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The Practice and Challenges of Digital Technology in Ship Energy Efficiency Management

Zhihan Qiu

Edinburgh College of Art, The University of Edinburgh, Edinburgh, EH3 9DF, United Kingdom

Abstract

The global shipping industry, as a core vehicle for international trade, is also a key area of carbon emissions. In recent years, the International Maritime Organization (IMO) has successively introduced policies such as amendments to Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) and the Carbon Intensity Index (CII), explicitly requiring ships to reduce fuel consumption and greenhouse gas emissions. Ship energy efficiency management has become a core issue for sustainable operations for shipping companies. Traditional energy efficiency management relies on manual record-keeping and empirical judgment, suffering from data lag, a single analysis dimension, and insufficiently targeted optimization solutions, making it difficult to meet the needs of refined emissions reduction. Digital technology, with its advantages of real-time data collection, multi-dimensional analysis, and dynamic optimization, offers new solutions for ship energy efficiency management. This paper examines the application of digital technology in ship energy efficiency management. First, it identifies the core requirements of ship energy efficiency management and the compatibility of digital technology. Then, it analyzes the practical path and existing challenges of digital technology from four perspectives: data collection and processing, energy efficiency optimization strategies, technical bottlenecks, and industry implementation challenges. Finally, it offers targeted recommendations based on the current state of the industry. Research has found that technologies such as the Internet of Things, big data, and artificial intelligence have achieved initial application in ship fuel consumption monitoring, route optimization, and power system control. However, challenges remain, such as poor data interoperability, high investment costs for small and medium-sized shipbuilders, and insufficient digital skills for crew members. This study can provide practical references for shipbuilders in advancing the digital transformation of energy efficiency management and offer insights into how the industry can address digital implementation challenges.

Keywords

Ship Energy Efficiency Management; Digital Technology; Internet of Things; Big Data Analysis; Ship Operations Optimization; Carbon Emission Reduction; Data Interoperability.

1. Introduction

The shipping industry handles over 80% of global freight transport and contributes approximately 3% of global anthropogenic carbon emissions. With the advancement of the "dual carbon" initiative, the pressure to reduce emissions is increasing. The IMO released the CII requirements in 2023. Starting in 2026, ships over 5,000 gross tonnage will be classified into carbon intensity levels A-E. Ships in Level D will require improvement plans, while those in Level E will be restricted from operation. This will force shipbuilders to shift from passive compliance to proactive energy efficiency optimization. The core of ship energy efficiency management is to reduce fuel consumption and emissions while ensuring safety and efficiency.

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The operational phase is significantly impacted by the navigation environment, operating habits, and equipment status, making it the most challenging to manage. Previously, crew members manually recorded fuel consumption and engine parameters, which were then collated and analyzed ashore after docking. This process was time-consuming, made it difficult to detect abnormal data in a timely manner, and delayed optimization solutions. For example, a bulk carrier experienced a minor leak in its engine fuel injection system while crossing the ocean, resulting in an 8% increase in fuel consumption for three days. This was only discovered after docking and a review, resulting in wasted fuel and increased carbon emissions.

Digital technologies can address this problem: the Internet of Things collects real-time data on equipment parameters and navigation environments; big data identifies energy efficiency patterns; AI generates dynamic optimization solutions; and digital twins create virtual models to simulate energy efficiency. These technologies transform ship energy efficiency management from "post-hoc statistics" to a closed-loop system of "real-time monitoring - dynamic analysis - proactive optimization."

However, digitalization is challenging to implement: compatibility issues arise with equipment installed on older ships; unstable offshore satellite signals lead to data interruptions; small and medium-sized shipowners cannot afford the costs of system development and maintenance; and there is a lack of unified industry data standards, resulting in inconsistent data formats that hinder cross-company sharing. This article focuses on the "Practices and Challenges of Digital Technology in Ship Energy Efficiency Management," analyzing its adaptability, identifying potential solutions, identifying bottlenecks, and offering recommendations. These recommendations can serve as a reference for shipbuilders and help facilitate the low-carbon transition of shipping.

2. Analysis of the Core Requirements of Ship Energy Efficiency Management and the Compatibility of Digital Technologies

The core requirements of ship energy efficiency management focus on policy compliance, cost control, environmental responsibility, and emergency response. Different digital technologies can specifically address these issues.

Regarding policy, the IMO's CII and EEDI require shipbuilders to accurately record and report fuel consumption and carbon emissions, and to demonstrate that energy efficiency is being optimized. Traditional manual recordkeeping is prone to omissions and alterations, and does not cover data from the entire voyage cycle. The Internet of Things can solve this problem: high-precision sensors installed in fuel pipes, carbon emission monitors in chimneys, and voyage recorders in the bridge can collect fuel consumption, carbon emissions, and speed data in seconds and transmit them directly to shore-based platforms, making them tamper-proof. One container shipbuilder installed IoT devices on 20 ships and saw the compliance rate for energy efficiency data reporting increase from 78% to 99%, fully complying with IMO requirements. Cost control is a top priority for shipbuilders, with fuel accounting for 50%-70% of operating costs. Previously, crews adjusted engine loads based on experience, resulting in inconsistent results[1]. Big data combined with AI offers a different approach: By collecting historical voyage data, the relationship between fuel consumption, speed, and sea conditions is analyzed. Then, based on current sea conditions and load, optimal engine speed and route recommendations are provided in real time. One bulk carrier has implemented this technology, achieving a 6%-8% reduction in fuel consumption on trans-Pacific routes without reducing speed, saving a single vessel 1.2 million RMB in fuel costs annually.

Environmental responsibility requires shipbuilders to proactively reduce carbon emissions, and digital twins can help. They can create virtual models of ships and simulate energy efficiency throughout their lifecycle: during design, different hull and powertrain

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configurations can be tested to select the most energy-efficient. During operation, real-time data can be used to simulate the impact of operations on carbon emissions. During maintenance, equipment wear can be predicted to prevent increased fuel consumption. One design company used this technology to optimize a bulk carrier's hull, reducing sailing resistance by 5% and carbon emissions by 4.8%.

When equipment failure causes a sudden increase in fuel consumption, emergency response can be swift. Edge computing can process data in real time onboard. If a sudden 20% increase in fuel consumption is detected, an alarm is immediately issued and the fault location is determined, allowing crew members to address the issue promptly. Previously, shore-based analysis took 10-30 minutes, but now it only takes 1-2 minutes, saving fuel waste.

In general, these four requirements correspond perfectly to the Internet of Things, Big Data + AI, digital twins, and edge computing. However, in actual implementation, considerations must be given to offshore environments and compatibility with older vessels to ensure the technology is not inconvenient to use[2].

3. Practical Application of Digital Technology in the Collection and Processing of Ship Energy Efficiency Data

Ship energy efficiency data is the foundation of management. The timeliness and comprehensiveness of its collection, as well as the accuracy and efficiency of its processing, directly impact management effectiveness. Many shipbuilders are using digital technology to advance "full-dimensional collection," "real-time transmission," and "precise processing," while also ensuring data security.

Data collection relies on the "all-encompassing" coverage of the Internet of Things. Previously, only core data such as fuel consumption and engine speed were collected, with collection points concentrated in the engine room and limited in scope. Shipbuilders are now installing a variety of sensors in key areas: fuel systems increase density and temperature to prevent waste, power equipment with vibration and temperature sensors to monitor status, wind speed and current sensors, and GPS, even recording rudder angle and throttle data from the bridge. One container shipbuilder has installed over 230 sensors on 15 large ships, capable of collecting 56 data items once per second-compared to the previous rate of once per hour, with four times more dimensions and 3,600 times the frequency[3].

Transmitting data over long seas often suffers from high latency and high costs. A solution is currently being implemented using "edge computing + satellite + 5G": Transmitting critical data over long seas prioritizes critical data, temporarily storing common data, and backhauling it in batches from shore using 5G. Satellites use a combination of high-throughput and traditional maritime satellites to distribute data and reduce bandwidth. After using this technology for transatlantic operations, a bulk carrier has reduced latency for critical data from 15-20 minutes to 5-8 minutes, and reduced the return time for common data near shore from 6 hours to 2 hours, reducing transmission costs by 30%. Data processing, powered by big data and intelligent algorithms, involves three steps: First, data cleaning, identifying anomalies and filling in gaps, raising accuracy from 82% to 98%; second, data integration, creating a central platform, and converting data into a unified format, storing it by "vessel-voyage-time"; third, identifying correlations, such as determining the optimal engine speed based on the fact that fuel consumption is lowest at a speed of 18 knots and wind speeds <5 m/s. One oil tanker company used this step to identify 12 key factors affecting energy efficiency, providing guidance for optimization.

Data security is also ensured: transmission is encrypted to prevent interception, storage is encrypted to prevent tampering, and permissions are set: crew members only view real-time

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data for their own ship, while management view historical data for all ships. An international shipping group implemented this approach with no security issues.

In short, digitalization has transformed data processing from "single, lagging, and manual" to "comprehensive, real-time, and intelligent." However, issues such as sensor incompatibility on older ships and sensor failure during typhoons require further improvement and adaptation.

4. Practical Application of Ship Energy Efficiency Optimization Strategies based on Digital Technology

With reliable energy efficiency data, digital technology can help shipping companies reduce fuel consumption in four areas: routes, propulsion systems, port operations, and equipment maintenance. It has been applied to multiple ship types, and the results are supported by data.

Previously, route optimization relied on fixed routes or empirical experience, ignoring real-time wind and ocean currents, which resulted in increased fuel consumption. Now, 3-5 years of data are used to model optimal routes, such as sailing around low-pressure areas in the North Pacific during winter. Departure routes are selected based on forecasts, and adjustments are made during voyage based on weather conditions. One container shipping company, operating the Shanghai-Hamburg route, makes 3-5 adjustments per trip, reducing fuel consumption by 7%-9%, saving 80 tons of fuel per 12,000 TEU vessel.

The propulsion system is the most fuel-intensive. Main engine parameters are now monitored in real time, optimized according to demand to prevent over-exertion and provide early warning of failures. Auxiliary engines are adjusted based on power consumption, with one engine shut down if power consumption falls below 50%. After using this system on eight 76,000-ton bulk carriers, main engine fuel consumption decreased by 5%-6%, and auxiliary engine fuel consumption by 15%-18%, saving 150 tons of fuel per vessel annually.

During port operations, ships often idle their main engines for 8-12 hours while docking for loading and unloading, which is a significant fuel drain. We now simulate processes in advance to reduce waiting times, coordinate equipment preparation in real time after docking, and connect shore power to shut down the main engines during loading and unloading. After collaborating with a port company, idling time at dock has been reduced to 6 hours, saving 15 tons of fuel per trip.

Equipment maintenance used to be problematic: delayed repairs were costly, and frequent repairs resulted in missed sailings. Now, we collect real-time equipment data to create a "health profile," which, combined with manuals, predicts lifespan. For example, if an main engine bearing has 300 hours remaining, it's time to replace it. After using this system for a tanker company, maintenance accuracy increased by 35%, over-maintenance decreased by 40%, and annual maintenance costs saved per vessel by 200,000 yuan.

In summary, digital optimization in four scenarios, through dynamic adjustment, real-time coordination, and precise maintenance, helps shipowners save fuel and reduce carbon emissions. Promotion needs to consider differences in ship types and avoid a rigid, one-size-fits-all approach[4].

5. Key Technical Bottlenecks in the Digital Practice of Ship Energy Efficiency Management

Digital technology is widely used in ship energy efficiency management, but its implementation still faces four technical hurdles. These issues are related to the unique high-salt fog environment of offshore vessels, inherent technical limitations, and poor interoperability between different technologies, directly impacting effectiveness and promotion.

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The most prominent problem is data connectivity, which can be categorized into three levels: Data connectivity between devices is poor. The main engine, auxiliary engines, and sensors onboard each use their own formats, making them impossible to analyze together. Manual format conversion is required, which is time-consuming and prone to errors. Data connectivity between ship and shore is poor. Insufficient bandwidth for offshore satellites prevents non-critical data from being transmitted back to shore. Furthermore, data stored onshore and onboard differ in formats, leading to data loss during synchronization[5]. Data connectivity is poor between ship companies, and there is no unified industry standard. For example, some calculate "fuel consumption per nautical mile" as total fuel consumption, while others only calculate main engine fuel consumption. This makes data comparison and experience sharing impossible, resulting in "data silos."

Offshore operations rely on edge computing onboard ships for data processing, but this equipment is inadequate. First, performance is insufficient. The small space and limited power supply onboard make high-performance chips unsuitable. Even simple fuel consumption anomaly detection is slow, let alone real-time route optimization. Second, it's not durable. Ordinary equipment can't withstand the high salt spray, high vibration, and fluctuating temperatures at sea. Edge equipment in the main engine room breaks down every three to four months on average, resulting in a high failure rate. Once broken, real-time data processing becomes impossible.

Data security is also a concern. During data transmission, satellite signals are easily intercepted, and commonly used encryption methods are ineffective in the high-latency environments of open seas. When storing data, shipboard hard drives and SD cards are prone to damage and loss due to vibration and salt spray, and some crew members can even arbitrarily delete or modify data. Shore-based data platforms are also vulnerable to hacker attacks. Small and medium-sized shipbuilders lack professional security teams. Approximately a quarter of shipbuilders in the industry have experienced data security issues, 80% of which are small and medium-sized.

Digital twin technology also has shortcomings. First, the model is inaccurate. With too many components on board, it's difficult to accurately simulate propeller hydrodynamics and the combustion process of the main engine. Simplifications are necessary, resulting in significant errors and a lack of targeted optimization solutions. Second, synchronization is slow. The model must receive real-time, second-level sensor data, which onshore servers cannot process. Latency often exceeds expectations, making it impossible to simulate energy efficiency changes after parameter adjustments in real time, and only allows for general trends.

These four obstacles-data connectivity, weak edge computing, security risks, and inaccurate and slow digital twins-have prevented digitalization from achieving its full potential. These challenges require technological innovation and concerted industry efforts.

6. Industry Implementation Challenges and Lack of Collaborative Mechanisms for Digital Ship Energy Efficiency Management

In addition to technical challenges, digitalization also faces non-technical industry-level hurdles in the implementation of ship energy efficiency management, focusing on cost, talent, standards, and collaboration. These challenges are particularly pronounced for small and medium-sized SMEs, directly hindering technology adoption[6].

The primary concern for small and medium-sized SMEs is the high investment required for digitalization. Digitalization requires hardware, software, and operations and maintenance costs. Installing over 200 sensors, edge devices, and satellite equipment on a single ship costs hundreds of thousands of yuan; the hardware alone for ten ships can reach tens of millions of yuan. Software must be customized or require an annual service fee. Data and electronics

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engineers also need to be hired, costing hundreds of thousands of yuan annually. However, small and medium-sized shipbuilders only generate annual net profits of several million to over ten million yuan, with digitalization investments accounting for more than half of that profit and requiring three to five years to recoup the investment. Large shipbuilders, on the other hand, can enjoy discounts on bulk purchases, with a two- to three-year payback period after cost amortization. This creates a situation where "large ships lead the way, while smaller ships wait and see."

Seafarers' inability to keep up with digital skills is also problematic. Operating systems require both shipbuilding and technical expertise, but experienced crew members lack operational skills, leading to data deletion errors and missed alarms. Younger crew members can operate the equipment but lack sailing experience, making them unable to understand the underlying faults in the data. Some shipbuilders' post-training assessments show a pass rate of just over 60%, with only 40% passing the data interpretation test. Furthermore, training often consists of intensive three- to five-day courses that are ill-suited to real-world sailing scenarios, resulting in learning that is often unapplied. Many ships, however, "install the system but don't use it, relying solely on experience."

The lack of unified industry standards adds to the complexity. When calculating carbon emissions, some use "fuel consumption multiplied by a coefficient" while others rely on real-time monitoring, resulting in results that differ by several percentage points and are impossible to compare. Equipment incompatibility means that switching brands requires a complete overhaul of the data collection system, incurring additional costs. Data review and optimization plan development are also haphazard, leaving some shipbuilders unaware of errors caused by using unreviewed data. This transformation is like "navigating without a map," creating high risks and high costs.

Lack of coordination among stakeholders also delays matters. Shipowners lack knowledge of port berth availability, leading to wasted fuel waiting after arriving at port. Maritime authorities fail to issue timely no-sail notices, forcing shipowners to take detours and waste fuel. Equipment manufacturers fail to disclose optimal engine parameters, making precise optimization difficult. Offshore weather forecasts are inaccurate and slow to update, making real-time route adjustments impossible. Sometimes, a shipbuilder saves 5% on fuel by choosing a route, but an extra two hours of waiting at port can cost them another 3%, effectively wasting their efforts[7].

To address these issues, the government, industry associations, shipbuilders, and equipment manufacturers must collaborate: provide subsidies to small and medium-sized shipbuilders, provide practical training, establish unified standards, and build an information sharing platform.

7. Conclusion

This paper examines the practical applications and challenges of digital technology in ship energy efficiency management, analyzing its compatibility, practical applications, bottlenecks, and industry challenges. It outlines a comprehensive approach to digitalization in support of energy efficiency management, providing a reference for industry transformation. The results show that digitalization has been implemented in multiple scenarios, but its effectiveness is limited by technical and industry challenges, requiring technological innovation and industry collaboration for breakthroughs.

In practice, digitalization and energy efficiency management requirements are perfectly aligned: the Internet of Things addresses the challenge of full-dimensional data collection, big data and AI enable precise analysis and dynamic optimization, edge computing ensures real-time processing of offshore data, and digital twins simulate the entire equipment lifecycle.These technologies have demonstrated effectiveness in data processing, route optimization, power generation, port operations, and equipment optimization. For example, a container ship reduced fuel consumption by 7%-9% through route optimization, and a bulk carrier saw its main engine fuel consumption drop by 5%-6% after power optimization. Both are supported by actual operational data. Transformation should follow the principle of "first data collection, then optimization, and finally, full-chain coordination," providing clear direction for shipbuilders.

Currently, shipbuilders face two challenges: technical data disparity, insufficient edge computing capabilities, data insecurity, and inaccurate and slow digital twin development. Furthermore, the industry faces high investment costs for small and medium-sized shipbuilders, lack of operational expertise by crew members, a lack of standardized standards, and a lack of cooperation from various stakeholders.

Suggestions: Industry associations should take the lead in defining data and technical standards, developing cost-effective edge devices and accurate digital twins. The government should provide subsidies and low-interest loans to small and medium-sized shipbuilders. Shipbuilders should collaborate with vocational schools to cultivate individuals who are both skilled in sailing and technically savvy. Maritime authorities should establish collaborative platforms to integrate data from various sources. Two areas of future research are possible: low-cost retrofitting of older vessels, and how digitalization can be adapted to new energy vessels powered by LNG, ammonia, and other fuels.

In general, digitalization is a promising approach to ship energy efficiency management and a key to carbon reduction in the shipping industry. While there are challenges currently, technological advancements and a robust industry ecosystem will undoubtedly drive the shipping industry towards greener and more efficient development.

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