INTRODUCTION

The modern shipping industry faces unprecedented challenges and opportunities in the pursuit of sustainability, operational efficiency, and regulatory compliance. A central tenet in this transformation is the enhancement of energy efficiency in maritime operations through improvements in navigation methods. This monograph systematically explores scientific, technical, and operational approaches to optimizing navigational decisions to reduce fuel consumption, emissions, and navigational risks. The chapters are structured to progressively develop and integrate concepts from strategic theory to applied system design, encompassing classical navigation, artificial intelligence, meteorological tools, and the emerging prospects of underwater and alternative fuel navigation.

Chapter 1. A strategic approach to energy-efficient methods of navigation, maneuvering and ship control. The foundation of the monograph is laid in Chapter 1, which outlines a strategic framework for improving energy efficiency through navigational methods rather than relying solely on hardware retrofits. It critically assesses current industry practices that prioritize technical upgrades and highlights the underutilized potential of operational strategies such as trajectory control, observation accuracy, and measurement refinement.

The chapter introduces a comprehensive model for evaluating vessel fuel consumption across various operational contexts. Through the application of mathematical modeling – particularly orthogonal decomposition of observation error distribution – it is demonstrated that energy consumption can be significantly reduced by optimizing the precision of navigational data. This method not only enables minimization of route deviation but also establishes a quantitative basis for real-time adjustments. The integration of strategic navigation, voyage planning, and situational control is shown to be a critical dimension in energy management, with benefits that span both economic and ecological outcomes.

Chapter 2. Energy-efficient ship route planning considering meteorological navigation conditions. Chapter 2 expands upon strategic navigation by introducing the role of meteorological conditions in energy-efficient route planning. It provides a detailed analysis of modern meteorological decision support systems such as SPOS, WNI, and BON VOYAGE, demonstrating their effectiveness in aligning navigational decisions with real-time and forecasted environmental data.

A case study on the Strait of Gibraltar illustrates how optimizing vessel trajectory according to hydrodynamic current profiles can yield fuel savings of up to 15%. The chapter emphasizes the necessity of integrating oceanographic

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models, current velocity datasets, and atmospheric reanalysis data into the route optimization process.

By coupling hydrometeorological variability with ship operational profiles, the chapter articulates a decision-making framework that allows captains and operators to select weather-optimized paths, reducing fuel use, time at sea, and greenhouse gas emissions. The result is a compelling argument for making meteorological data central to energy efficiency strategy.

Chapter 3. Consideration and assessment of navigational risks to improve energy-efficient ship management. In Chapter 3, the monograph addresses a crucial intersection between safety and efficiency by introducing navigational risk as a variable in energy management. It critiques conventional energy-saving approaches – particularly slow steaming – for their failure to consider navigational hazards posed by narrow channels, high-traffic zones, or adverse weather conditions.

The chapter presents a multi-criteria decision-making framework that incorporates fuel consumption, collision risk, and hydrometeorological conditions. A classification of navigational risks is developed, spanning technical, human, digital, and environmental categories. Risk assessment methods such as FMEA, HAZID, ETA, and risk matrices are presented as critical tools for integrating energy efficiency with safety management.

Digital navigation platforms, including NAPA, StormGeo, and Wärtsilä Voyage, are reviewed for their ability to enhance route planning through AI-powered risk modeling. The study also examines ISO 31000:2018 as a guiding structure for implementing adaptive maritime risk management. Ultimately, Chapter 3 argues that energy efficiency cannot be decoupled from navigational risk mitigation and calls for harmonized, data-driven systems that ensure both goals are met simultaneously.

Chapter 4. Choosing the best maneuver for vessel separation taking into account the energy efficiency of the trajectory. Chapter 4 transitions from voyage-level planning to tactical decision-making during ship encounters, particularly vessel separation and evasive maneuvering. Traditional maneuvering practices based solely on collision avoidance are contrasted with newer models that incorporate fuel consumption optimization into real-time decisions.

The chapter highlights the integration of radar overlay on ECDIS as a transformative approach that enhances situational awareness while enabling the calculation of energy-optimal maneuvers. It introduces a conceptual model based on the Open Sea Model, which predicts ship trajectories under different separation scenarios and quantifies fuel consumption implications for each alternative.

Special emphasis is placed on the trade-offs between safety and energy use in restricted areas or in low-visibility conditions. Through model-based analysis and system integration with AIS and ARPA, the study proposes a methodology that selects maneuver options minimizing route deviation, time loss, and fuel consumption. This chapter establishes that navigation technology, when coupled with performance modeling, can guide energy-smart tactical decisions even under intense navigational stress.

Chapter 5. Analysis of possible risks, which affect energy efficiency of the ship while maneuvering and mooring. Chapter 5 focuses on the energy-intensive nature of auxiliary operations, particularly maneuvering and mooring. It identifies a variety of risks that impact energy performance during these phases, including mechanical overloads, adverse current or wind conditions, and pilotage errors.

The chapter provides a risk matrix that categorizes energy efficiency hazards into ten thematic groups. It emphasizes the role of digital risk platforms – possibly operated by third-party entities such as insurance firms – to deliver real-time, round-circle assessments covering all stakeholders in a maneuvering operation.

Significant attention is given to new risk categories emerging from modern shipping practices, including AI malfunctions, cybersecurity threats, and autonomous tug behavior. The chapter advocates for real-time risk assessment systems capable of dynamically adjusting to evolving port conditions and external threats. The conclusion is clear: auxiliary navigation must no longer be treated as isolated from energy efficiency planning.

Chapter 6. Modern approaches to maritime navigation: integrating artificial intelligence into ship course-keeping systems. Chapter 6 presents a technological deep dive into how artificial intelligence can transform course-keeping systems to enhance both safety and energy performance. It traces the evolution of autopilot systems from classical PID controllers to neural networks, fuzzy logic systems, adaptive algorithms, and reinforcement learning.

AI-powered autopilots are shown to deliver superior accuracy in maintaining course under variable sea conditions, reducing fuel consumption by 10–15% and improving maneuverability. The study details the capabilities of backstepping control, LSTM prediction, and hybrid ANFIS systems in managing non-linear dynamics inherent in ship movement.

Furthermore, the integration of AI with azimuthal propulsion and energy-saving devices such as Becker Mewis Ducts demonstrates quantifiable improvements in efficiency. The chapter concludes that future energy-efficient maritime navigation systems will rely heavily on adaptive, intelligent automation capable of responding to disturbances in real-time without human intervention.

Chapter 7. Analysis of modern underwater navigation and design capabilities of underwater cargo vessels. Chapter 7 explores an innovative frontier: underwater cargo vessels as a paradigm shift in maritime logistics. In contexts marked by geopolitical instability, piracy, or restricted surface navigation, submerged transport offers an alternative with notable energy efficiency advantages.

The chapter surveys the current state of underwater navigation, including Doppler Velocity Logs, Long Baseline acoustic positioning systems, and Kalman filter-based data fusion. It introduces novel behavioral and hierarchical control system architectures that enable underwater vehicles to operate autonomously in dynamic environments with limited computational resources.

The potential for underwater freight corridors to reduce exposure to weather-related resistance, surface currents, and wave drag is examined, with projections suggesting increased route capacity and fuel savings. The chapter proposes that underwater vessels – once considered speculative – are increasingly viable and should be integrated into future discussions on sustainable and secure shipping solutions.

Chapter 8. Meteorological and hydrographic support of energy-saving maritime transport. Chapter 8 returns to the topic of environmental data support, focusing on the integration of meteorological and hydrographic tools for route optimization. It presents an interdisciplinary approach combining satellite altimetry, ARGO drifters, gravimetric monitoring (GRACE), and real-time buoy data.

A novel concept is introduced: using Earth's gravitational anomalies and geoid shape variations as predictive indicators of monsoon dynamics and sea-level shifts. This approach enhances long-term voyage planning in regions like the Indian Ocean, where monsoonal variability plays a critical role.

Technological and organizational models for data integration are proposed, including dynamic digital routing systems that synthesize hydrographic forecasts with ECDIS overlays and voyage management platforms. The chapter argues that deep integration of geophysical, meteorological, and navigational data streams forms the backbone of truly adaptive, energy-conscious shipping.

Chapter 9. Development of a system for assessing navigational and energy safety on inland waterways. Chapter 9 shifts focus to inland navigation, examining Ukraine's river systems as a testbed for integrated navigational and energy safety systems. It presents a system architecture combining sensor networks, River Information Services, and AI-based risk analysis tools.

The chapter highlights the infrastructural and ecological constraints specific to inland waterways – such as shallow waters, outdated fairway equipment, and fluctuating hydrological conditions – and proposes an energy-oriented safety assessment system that addresses these challenges. Key components include hydrometeorological sensors, AIS-based traffic visualization, and machine-learning-based forecasting modules.

The proposed system supports real-time decision-making, reduces fuel consumption, and minimizes environmental impact, aligning with broader goals of green transport and sustainable development. This chapter serves as a regional application of the monograph's wider theoretical and technological framework.

Chapter 10. Digital strategies for enhancing the efficiency of cargo ships maintenance. 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.

The monograph establishes that the path to energy-efficient maritime transport is not confined to fuel substitution or hardware retrofits. Instead, it lies in a comprehensive transformation of navigational thinking – one that synthesizes strategic planning, AI-powered decision-making, environmental integration, risk management, and frontier technologies such as underwater freight.

By sequentially examining each aspect of ship operation – from open-sea voyage planning to inland waterway optimization – this work presents a unified scientific and practical framework. The result is a blueprint for next-generation maritime operations that meet the dual demands of economic competitiveness and environmental stewardship.