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The impact of digital technologies on the efficiency and sustainability of maritime transport

Nicoleta Acomi¹, Oleksandr Barban^{1*}

¹PhD. Eng, “Constanta Maritime University”, Navigation and Naval Transport Faculty, Navigation Department, nicoleta.acomi@cmu-edu.eu

¹Eng. “Constanta Maritime University”, Navigation and Naval Transport Faculty, Research Department, barbanoleksandr@gmail.com

***Corresponding author: barbanoleksandr@gmail.com**

Abstract. The maritime transport industry is undergoing continuous transformation driven by the advancement of digital technologies, which enhance operational efficiency and promote environmental sustainability. Traditional shipping often relies on manual processes that lead to inefficiencies and increased costs. This study examines the impact of digital solutions such as automation, artificial intelligence (AI), the Internet of Things (IoT), and blockchain in maritime operations. These technologies can optimize route planning, fuel consumption, and real-time decision-making, resulting in improved efficiency and reduced emissions. Moreover, smart sensors and predictive analytics contribute to regulatory compliance and support green shipping initiatives. This research employs a mixed methodology including a systematic literature review guided by the PRISMA framework and a thematic qualitative analysis of case studies and industry reports, to assess the impact and challenges of digital technologies on maritime transport. Key findings show a high potential of digitalization to mitigate greenhouse gas emissions and to improve safety. However, challenges such as high implementation costs, cybersecurity risks, and regulatory constraints remain barriers to the adoption and integration of digital tools. This paper concludes that digitalization brings several opportunities for maritime transport, and at the same time, an integrated approach is necessary to overcome challenges and maximize long-term benefits.

Keywords: sustainability; maritime transport; digital technologies; efficiency.

1. Introduction

Like many other service industries, the maritime sector faces challenges from global competition and growing efficiency demands. The strategic elements of its service excellence include human safety and environmentally safe operations, as well as management and operations efficiency, which are identified by service efficiency outcomes and made possible by technological applications for process efficiency (Gavalas et al, 2022).

Undoubtedly digital technologies can generate positive impacts on efficiency at the firm and industry level. However, there is no assurance that adopting digital technology would result in increased efficiency. The ability of businesses to adopt matching investments and modernizations to improve business operations and systematize a number of everyday routine tasks is one of the organizational capital and management abilities that determine them. Moreover, efficiency benefits can take time to materialize (Gal et al, 2019).

Digitization in the shipping industry can take different forms to improve operation and business in general. Among the activities that have been already digitized package tracking, document management, network design, pricing, and empty container repositioning. Of course, digitization has two sides, an

internal one within the shipping company itself and the other side that deals with customers. To succeed in adopting digitization, any company should have a clear vision about digitization, integrating new technologies, IT capabilities and mindsets into their traditional business (Mohsen, 2022).

Digitalization in the maritime sector should be viewed as an integral component of broader global initiatives aimed at enhancing supply chain resilience (Pavlinović et al, 2023). The process of digitalization in the seaports and maritime industry can lead to increased safety, a stronger economy, and greener maritime transportation.

The maritime sector holds great potential, as well as several obstacles. These include high operating costs, inefficient fuel, and strict environmental restrictions. Traditional ship management uses old and manual procedures, which cause delays and higher emissions. To address these challenges, it is necessary to shift towards digitalization. The adoption of technologies such as automation, artificial intelligence (AI), the Internet of Things (IoT), and blockchain can optimize operations and enhance sustainability.

This research aims at investigating how digital technologies impact the efficiency and sustainability of maritime transport. The study examines various technological advancements and their applications, to highlight how digitalization improves operational performance, reduces downtime, and promotes sustainable practices. In addition, this research investigates the barriers and challenges to digital adoption and identifies future trends that may influence the maritime sector's shift to more intelligent, environmentally friendly operations.

The article continues with research methodology that presents the analytical methods employed within this study. This is followed by a literature review that synthesizes key findings from previous research conducted by other authors on the same topic of impact of digital technologies in maritime transport. The subsequent section summarizes the results of the qualitative analysis and the specific impacts of various technologies. The results and discussion section then explores the main barriers to digital adoption and emerging trends in industry. Finally, the article concludes with a summary of the main findings and recommendations for future research.

2. Research methodology

This study employs a mixed research methodology to explore the impact of digital technologies on the efficiency and sustainability of maritime transport. The methodology is grounded in a systematic literature review, guided by the PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses framework (Haddaway et al, 2022). Relevant academic and industry sources were identified through searches in databases, with a specific focus on the application of digital solutions in maritime logistics, operational optimization, environmental performance, and risk management.

In addition to the literature review, a thematic qualitative analysis was conducted to assess the practical implementation and perceived impact of key digital technologies. This involved examining case studies, white papers, and policy documents from maritime authorities, shipping companies, and technology providers. The data was analyzed using thematic coding to identify patterns related to technological benefits, implementation challenges, and sustainability outcomes. This qualitative approach enables an in-depth understanding of how automation, AI, machine learning, IoT, blockchain, and big data analytics are transforming maritime operations.

3. Literature review

The literature review was conducted following a systematic approach based on the PRISMA methodology. The search strategy utilized keywords such as “Sustainability”, “Maritime Transport”, “Artificial Intelligence” and “Machine Learning”. Inclusion criteria comprised peer-reviewed articles published between 2019 and 2025 that directly address the application of artificial intelligence in maritime safety, risk management, and operational efficiency. The Web of Science (WoS) extensive database was used as the primary source of data. Other academic databases were searched, including Google Scholar and ResearchGate, for retrieval of articles. In addition to academic publications, relevant

industry reports and white papers were included where they provided substantial insights into the practical implementation of AI technologies within the maritime sector.

Table 1. Systematic refinement of the publications.

Parameter	Content	Count
Keyword search	WOS = ("Sustainability" OR "Green") AND ("Maritime Transport" OR "Shipping") AND ("Artificial Intelligence" OR "Machine Learning" OR "Internet of Things" OR "Blockchain" OR "Big Data")	285
Time frame selection	Publication between 2019 – 2025 were selected	271
Document type selection	"Article", "Proceeding papers", "Review Article", "Early Access"	269
Open Access	Only the open access documents were included	195
Abstract screening	To ensure the relevance of the topic, authors conducted abstract screening	183

The filtering process, Figure 1, adhered to a systematic approach, narrowing the dataset to open access and relevant studies.

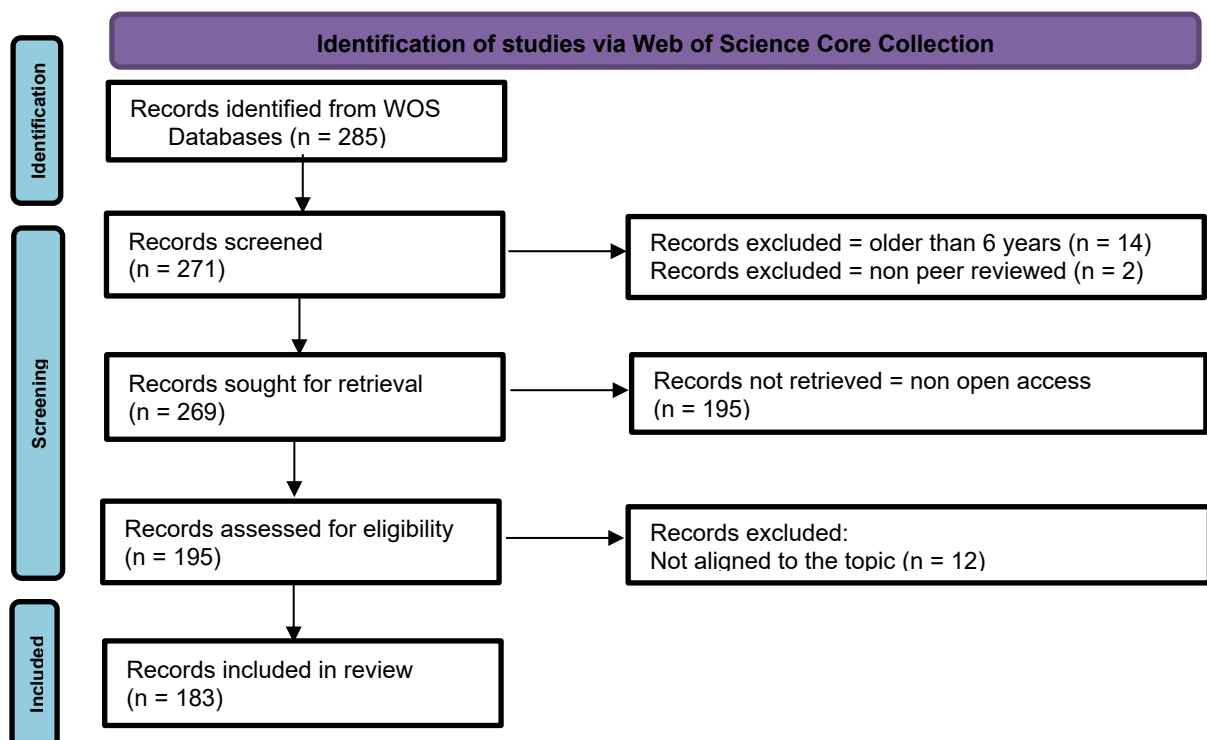


Figure 1. PRISMA filtering process

The application of artificial intelligence (AI), machine learning (ML), the internet of things (IoT), blockchain, and big data analytics (BDA) in maritime transport, logistics and operations is examined in this part of literature study.

Research area 1 - Artificial intelligence. AI has emerged as a transformative tool in reducing emissions and improving efficiency within the maritime sector. Unlike traditional, manual methods, AI analyzes real-time data - like weather, currents, and engine performance - to identify efficient routes and settings. Integrated with ship systems, AI enables coordinated fuel management, combining route planning with automated engine controls for optimal performance. Real-world case studies have shown that this integration can significantly reduce fuel consumption and CO₂ emissions, enhancing both environmental sustainability and cost efficiency (Durlík et al, 2024). However, adoption faces obstacles, especially due to outdated legacy systems. Upgrading to AI-compatible infrastructure is costly and complex, making it challenging for smaller companies to implement. High implementation costs are another critical challenge. The initial investment required for AI infrastructure, including hardware, software, and skilled personnel, can be prohibitively high for many companies (Vu et al., 2024). This includes costs for sensors, data storage, computing power, and ongoing maintenance. The financial burden of these investments can be a significant deterrent, especially for small- to mid-sized enterprises that may not have the capital to support such expenditures (Durlík et al, 2024).

Research area 2 - Machine Learning. ML a key subset of AI, enables systems to learn from data and adapt to new conditions without relying on explicitly programmed instructions. Instead of predefined rules, algorithms detect patterns and generate rules automatically, enabling adaptation to new situations. This is especially important in maritime operations, where incidents often result from a chain of risky events. By applying ML techniques, maintenance teams can detect faults more accurately and quickly, improving overall system safety and operational efficiency. (Simion et al, 2024) Techniques like clustering reveal insights, while reinforcement learning adjusts process parameters based on feedback for better control. Not every machine learning technique is suitable for every business problem. Identifying the most suitable algorithm and model framing for a given real-world application can be a challenging task. Usually, machine learning models have to be integrated with existing systems. As a result, in order to apply machine learning in real-world maritime applications it is necessary to involve a high degree of customization (Kretschmann et al, 2020).

Research area 3 - Internet of Things. The adoption of IoT in maritime logistics can help to streamline the supply chains, as well as to offer a real-time overview across the value chain. This technology has a large applicability for keeping track of people, shipments, and other goods (Song et al, 2020). In addition, several procedures can be automated which generate multiple advantages: eliminate human labor and human error, improve quality and predictability, and finally reduce operating costs. Moreover, intelligent systems communicate across connected networks and enable human-machine interactions. Real time monitoring helps to resource optimization, supply chain transparency (Noto et al., 2023). With all these advantages, the findings show that the maritime industry faces challenges in implementation of IoT technologies. Among the challenges: the reliability of data, efficiency of transmission, and the accuracy of sensors are critical issues, particularly in extreme environmental conditions. Numerous sensors onboard ships produce enormous amounts of data, but the poor transfer of this data to shore-based centers can result in uncertainty and operational inefficiencies. (Aslam et al, 2023).

Research area 4 – Blockchain. Transportation process includes a large amount of documentation. If this is ineffective and capable of being affected by errors, transportation may face risks. Blockchain technology offers innovative solutions to address these potential inefficiencies and can improve trust and transparency in maritime logistics. It is able to provide a secure, decentralized ledger system that minimizes administrative errors, reduces fraud, and streamline processes such as electronic bills of lading (Ben Farah et al., 2024). In addition, blockchain enhances data analytics by ensuring the integrity and traceability of records throughout the supply chain (Liaqat et al, 2024). However, blockchain adoption faces several barriers (Singh et al., 2023), in particular for being adopted in marine logistics (Mohammad & Hamidi, 2022). Organizational challenges include a widespread lack of understanding of technology and its potential applications, especially among small and medium-sized enterprises. Operationally, referring to the use of new technologies instead of the old structure which is costly for any organization. Technical challenges, since the nodes in the chain must process all the transactions carried out in the system, when a deal is developed in the global context, the technology will take a lot

of energy and the calculations within the block will have significant energy consumption, so it is limited in scalability (Hamidi et al, 2024). Successful mass adoption requires a clear development roadmap supported by industry-wide collaboration, education, and training, alongside essential legalization and standardization through close coordination between governments and industry (Nguyen et al, 2023).

Research area 5 – Big Data Analytics. BDA involves analysing diverse data to enhance decision-making. Key benefits include a) cost reduction through big data and cloud-based tools; b) faster, more informed decisions via in-memory analysis and rapid data processing; c) improved goods and services by better understanding customer needs and enabling tailored or new product development (Purnama et al, 2024). Additionally, big data contributes to compliance with environmental regulations by tracking emissions and operational metrics in real time (Liu et al, 2024). Nonetheless, the accuracy and validity of data remain concerns (Nabeel, 2024). Despite technological advances in data acquisition systems, the errors from measurement or the inaccurate data entries can result in poor analyses and suboptimal decision-making.

4. Qualitative analysis

The qualitative analysis presented in this section is based on case studies, academic research papers, technical reports, and expert perspectives to present the role of digital technologies for enhancing efficiency and promoting sustainability. The study includes practical applications, benefits, and challenges of integration of automation, artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), blockchain, and big data analytics into maritime operations. The findings are presented in thematic areas that emphasize technological applications, advantages as well as the challenges.

4.1. Automation and Artificial Intelligence

The use of Artificial intelligence and automation can minimize human error, optimize logistics, and streamline ship management. There are several automated systems designed to manage tasks such as real-time cargo tracking, remote vessel monitoring, and autonomous navigation. For example: Unmanned Surface Vessels (USVs) are equipped with sensors and AI algorithms and can be used for autonomous navigation or for environmental data collection. Another application of AI refers to predictive capabilities. Predictive maintenance includes collection and use of sensor data to examine and detect early signs of system failure. Therefore, the integration of this AI function improves reliability (Simion et al, 2024).

The study shows that the primary challenge in deploying AI and automation lies in integrating these technologies with legacy systems. Many maritime companies operate with outdated infrastructure that lacks compatibility with advanced AI tools. Additionally, high implementation costs, including investment in hardware, software, and skilled personnel, pose barriers, especially for small- and medium-sized enterprises.

Automation and AI support decarbonization by enhancing fuel efficiency and reducing emissions. AI-powered route optimization considers factors such as weather conditions and traffic, contributing to significant fuel savings and lower CO₂ output. Furthermore, predictive maintenance reduces the need for reactive interventions, extending the lifespan of equipment and minimizing waste. These developments align with global sustainability goals and are shaping the future of eco-efficient maritime logistics (Durlík et al, 2024).

4.2. Machine Learning as a Subset of Artificial Intelligence

When considering the use of machine learning in industrial or logistical processes, the first step is often to define the desired solution while taking the available data into account. The intended result is frequently described as some form of optimization in terms of time, money, or safety enhancements.

ML enables the automation of complex workflows by learning patterns from large datasets, thereby reducing reliance on human intervention and improving operational efficiency. It is especially effective in predictive maintenance, where models trained on sensor data can detect anomalies and forecast equipment failures before they occur. Applications like clustering and reinforcement learning provide

real-time feedback loops for optimization, allowing systems to self-adjust based on performance data. ML also supports safety improvements by identifying patterns of operational risk and flagging potential hazards in navigation or engine behavior.

The practical deployment of ML in maritime operations requires high-quality, labeled data, which is often limited by sensor availability, inconsistent formats, or legacy systems. Installing modern sensory equipment can be costly, and integrating expert knowledge into machine-learning models remains a complex task. Additionally, not every ML algorithm suits every use case model selection and framing are crucial, which demands expertise that may be lacking in traditional shipping organizations (Vu et al., 2024).

Machine learning contributes to environmental and economic sustainability by reducing fuel consumption through route and engine optimization, extending asset lifespans via predictive maintenance, and minimizing downtime. Additionally, anomaly detection helps prevent safety incidents that could lead to environmental hazards. These efficiencies support more resilient and sustainable shipping practices (Makridis et al, 2020).

4.3. IoT and Smart Shipping in Green Ships

IoT integration in maritime logistics has completely changed how ships function, especially when it comes to sustainability.

IoT enables a connected network of onboard sensors and devices that continuously collect, transmit, and process data related to vessel operations. Real-time monitoring of parameters such as fuel consumption, emissions, hull integrity, and engine performance allows operators to detect inefficiencies and make informed adjustments to optimize operations. Predictive maintenance is also a major application: IoT-enabled systems detect signs of wear in components like propellers and engines, enabling timely interventions before critical failures occur (Nathisiya & Radhakrishnan, 2024). Furthermore, IoT platforms support advanced energy management by integrating hybrid propulsion systems and optimizing the use of alternative energy sources like wind and solar.

Despite its potential, IoT implementation in maritime operations faces several hurdles. One key issue is data transmission in remote marine environments, which can be unreliable and slow, limiting the effectiveness of real-time analysis (Fang, 2020). Additionally, maintaining sensor accuracy in harsh sea conditions and integrating IoT with existing ship management systems can be complex and costly. These challenges are particularly pronounced for older vessels and smaller operators.

IoT-driven solutions contribute significantly to green shipping initiatives. By facilitating fuel optimization and predictive maintenance, IoT reduces unnecessary fuel consumption and carbon emissions. Energy control systems also help shift energy use toward renewable sources when demand is low, further decreasing environmental impact (Noto et al., 2023). Overall, IoT supports a more proactive and sustainable approach to maritime logistics, aligned with international emissions reduction goals.

4.4. Blockchain and Cybersecurity in Maritime Logistics in the Context of Green Ships

In marine logistics, blockchain technology and cybersecurity solutions ensure openness, security, data collection - as presented in Figure 2, and efficiency in digital operations which are crucial as business moves toward more environmentally friendly practices.

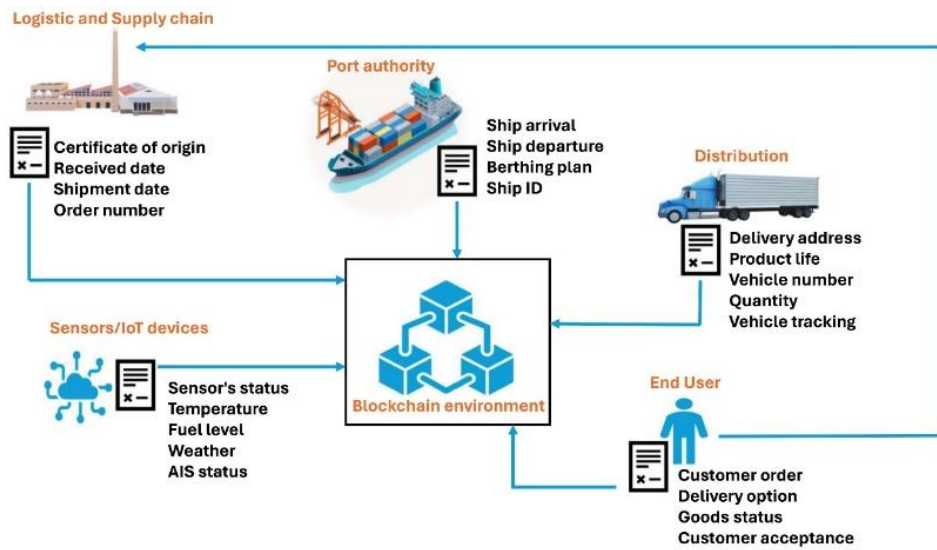


Figure 2. Blockchain environment, Source: (Ben Farah, et al., 2024)

Blockchain provides a decentralized, tamper-proof ledger for storing and sharing data among shipping stakeholders (Durán et al, 2024). In the context of green ships, it ensures transparency in tracking emissions, fuel consumption, and compliance with environmental standards. Smart contracts automate cargo documentation, customs clearance, and compliance verification, reducing administrative overhead and increasing operational speed (Hariyani et al, 2025). These technologies foster trust between shipping companies, regulators, and third-party verifiers by ensuring data authenticity and traceability (Cromwell et al, 2025).

Despite its promise, blockchain adoption is constrained by organizational and technical barriers. Many maritime stakeholders, particularly small and medium-sized enterprises, lack the expertise and infrastructure to implement blockchain solutions effectively. Additionally, concerns over energy consumption, scalability, and interoperability persist, especially for global applications (Fava, 2021).

Blockchain reinforces sustainability by enhancing data credibility for emissions reporting, supply chain traceability, and fuel optimization. It ensures that green shipping practices are verifiable and resistant to fraud or manipulation. Meanwhile, strong cybersecurity protocols, such as blockchain-based authentication, encryption, and intrusion detection, help protect sensitive operational data and reduce the risk of disruption to environmentally critical systems (Liaqat et al, 2024).

4.5. Enhanced Decision-Making through Big Data and Analytics

Big Data and analytics integration in maritime transportation has greatly enhanced decision-making, enabling shipping firms to maximize efficiency, cut expenses, and improve sustainability. Businesses are able to make well-informed strategic decisions that increase efficiency and dependability by gathering and evaluating enormous volumes of real-time data from sensors, weather predictions, fuel consumption records, and cargo monitoring systems.

Big Data systems collect and process vast amounts of information from onboard sensors, satellite feeds, cargo monitoring systems, and weather forecasts (Zhou et al., 2025). When analyzed with AI-driven tools, these datasets support predictive maintenance, anomaly detection, and real-time decision support. For example, predictive analytics identify patterns that indicate machinery wear, enabling timely repairs and reducing the likelihood of costly breakdowns. Additionally, cargo tracking and environmental monitoring have become more accurate, supporting seamless operations and regulatory compliance.

Despite growing capabilities, the maritime sector faces challenges in standardizing and integrating data from heterogeneous sources. Sensor reliability, transmission quality at sea, and the need for skilled

personnel to manage analytics platforms remain key barriers (Wang et al, 2016). Inconsistent data entry or system errors may lead to flawed insights, undermining the reliability of the decision-making process.

Big Data enables greener shipping by optimizing voyage planning and reducing fuel consumption. AI-powered route optimization analyzes real-time weather, port congestion, and ocean current data to determine the most efficient paths (Durlík et al, 2024). Combined with adaptive speed control, these insights allow vessels to maintain delivery performance while significantly lowering greenhouse gas emissions. These applications position Big Data as a key driver of operational resilience and environmental sustainability in maritime logistics.

5. Results and discussions

The thematic qualitative analysis reveals that digital technologies, particularly Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), Blockchain, and Big Data Analytics (BDA), are playing a pivotal role in modernizing maritime operations and driving sustainability. These technologies offer substantial technological benefits, including enhanced decision-making, predictive maintenance, improved fuel efficiency, streamlined cargo management, and real-time monitoring. AI and ML algorithms facilitate route optimization and predictive insights; IoT networks allow for continuous tracking of vessel and environmental performance; blockchain secures data integrity and automates compliance processes; and BDA provides actionable intelligence to support strategic planning.

However, these advancements are tempered by significant implementation challenges. Chief among them are high upfront costs, system interoperability issues, and the complexity of retrofitting legacy infrastructure. Many companies face financial barriers due to the substantial investment required for sensors, data systems, skilled personnel, and cybersecurity frameworks. The lack of standardization across platforms complicates real-time data exchange between stakeholders. Additionally, evolving regulatory requirements introduce legal uncertainty, while rapid technological obsolescence adds long-term financial risk. Human factors, such as resistance to change and insufficient digital literacy among maritime professionals, further impede the pace of adoption.

Despite these barriers and challenges, the sustainability results are compelling. Predictive maintenance and route optimization can reduce fuel use and emissions; blockchain technology ensures transparent compliance with environmental regulations; and IoT can serve to support hybrid propulsion and renewable energy use. In brief, digitalization is improving operational efficiency and bringing maritime logistics into line with global ESG and decarbonization goals. Looking forward, the success of these technologies requires strong cross-sector collaboration, including investment in training, legal and technical frameworks to support scalable adoption in maritime sector.

6. Conclusions

The digital transformation of the maritime industry is an important step towards improved efficiency, sustainability, and security. As the global demand for shipping continues to rise, the role of digital technologies increases. Automation, artificial intelligence, blockchain, and big data analytics all help to optimize processes and lessen their negative effects on the environment. The improvement of operational efficiency is one of the main advantages of digitization in maritime transportation. AI-driven route optimization, predictive maintenance, and automation of cargo handling contribute to cost reduction and efficient consumption of fuel. These advancements not only increase profitability but also minimize downtime and increase revenue.

Another advantage is the promotion of sustainability in maritime logistics. The use of green and digital solutions has become essential due to the expansion of environmental legislation. Modern technologies such as real-time emissions monitoring, smart fuel management, and hybrid propulsion systems are assisting the shipping industry in making the shift to low-carbon and ecologically friendly operations.

However, despite these advancements, technical and economic barriers continue to hinder widespread digital adoption. High implementation costs, lack of standardization, cybersecurity risks, and resistance to change remain major obstacles for many maritime companies, particularly smaller

operators. Overcoming these challenges requires industry-wide collaboration, regulatory support, and investment in digital infrastructure and workforce training.

Looking ahead, future trends in maritime digitalization will be defined by increased automation, the expansion of blockchain in logistics, and the evolution of smart ports. The development of autonomous vessels, AI-powered decision-making, and enhanced cybersecurity frameworks will further strengthen the industry's resilience and competitiveness. As the maritime sector moves towards a more interconnected and data-driven ecosystem is needed for long-term success.

Digital technologies are reshaping maritime transport and offer transformative benefits that enhance efficiency, sustainability, and security. The continuous advancement of digital solutions presents vast opportunities for optimizing global shipping operations. Stakeholders must proactively invest in and adapt to these changes to ensure a more efficient, eco-friendly, and technologically advanced future for the maritime industry.

This study contributes original value by offering an integrated thematic analysis of how key digital technologies are implemented and perceived across the maritime industry. Unlike previous research that often focused on single technologies in isolation, this paper examines their combined influence on operational efficiency, sustainability, and security, grounded in both academic literature and real-world case evidence. The study offers a unique, cross-functional framework for comprehending marine digitalization in the context of green shipping by tying technology functions to industry-specific sustainability results and difficulties.

Despite its comprehensive scope, the study has several limitations. First, the qualitative analysis was based primarily on secondary sources such as case studies, policy documents, and white papers, which may not capture the full spectrum of operational realities or regional differences. Second, the absence of direct stakeholder interviews or field data limits the empirical depth of the analysis. These limitations could be addressed in future research through in-depth interviews, longitudinal case studies, or mixed-method approaches that combine qualitative insights with quantitative performance metrics.

The findings of this study have strong practical implications for maritime stakeholders, including shipping companies, port authorities, regulators, and technology providers. The identification of recurring patterns, such as implementation challenges and sustainability benefits, can inform strategic planning, investment decisions, and technology adoption frameworks. Organizations can use these insights to prioritize digital upgrades, develop workforce training programs, and align technological investments with environmental compliance goals.

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