ship's energy efficiency. This is achievable through the implementation of modern digital strategies capable of ensuring reliable vessel performance, minimizing fuel consumption, supporting environmental compliance, and optimizing equipment lifecycle management.

The analysis carried out has demonstrated that a number of key issues in ship maintenance can be addressed through the transformation of maintenance systems with a focus on digital adaptation and energy efficiency:

1. Reduction of delays and stoppages. The use of predictive analytics enables early detection of critical failures, reducing the number of unscheduled stops, optimizing logistics, and minimizing idle time with engines running.

2. Energy-saving maintenance planning. Through the use of digital models, maintenance planning takes into account energy consumption, load periods, and equipment operating modes, thus minimizing fuel expenditure.

3. Optimization of repair costs. By collecting and analyzing operational data, digital systems can accurately determine the optimal timing for replacing components, avoiding both premature and delayed interventions – each of which impacts the vessel's energy performance.

4. Centralized monitoring. Continuous remote monitoring of a ship's energy systems in real time enables rapid response to malfunctions and facilitates the development of a comprehensive database on energy consumption patterns under different operational conditions.

5. Standardized data exchange. The use of unified digital platforms facilitates interaction between onboard subsystems, the engine room, and shore-based technical offices, allowing for synchronized actions and the avoidance of energy waste.

6. Reduced environmental risks. A lower number of technical failures directly contributes to a reduced likelihood of fuel spills, unauthorized emissions, or other breaches of environmental safety regulations.

7. Standardization and transparency. Energy efficiency is no longer treated as a secondary outcome but becomes a core objective of maintenance planning, contributing to improved CII ratings and compliance with MARPOL Annex VI requirements.

Based on the conducted research, a structural-logical scheme for the digital transformation of cargo ship maintenance systems has been proposed, aimed specifically at reducing energy losses. This framework accounts for the full cycle – from data collection to management decisions based on analytics. In particular, the use of digital twins, intelligent diagnostics, and risk visualization allows for energy-balanced management of a vessel's technical condition.

Digital strategies in the context of cargo ship maintenance encompass:

1. Process digitalization, which minimizes human error and improves diagnostic accuracy.
2. Analytical processing of energy system data to identify efficiency trends and changes in performance.
3. Modeling and forecasting, which provide the foundation for making optimal energy decisions.
4. Digital communication with stakeholders, ensuring transparency and coordination between crew, technical teams, and company management.
5. Platform integration, enabling unified control of fuel and technical parameters within a single digital environment.

Thus, the implementation of digital strategies in cargo ship maintenance systems opens up extensive opportunities for cost reduction, enhanced safety, environmental sustainability, and – most importantly – a transition to an energy-efficient paradigm of maritime operations.

In the context of cargo ship maintenance, digital strategies involve the application of digital models, digital shadows, and digital twins (Fig. 10.1), combined with data analytics (Fig. 10.2, 10.3), to enhance maintenance efficiency, forecast service requirements, and define optimal maintenance and repair schedules.

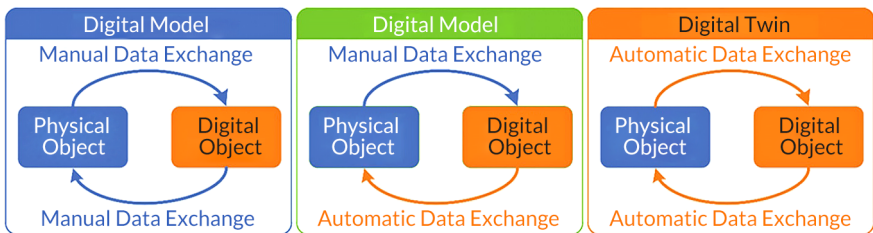


Fig. 10.1 Differences in data topology between digital model, digital shadow, and digital twin

Considering the need to improve the energy efficiency of cargo ship operations, the implementation of advanced digital tools for technical maintenance emerges as a key aspect. One of the most promising directions in this digital transformation is the use of digital representations of ship systems – namely, digital models, digital shadows, and digital twins. These approaches enable real-time monitoring of equipment conditions, reduce the risk of unscheduled shutdowns, help avoid excessive fuel consumption, and optimize the performance of onboard energy systems.

A *digital model* lacks automated data exchange between the physical and digital entities. Data must be manually entered for condition analysis, which limits the system's ability to react promptly to technical deviations that directly affect fuel efficiency – such as malfunctioning main engines or fuel supply systems.

A *digital shadow* offers a one-way data flow from the physical object to the digital environment. This partially supports fuel performance monitoring but does not allow the digital system to influence energy management processes. It follows the "human-in-the-loop" (HITL) principle, where decision-making relies on operator intervention, reducing the level of automation and energy optimization potential.

The most promising solution for improving energy efficiency is the *digital twin*. It provides two-way, real-time automated data exchange, enabling dynamic adjustment of engine parameters, fuel optimization, fault prevention, and condition-based maintenance. Due to the full integration between the physical and digital environments, digital twins significantly contribute to reducing a vessel's carbon footprint [3].

As part of this study, a classification of predictive analytics methods was developed, forming a crucial component of energy-efficient maintenance systems. This classification includes three main categories:

1. Machine learning and intelligent data analysis – these methods identify hidden dependencies between operational parameters and equipment condition. They are especially useful in detecting anomalies in fuel consumption or reductions in power-plant efficiency. Neural networks, clustering techniques, and ensemble models are used to forecast risks of increased fuel usage at early stages [4].
2. Probabilistic models – these incorporate Bayesian logic, probability distributions, and Monte Carlo simulations to account for uncertainty in predicting the lifespan of components that have a direct impact on fuel consumption.
3. Statistical analysis – techniques such as regression, correlation, and variance analysis are used to establish relationships between operational parameters and the frequency of energy-inefficient malfunctions.

The proposed classification offers a structured approach to energy-conscious technical maintenance. It provides the foundation for developing analytical models that not only predict failures but also identify the most fuel- and cost-efficient service strategies, taking into account time, economic costs, and environmental impact.

In conclusion, digital representations – especially digital twins – combined with predictive analytics tools, enable a paradigm shift in managing the technical condition of cargo vessels. This integrated approach ensures long-term energy efficiency, optimized performance, and greater reliability of onboard systems.

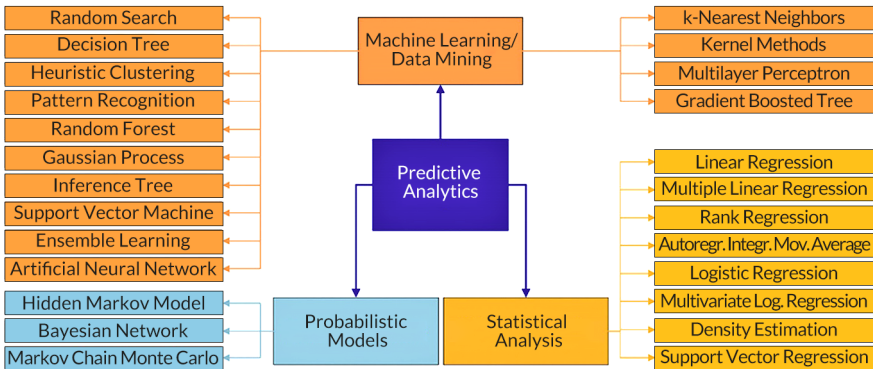


Fig. 10.2 Classification of predictive analytics methods

As part of the study, the role and significance of digital technologies in the maritime transport sector were analyzed in the context of achieving energy efficiency. Particular attention was paid to the use of sensor systems, platforms for monitoring the condition of onboard equipment, and data analytics for predicting equipment failures and optimizing technical maintenance with minimal fuel consumption. These approaches enable timely intervention, reduce the number of emergency stops, prevent energy overconsumption during critical operating modes, and optimize repair logistics with consideration of the vessel's energy parameters [1].

Prescriptive (recommendation-based) analytics plays a particularly important role in energy-efficient management, allowing not only the identification of problems but also the generation of actionable recommendations to improve vessel performance. As part of the study, a classification of prescriptive analytics methods was developed (Fig. 10.3), covering six key approaches relevant to the management of ship maintenance with a focus on minimizing energy consumption:

1. Machine learning and intelligent data analysis. These methods support the development of recommendation systems based on large volumes of historical and sensor data. For instance, classification algorithms can identify parameters indicative of future engine efficiency degradation, while clustering can reveal operational regimes with elevated fuel consumption. Such tools are already being integrated into next-generation marine navigation platforms [2].

2. Evolutionary computation. The use of genetic algorithms and optimization strategies enables modeling maintenance tasks as problems of minimizing energy resource use across the entire lifecycle of ship components. These methods are

effective in complex environments with numerous variables and constraints (e.g., port availability windows, predicted wear levels, or expected loads).

3. Simulation modeling. These techniques create digital environments to test the impact of various maintenance scenarios on overall vessel energy performance. For example, simulating the choice between on-the-go or in-port repair allows the prediction of potential energy losses due to reduced propulsion efficiency or engine overheating.

4. Probabilistic models. This approach accounts for high uncertainty levels typical of maritime operations. By incorporating probabilities of equipment failure and operational delays, more flexible maintenance schedules can be developed, reducing unplanned downtime – a key source of fuel overconsumption.

5. Logic-based models. Systems grounded in rule-based or logical constraints allow the enforcement of energy performance standards during service planning. For example, maintenance actions may be triggered only when energy consumption exceeds specified thresholds.

6. Mathematical programming. Optimization techniques help identify the best maintenance schedules that minimize time and resource losses. These approaches take into account both the energy use of each equipment unit and the impact of repair modes on the vessel's overall energy profile.

Thus, the systematic classification of prescriptive analytics methods enables a structured approach to decision-making in the field of ship maintenance, taking into account energy-related constraints. This not only contributes to reducing operational costs but also aligns with contemporary environmental standards in the maritime industry, which emphasize the rational use of resources and the reduction of harmful emissions resulting from inefficient vessel operation.

The developed classification (**Fig. 10.3**) serves as an important tool for organizing and understanding various approaches to prescriptive analytics. It provides a framework for systematizing available methods and selecting the most appropriate ones for solving specific problems.

The classification presented in **Fig. 10.3** holds significant potential in the domain of technical maintenance for cargo vessels. It assists both researchers and practitioners in identifying and applying effective decision-making techniques that enhance vessel maintenance processes and contribute to improved operational efficiency and energy performance.

At the next stage of the study, key aspects were identified that play a crucial role in the development and implementation of digital strategies for maintenance systems of cargo ships, with a focus on energy efficiency. In particular, sensor accuracy and monitoring tools, the adaptability of fault prediction algorithms to specific operational

conditions, and energy-conscious resource allocation during maintenance planning were emphasized. The application of energy-efficient solutions helps avoid fuel over-consumption due to delayed repairs or improper equipment operation [5].

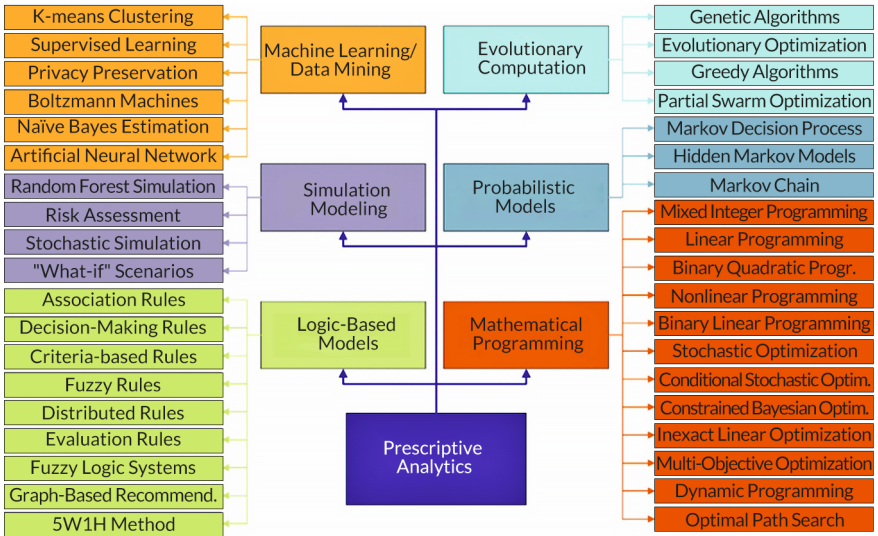


Fig. 10.3 Classification of prescriptive analytics methods

Subsequently, a comparative analysis of two classifications of analytical approaches (Fig. 10.2, 10.3) was conducted. The primary objective was to determine how well each classification aligns with the goals of creating a structural-logical scheme aimed at enhancing the energy efficiency of ship maintenance systems through digital technologies. The results of the analysis demonstrated that the classification of prescriptive (recommendation-based) analytics methods is the most relevant. It provides a structured approach to decision-making based on multifactor analysis, enabling not only prediction but also optimization of energy consumption during vessel operation [6].

The choice of this classification (Fig. 10.3) is driven by the need for strategic management of the vessel's technical condition, focusing on reducing downtime, fuel loss, and excessive load on main propulsion systems. This approach improves decision-making in favor of energy efficiency and the sustainability of vessel operations.

Based on the obtained findings, a structural-logical scheme for the implementation of digital strategies in the maintenance of cargo ships was developed (Fig. 10.4).

It includes the stages of onboard sensor data collection, equipment condition analysis, failure prediction, modeling of maintenance scenarios, and optimal distribution of technical and fuel resources.

The anticipated benefits of implementing this scheme include reduced costs for unplanned repairs, lower fuel consumption due to the maintenance of optimal technical condition, increased energy efficiency of ships, reduced environmental impact, and improved reliability of ship systems. In the long term, such a system can be integrated into platforms such as SPOS, ECDIS, and SmartShip, providing automatic control over equipment energy consumption and technical condition [5, 6].

In the final part of the study, practical aspects of applying this scheme in real operational conditions were explored. The need for algorithm adaptation to various types of ships, as well as further research aimed at reducing prediction errors in equipment condition assessment, is emphasized.

Based on the conducted analysis, the author concludes that the proposed structural-logical scheme can significantly improve the energy efficiency of cargo ship operation, reduce operating costs, and enhance the overall stability of maritime logistics.

The implementation of digital strategies – particularly the concepts of the digital model, digital shadow, and digital twin – combined with prescriptive analytics will contribute to transforming maintenance into an energy-efficient, dynamic system. The main positive outcomes include:

1. Automated monitoring: continuous data streams from sensors allow for timely detection of technical faults that contribute to fuel overconsumption.
2. Detailed digital modeling: enables virtual testing of vessel operating modes and forecasting the consequences of certain technical failures from the perspective of energy use.
3. Maintenance optimization: data analytics helps schedule maintenance during periods of low operational load, reducing unproductive energy consumption.
4. System reliability: timely replacement or repair of components minimizes the risk of efficiency drops in ship engines.
5. Rational resource use: prescriptive analytics optimizes the procurement of spare parts and crew scheduling in accordance with the ship's actual needs.
6. Crew training: the systems can simulate technical fault scenarios and appropriate energy-saving response actions.

Overall, the implementation of digital strategies will enhance predictability, efficiency, and energy savings in the maintenance systems of cargo ships. This approach allows for cost reductions, lower greenhouse gas emissions, and extended service life of ship systems.

### 10.3 Development of optimal parameters for the maintenance system of cargo ships through digital strategies

In today's world, ships play a key role in the global transportation system by enabling the movement of large volumes of cargo across the globe. This imposes high demands on the efficiency and reliability of shipboard equipment. Maintenance systems for cargo ships are critical for ensuring their proper operation and safety.

However, there are certain problems and challenges associated with the current state of ship maintenance systems. In particular, the reliability and efficiency of maintenance are critical issues for cost optimization and improving the performance of maritime transport. Optimizing the parameters of maintenance systems can address these issues and enhance the functioning of cargo vessels.

In this context, the problem of improving the efficiency and optimizing the maintenance systems of cargo ships through the implementation of digital strategies becomes increasingly relevant. The challenge lies in the fact that maintenance of cargo vessels requires significant expenditure and management of various parameters, including reliability, safety, regularity, and cost.

Firstly, the condition of a cargo ship must meet reliability and safety standards, as well as ensure voyage regularity.

Secondly, maintenance costs must be optimized to reduce overall vessel operation expenses.

Therefore, this study aims to examine the parameters of ship maintenance systems and identify optimal values that ensure maximum efficiency and minimized management costs for cargo vessel operations. Addressing this problem requires the development of digital strategies and methods aimed at improving performance and reducing costs during ship maintenance.

The authors of study [7] emphasize the need to reorganize maintenance and logistics services to improve the economic performance of maintenance systems. Article [8] explores approaches to optimizing maintenance parameters with regular control intervals, considering such criteria as minimizing the unit cost of operations and maximizing the technical utilization rate.

Additionally, the reviewed works suggest that modern digital tools and technologies can optimize the parameters of cargo ship maintenance systems. Shorter maintenance periods for selected equipment groups can enhance the vessel's average reliability at sea with minimal cost [9]. The maintenance system integrates information flow using various maintenance strategies [10]. A hybrid multi-criteria decision-making method is suitable for selecting appropriate maintenance actions for each unit of shipboard technical equipment, systems, and complexes [11].

The analyzed articles collectively highlight the importance of reorganizing maintenance services, optimizing service intervals and threshold values, and applying reliability-enhancing methods to improve cargo ship maintenance systems.

The analysis of existing studies has shown that there are several potential issues that can be addressed through the implementation of digital strategies in cargo ship maintenance systems. Key issues include:

1. Insufficient reliability: improved reliability of shipboard equipment and mechanisms can reduce accident rates and enhance safety at sea.
2. Rising costs: improving the maintenance system can help address increasing maintenance costs caused by unplanned repairs and high expenses for spare parts.
3. Performance enhancement: implementing optimized maintenance parameters can reduce downtime for repairs and extend the vessel's operational life, thereby positively impacting productivity.
4. Reduced environmental impact: effective maintenance can help reduce emissions of toxic substances and enhance the ecological sustainability of ships.
5. Increased competitiveness: since shipping companies operate in a competitive environment, optimizing the maintenance system can provide a competitive edge.

Thus, this Chapter proposes approaches for optimizing the parameters of cargo ship maintenance systems using digital strategies, which can address the aforementioned problems and contribute to enhancing the efficiency and reliability of ships in maritime transport.

The issue of improving the efficiency of cargo ship maintenance systems is highly relevant both at the design stage and during the operational lifecycle. **Fig. 10.4** presents a conceptual scheme of system interaction that forms the basis for enhancing the effectiveness of maintenance systems for cargo vessels through the implementation of digital strategies. These strategies define an integrated approach to solving the challenges of managing and improving the performance of maintenance processes.

The selection of a specific digital strategy for managing the cargo ship maintenance system requires decision-making regarding the choice and implementation of appropriate combinations of digital technologies. This process involves adjusting the maintenance plan in accordance with the selected digital strategy. In this context, the modern integrated system "ShipDiMRO" is utilized to support managerial decision-making.

Consideration of various digital maintenance strategies for cargo vessels takes place with respect to the vessel's lifecycle stage. The selection of a particular strategy is based on approaches to achieving optimal maintenance system parameters, which are reflected in the management processes carried out within the ship maintenance system. The variability in decision-making regarding the optimization of maintenance system parameters arises from the absence of a single universal

solution. Choosing the most suitable optimization approach requires analysis from different perspectives and with the use of diverse methodologies, enabling the selection of the optimal course of action under specific conditions.

An analysis of the presented system (as illustrated in Fig. 10.4) makes it evident that within the framework of managing the optimal parameters of a cargo ship maintenance system using digital strategies, two essential and interacting components can be distinguished – informational and managerial (executive).

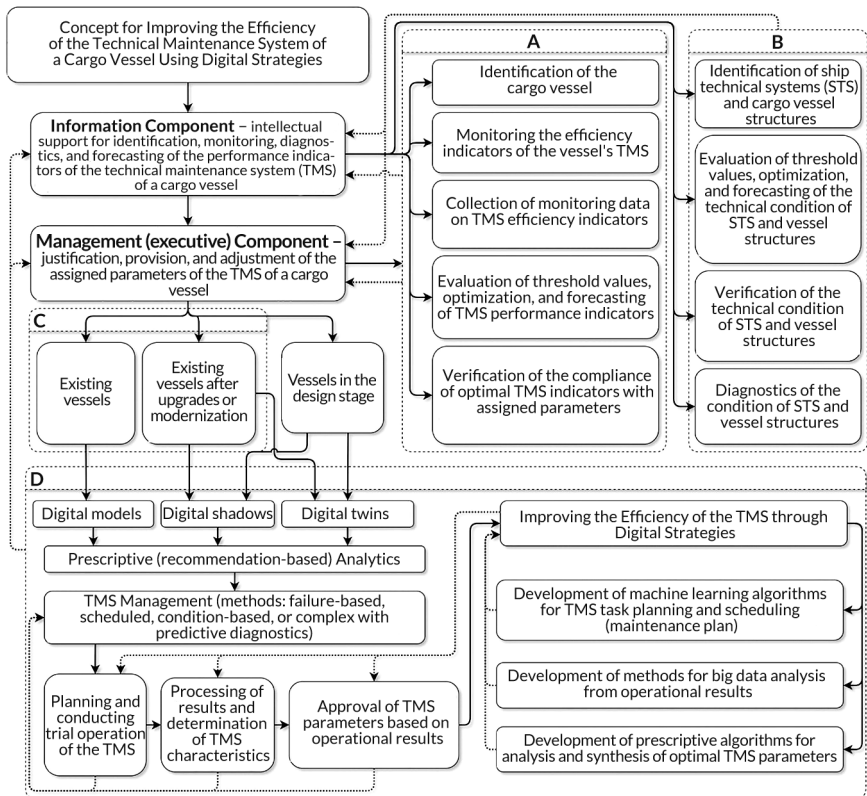


Fig. 10.4 System interaction scheme for improving the efficiency of cargo vessel maintenance systems based on digital strategies

The informational component encompasses remote support for processes of identification, monitoring, diagnostics, and forecasting of both the maintenance system's

performance indicators and the technical condition parameters of ship systems, structures, and cargo vessels within the context of an intelligent transport system (ITS).

On the other hand, the managerial (executive) component involves the creation and implementation of digital processes aimed at ensuring the optimal parameters of the cargo vessel maintenance system during operation.

The characteristics of information interaction that emerge within the processes aimed at ensuring the specified performance indicators of a cargo ship maintenance system are presented in **Fig. 10.4** (segments A and B). The processes of managerial (executive) support for the defined maintenance system parameters (segments C and D) are based on information that reflects the actual technical condition of the ship's systems, structures, and the performance indicators of the maintenance system itself – obtained through identification, monitoring, diagnostics, and forecasting (segments A and B). These processes utilize an automated condition monitoring system (ACMS) in combination with the "ShipDiMRO" system, which operates within the framework of the ITS. These procedures involve data collection during monitoring, evaluation of threshold values, and long-term optimization of technical condition parameters and maintenance system effectiveness.

At the final stage of segment A, the system verifies whether the achieved performance indicators of the ship maintenance system meet the pre-established parameters.

The informational component within segment B, in addition to the aforementioned functionalities, includes a broad range of features. These include the assessment of threshold values, optimization and forecasting of the technical condition parameters of the ship's systems and structures, and the ship as a whole. Furthermore, the system evaluates compliance of the current technical condition with the specified maintenance parameters and manufacturer or owner requirements. Notably, the informational layer also includes diagnostic capabilities based on collected data.

Based on the accumulated information in segment A, management of maintenance parameters begins, both for existing cargo vessels (segment C) and for those under design. In segment D, the development of a digital strategy aimed at increasing the maintenance system's efficiency is initiated, depending on the available digital technologies at a particular stage in the ship's life cycle. These technologies may include digital models, digital shadows, digital twins, and prescriptive analytics. A relevant digital strategy for improving maintenance system efficiency is then formed by combining these technologies and is subsequently implemented within a specific management process [12, 13].

Maintenance system management refers to a targeted activity that includes the analysis, justification, provision, and adjustment of maintenance parameters required to meet reliability indicators for ship systems, structures, and the vessel as a whole. This management is carried out regardless of whether a predictive maintenance

method, failure-based maintenance, scheduled maintenance, or condition-based maintenance is applied.

The maintenance management process consists of three key sequential stages:

1. Planning and executing controlled operation of the maintenance system.
2. Processing results and defining maintenance system characteristics.
3. Approving the system parameters based on the outcomes of the controlled operation.

During the initial stage – planning and implementation – input parameters are received, which define either a baseline or a modified maintenance system for the cargo ship. Upon completing the control operation period, the next stage begins, where collected results are analyzed and a set of maintenance system characteristics is evaluated. Based on this analysis, the output parameters of the ship's maintenance system are formulated.

The effectiveness of parameter evaluation depends on the performance or quality of the applied software, modern mathematical methods, and the algorithms and programs developed accordingly. The third stage involves substantiating the compliance of the obtained maintenance parameters with the required ones. In the event of discrepancies between parameters revealed during the control operation and the necessary values, a decision is made to correct the parameters. These corrections may involve organizational measures within the shipping company or be implemented through structural or production modifications of technical equipment by the manufacturer.

The existence of feedback at each of the three stages of the maintenance management process makes it possible to adjust and manage the parameters of the cargo ship's maintenance system during controlled operation, bringing them to required values or modifying them to ensure the required reliability indicators are met. If the system meets all requirements, it is adopted as the baseline maintenance system for the respective vessel. This initiative then forms the foundation of the final stage in developing a digital strategy aimed specifically at increasing the efficiency of cargo ship maintenance systems.

During the synthesis of the maintenance system based on operational results, it is crucial to evaluate the parameters of the maintenance system and verify their compliance with the requirements and the defined reliability indicators for the ship's technical components and the cargo vessel as a whole. If the established requirements are not met, a decision must be made to either improve the vessel's design, enhance the organizational aspects and technologies of various maintenance types, or adjust the maintenance system parameters followed by an analysis of their optimality.

The goal of the cargo vessel maintenance system, according to the stated objectives, is to ensure the longest possible period of technical operability, while strictly

adhering to safety and service regularity requirements, and achieving this with minimal maintenance costs. In this context, the optimality of the maintenance system parameters can be evaluated by solving one of two problem formulations:

- the first formulation aims to ensure the required probability of remaining in an operable condition while maximizing operational profit;
- the second seeks to achieve a predetermined profit level with the highest possible probability of maintaining operability.

When treated parametrically, the set of solutions for both problems is equivalent, meaning only one problem needs to be solved. However, in the non-parametric variant (with fixed constraints), based on a selected target level of technical operability, it is necessary to find the most economically viable way to ensure this level. This stems from the fact that, under poorly substantiated cost constraints, one may achieve a maximum technical operability indicator that does not meet the actual requirements. Therefore, technical operability, as a more critical metric, should be treated as a constraint, while costs – being a less critical metric – are considered as the objective function. The following sections focus on the first problem formulation.

Improving the efficiency of the maintenance system means increasing the performance and optimizing the processes associated with maintaining and supporting the ship's technical operability. This may include reducing downtime for repairs, lowering the cost of spare parts, and extending the operational lifespan of equipment. All these changes help ensure higher-quality and more cost-effective ship operations.

Performance is a measure of how effectively goals or objectives are achieved. It reflects how well the actual results align with planned or expected outcomes. In the context of ship maintenance, performance may be evaluated based on the number of effective operating hours between maintenance stoppages, repair costs compared to budget, or reduced downtime, among others. An effective maintenance system achieves the highest possible performance with minimal expenditures.

To evaluate the effectiveness of a cargo vessel maintenance system across various stages of its refinement within a shipping company, the performance indicators outlined in Section 1 are used. In addition to the discussed metrics, an integrated indicator of maintenance system performance – the general reliability index (GRI) – may be introduced. This GRI is calculated using existing analytical models based on matrix theory, logical-probabilistic approaches, as well as Bayesian and minimax estimations [14].

To improve the performance of the maintenance system, a continuous process of enhancement of its constituent parameters is essential. One of the strategic directions for increasing efficiency through digital strategies (segment D) is the improvement of control elements across all three stages of the maintenance system management process. This enhancement (segment D) includes the development and implementation

of machine learning algorithms in shipping practices for planning the composition and frequency of maintenance activities at the first stage, big data analysis methods for processing operational results at the second stage, and prescriptive algorithms for analyzing and synthesizing optimal maintenance system parameters at the third stage (Fig. 10.4).

The outcomes of these improvements are transmitted through feedback loops to both the informational and managerial (executive) components of the process responsible for maintaining the specified parameters and performance indicators of the ship maintenance system.

## 10.4 Conclusion

As a result of the study, it was established that digital strategies in the field of cargo ship maintenance are capable of radically transforming traditional approaches to equipment servicing and repair. The implementation of digital twins, intelligent data analytics, and predictive maintenance makes it possible to reduce downtime, avoid emergency situations, minimize operational costs, and decrease fuel consumption. This, in turn, contributes to achieving the strategic goals of the International Maritime Organization regarding the reduction of greenhouse gas emissions and the transition to "green" shipping.

Special attention should be paid to the formation of a unified digital platform for managing the technical condition of a vessel, integrating sensor systems, digital models, and optimization tools. Such an approach enables a systematic assessment of energy consumption and the implementation of scenario-based modelling of future repairs in the context of energy use.

At the same time, the full implementation of digital strategies requires modernization of regulatory and methodological support, personnel training, and the creation of a unified information space among shipowners, port services, and technical inspections. Thus, digital technologies become the foundation of energy-efficient technical management of the cargo fleet, which is of critical importance in the context of the ecological transition and the global digitalization of the maritime industry.

The use of digital strategies in cargo ship maintenance systems is a key factor in achieving optimal efficiency and economic benefits in maritime transport and will lead to a number of positive changes and improvements:

1. The study identified that the optimal parameters of cargo ship maintenance systems can be achieved through digital strategies. It was found that the use of digital tools allows for the reduction of downtime for repairs, spare parts costs, and extends the operational life of equipment.

2. The research demonstrated that digital strategies enable the effective assessment of reliability and safety of vessel operations, reducing the risk of technical failures and accidents.

3. The application of digital approaches in the maintenance of cargo ships allows for the reduction of maintenance costs and ensures the efficient operation of vessels.

4. One of the key contributions of the article is the development of a system interaction scheme aimed at improving the efficiency of cargo ship maintenance systems based on digital strategies. This scheme includes the use of machine learning algorithms for maintenance planning, big data analysis for processing operational results, and the development of prescriptive algorithms for analyzing and synthesizing optimal maintenance system parameters. This approach ensures maximum outcomes with minimal costs.

The further use of the results of this study may include their practical application in shipping companies and port institutions. The implementation of digital strategies in the practical maintenance of cargo vessels can lead to a reduction in technical failures, increased productivity, and cost savings. Furthermore, these findings may serve as a basis for future scientific developments in the field of maintenance system optimization, including the development of new digital tools and methodologies.

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