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Maritime digitalization and PSC compliance: evidence from Greece

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Abstract

Purpose This study investigates the relationship between digitalization, particularly through telemetry, and its impact on Port State Control (PSC) deficiencies, detentions, and associated expenditures. The research emphasizes the importance of the application of digital tools in enhancing maritime safety and operational compliance mainly through the resulted reduction in PSC deficiencies.

Design/methodology/approach The study compares a fleet's performance and PSC outcomes 3 years before and 3 years after the implementation of telemetry-based digital monitoring systems. Empirical data were used to assess the factors influencing managerial decision-making related to digital adoption.

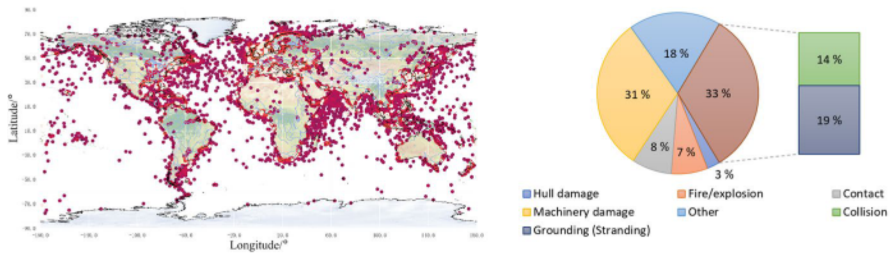
Findings The findings reveal that the integration of digital technologies, such as telemetry, led to a substantial reduction in PSC deficiencies and vessel detentions. This improvement translated into significant cost savings and enhanced compliance with international maritime safety standards. The decision to adopt digital monitoring was influenced by both regulatory pressures and operational performance goals.

Originality/value This study provides empirical evidence, for the first time, linking digitalization and telemetry with measurable improvements in regulatory compliance and operational efficiency. Moreover, this study is unique as it compares data from one fleet over time to avoid implications from other sources (e.g. management style, culture, crew's perceptions etc.) It offers a practical framework for decision-makers considering digital transformation in maritime operations.

Keywords Digitalization, Port state control, Deficiencies, Maintenance cost, Spare parts cost, Operational performance

Introduction

Over 80% of global merchandise trade by volume and more than 70% by value is transported by sea, figures that are even higher for many developing nations. The rapid growth of maritime transport, the expanding size of the global fleet, and the involvement of seafarers with varying levels qualification from over 150 countries introduce significant risks. These include potential property loss, threats to human life, and environmental harm, as evidenced by the rising number of maritime accidents (Yang et al. 2023). As shown in Fig. 1, the spatial distribution of maritime accidents in Fig. 1a reveals that these



(a) Statistical review and spatial distribution of global maritime accidents.

(b) Distribution of global maritime casualty events.

Fig. 1 The analysis of global maritime accidents from 2002 to 2022. (Zhang et al. 2025)

incidents are heavily concentrated along major global shipping routes. Furthermore, the statistical breakdown of casualty types in Fig. 1b highlights that machinery damage (31%) and fire/explosion (33%) account for most reported incidents (Zhang et al. 2025). This distribution underlines the vulnerability of ship systems and the importance of proactive maintenance practices in preventing failures.

A significant proportion of accidents is associated with deterioration mechanisms such as structural overloading, coating breakdown, low quality materials, misalignment of machinery, or vibrations induced by hydrodynamic and mechanical loads. These conditions often manifest as deficiencies later identified during PSC inspections. Previous research has established strong links between PSC deficiencies, maintenance quality, spare parts management, and accident occurrence (Cariou and Wolff 2015; Yang et al. 2018; Fan et al. 2022).

Ensuring vessel compliance through inspections during shipbuilding and throughout the service life therefore remains essential for mitigating these risks. These inspections enable timely maintenance and repairs based on identified defects or malfunctions (Lin and Dong 2023).

Ships are designed and operated in accordance with strict international safety and pollution prevention standards. Regular inspections are required to detect deviations from these standards and initiate corrective action when necessary (Lin and Dong 2023). While these practices remain central to maritime safety, growing attention has been directed toward digital technologies. Telemetry systems, predictive monitoring tools, and real-time data acquisition platforms are increasingly used alongside traditional inspection methods to improve situational awareness onboard (Ichimura et al. 2022; Liang et al. 2024; Zonta et al. 2020).

In this view, the present study examines whether telemetry-based digital tools can contribute to improved vessel compliance and cost efficiency. The research evaluates a fleet of bulk carriers that installed telemetry systems at different points in time, allowing performance to be compared across two equivalent three-year periods, before and after digitalization. This research design reduces the influence of external factors such as management practices, fleet culture, or crew composition. This allows the analysis to isolate the effects of digitalization more clearly.

Numerous studies emphasize the positive effects of digitalization across various domains (Dabbous et al. 2023; Xu et al. 2023; Zheng et al., 2023; Cirillo et al. 2021, Ichimura et al. 2022). Additionally in the maritime context, several research studies (Ma et al. 2024; Niu et al. 2024; Cao et al. 2023) suggest that digital technologies play a significant role in marine accidents, which are indirectly linked to PSC deficiencies and detentions resulting from poor maintenance of vessel equipment. Onboard monitoring systems facilitate real-time data collection and analysis (Liang et al. 2024), and intelligent sensors can strengthen safety system performance (Puisa et al. 2021). These developments underscore the importance of examining how telemetry may influence operational and compliance related outcomes.

To address this gap, the study evaluates the effects of telemetry on PSC performance, maintenance costs, and spare parts expenditure through three testable hypotheses.

PSC deficiencies and equipment deterioration are often linked, and digital monitoring can improve the timely identification of conditions that contribute to non-conformities.

H1: *PSC deficiencies are significantly lower after the implementation of telemetry systems.*

Maintenance costs constitute a significant portion of vessel operating expenses, and real-time sensor data can support proactive maintenance planning, reducing unplanned failures and associated costs (Karatuğ et al. 2023; Mouschoutzi and Ponis 2022).

H2: *Maintenance costs are significantly lower after the implementation of telemetry systems.*

Spare parts represent a substantial share of routine maintenance budgets, and improved monitoring can reduce unnecessary replacements and inappropriate part usage (Yang et al. 2021; Al Hanbali et al. 2022).

H3: *Spare parts costs are significantly lower after the implementation of telemetry systems.*

These hypotheses allow the study to quantify the operational benefits of telemetry using comparable pre- and post- implementation data from real fleet operations. Although digitalization has been widely discussed in the literature, empirical assessments linking telemetry to compliance and cost performance remain limited primarily because real operational datasets are rarely accessible. By integrating PSC inspection records, maintenance expenditure, and spare parts consumption, the study provides evidence-based insights into how digital monitoring technologies influence vessel performance and operational readiness.

To gain a comprehensive view of ship performance in real operational conditions, Zhang et al. (2024) in a previous study, collected high-frequency data with resolution of 60 s during extensive sea trials from a digitalization system. Figure 2 illustrates a typical telemetry system installed on a bulk carrier, highlighting the components that enable continuous monitoring.

The methodological framework employed in this study includes data collection from PSC inspection reports and internal cost records, categorization of vessels into pre- and post-telemetry periods, data cleaning and validation through normality and outlier tests, and paired sample t-tests to examine statistical differences. This integrated dataset spans six operational years and provides a robust basis for evaluating the impact of telemetry on vessel performance.

The findings indicate substantial reductions in PSC deficiencies, maintenance costs, and spare parts expenditure following the installation of telemetry systems. These reductions indicate that real-time monitoring enhances fault detection, improves maintenance planning, and reduces unplanned failures, thereby strengthening compliance readiness and operational efficiency across the fleet.

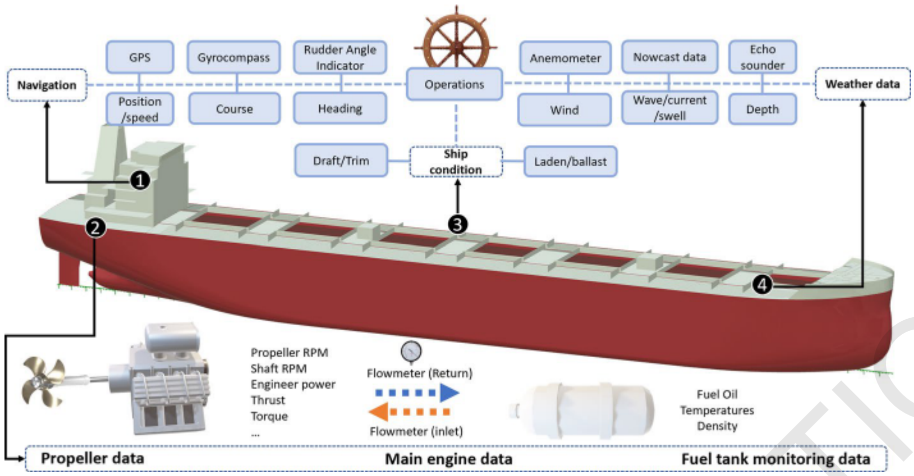


Fig. 2 Digitalization/telemetry system typical structure onboard a bulk carrier vessel. *Source* Authors

The structure of the paper is organized to ensure a coherent and systematic exploration of the research objectives. Sect. "Literature" reviews the relevant literature to contextualize the study within the existing body of knowledge. Sect. "Methodology" outlines the methodological framework employed for data collection and analysis. Sect. "Results" presents the empirical findings derived from the case study, while Sect. "Discussions and implications" interprets these results in light of the proposed research hypotheses, discussing their theoretical and practical implications. Sect. "Limitations and directions for future research" acknowledges the study's limitations, and proposing directions for future research and finally Sect. "Conclusions" concludes the paper by summarizing the key insights.

Literature

To establish a solid conceptual foundation for this study, this section reviews the relevant literature across four key domains: the definition and scope of digitalization in the maritime sector, trends in scholarly interest and keyword associations, the role of PSC in maritime safety, and the relationship between vessel maintenance, spare parts logistics, and operational costs.

Digitalization

The definition

Digitalization is widely recognized as the integration of digital technologies across sectors, enabling improvements in data accessibility, interoperability, and the efficiency of communication, computation, and storage (Gong and Riviere 2021). These technological capabilities form the foundation for transforming service delivery, operational models, and stakeholder relationships.

Liu et al. (2021) emphasize that digitalization facilitates the manipulation and distribution of products and services through enhanced data capabilities, while Proksch et al. (2021) highlight its role in fostering innovation and performance across industries. Despite differing emphases, both views converge on the transformative potential of digital technologies in reshaping organizational processes.

In the maritime domain, this transformation is particularly evident. Ichimura et al. (2022) frame shipping digitalization as a reconfiguration of traditional business models through Industry 4.0 technologies, including intelligent systems and automation aimed at improving safety, efficiency, and competitiveness.

Building on this synthesis, "Shipping Digitalization" can be defined as the strategic transformation of maritime operations and business models through the integration of digital technologies, such as sensors, data analytics, and automated systems, to enhance operational efficiency, ensure regulatory compliance, improve safety, and support data-driven decision-making across the vessel lifecycle.

Stimuli and rationale for this research on shipping digitalization

Understanding the impact of digitalization in the shipping industry is essential due to its rapidly evolving technological landscape and the sector's critical role in global trade. Maritime operations are becoming increasingly dependent on data-driven technologies to manage safety, efficiency, compliance, and environmental performance (Ichimura et al. 2022; Liang et al. 2024). Despite growing interest, there remains a need for empirical research that explores how these digital technologies affect operational outcomes in practice, particularly in areas such as equipment maintenance, inspection performance, and defect prevention.

Digitalization is more than a technological upgrade as it reshapes cost structures, compliance practices, and decision-making processes across the vessel lifecycle (Proksch et al. 2021; Xu et al. 2023). However, the benefits are not guaranteed, as studies highlight implementation challenges, including high costs, integration complexity, and the need for organizational adaptation (Dagkinis et al. 2023; Karatuğ et al. 2023). By investigating digitalization specifically within the shipping context, this study aims to bridge the gap between theoretical promise and real-world effectiveness, thereby offering practical insights for maritime stakeholders navigating the digital transition.

Research on the role and impact of digitalization in shipping has expanded steadily, as shown in Fig. 3. In alignment with several previous studies (Ametepey et al. 2024; Garg et al. 2025), this research also utilizes the Scopus database to ensure a comprehensive and reliable analysis.[1] Based on 1,944 documents indexed between 2017 and December

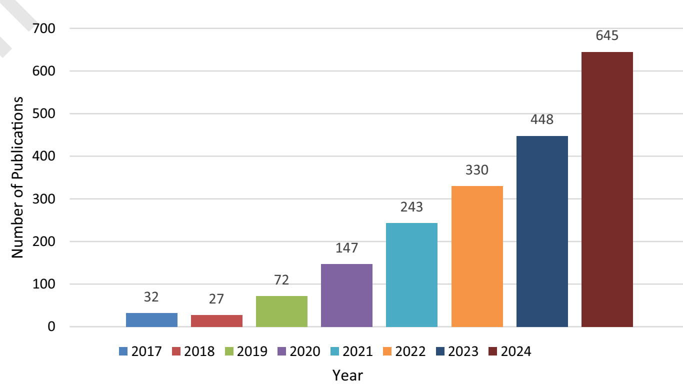


Fig. 3 Number of publications for digitalization over the years.*Source* Authors

[1] In this research the following query was employed to retrieve relevant results "digitalization OR digitalisation AND marine OR maritime OR shipping AND ship OR vessel AND PUBYEAR > 2015 AND PUBYEAR < 2026" AND (LIMIT-TO (LANGUAGE, "English")).

2024, with only a minor dip in 2018, the trend indicates a sustained and growing interest in this topic.

A complementary keyword-based screening was performed using Scopus internal indexing fields. By filtering the 1,944 documents in the Author Keywords and Index Keywords, the analysis identified 236 port related publications, representing approximately 12 percent of the dataset. This confirms that, while digitalization research is expanding rapidly, port focused studies still form a relatively limited share of the literature. Figure 4 presents the proportional distribution of port-related and non-port-related studies within the dataset.

As digitalization becomes more common in maritime operations, its effects are increasingly visible at the ship operator level. Operators often struggle to manage multiple digital platforms that must exchange data reliably while still interfacing with legacy onboard systems (Zeng et al. 2025). The adoption of IoT monitoring, machine learning diagnostics, and advanced sensing equipment also requires new technical skills, exposing gaps in data handling, system configuration, and digital maintenance routines (Elsisi et al. 2025). At the same time, interest in Artificial Intelligence (AI) continues to grow, but many operators find it difficult to assess deployment complexity and adjust these tools to diverse operational environments (Farzadmehr et al. 2025). Rapid shifts in technological trends further complicate long term investment planning (Jalali and Tei 2025). These challenges show that successful digital transformation for ship operators depends on structured training, careful planning, and alignment between technology and day to day operational needs.

Similar difficulties arise within port environments. Many ports rely on outdated systems, manual processes, and inconsistent data formats, which limits smooth integration of newer technologies and slows the flow of operational information (Zeng et al. 2025). Efforts to decarbonize ports add further complexity, since environmental measures must be coordinated with digital upgrades and implemented across multiple stakeholders (Fadiga et al. 2024). In addition, ports report shortages of personnel with the skills needed to support automation, digital platforms, and data driven decision making, highlighting the need for continuous upskilling (Lopes et al. 2025). AI-based tools face similar barriers, as their adoption often requires clear prioritization and structured evaluation of operational impact (Farzadmehr et al. 2025). These factors show that port digitalization requires coordinated planning, investment in people, and the gradual modernization of technical infrastructures.

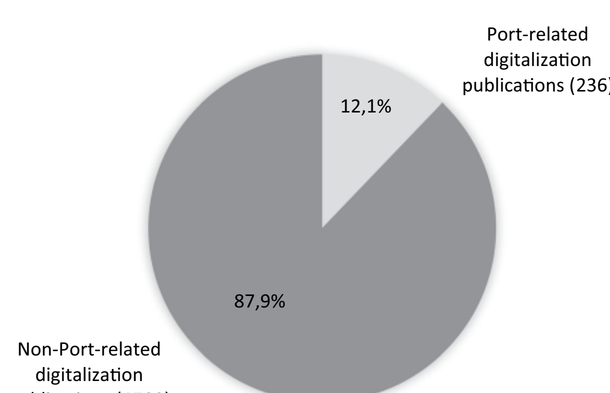


Fig. 4 Port-related versus non-port-related digitalization publications from 2017 to 2024.*Source* Authors

Digitalization also introduces new risks that affect both ships and ports. Cybersecurity and data integrity have become major concerns as navigation, cargo handling, and communication systems grow more interconnected. Cyberattacks frequently exploit procedural weaknesses, or limited staff awareness, making ransomware, malware, and denial of service incidents increasingly common in port settings (Tombak et al. 2025; Senarak 2024). The tighter connection between ship and shore systems increases the risk of unauthorized access, data manipulation, and disruptions to operational technologies (Tombak et al. 2025). Compromised data can delay decisions or interrupt essential services. Recent analyses also show that threats targeting Automatic Identification System signals, port communication networks, and automated systems are becoming more sophisticated (Peng et al. 2025). These developments underline the need for strong cybersecurity practices, regular vulnerability assessments, and targeted training to protect data integrity and operational continuity.

What differentiates this research is its combined methodological and thematic focus. While most prior studies concentrate on broad strategic or technological aspects, this work integrates a targeted operational lens with bibliometric and empirical approaches. It not only maps the intellectual structure and publication trends but also analyses how digitalization directly influences specific operational metrics, maintenance efficiency, inspection accuracy, and defect prevention rates, using real-world maritime datasets. This dual perspective enables the study to move beyond theoretical discussions and contribute actionable, evidence-based recommendations for ship operators, regulators, and technology providers. Additionally, by coupling bibliometric mapping with case-driven operational assessment, this research creates a rare bridge between large-scale trend analysis and fine-grained operational impact evaluation in the maritime digitalization discourse.

Figure 5 presents a network map of keyword co-occurrence derived from a full counting analysis conducted on the digitalization dataset using VOSviewer software. This analysis was undertaken to identify the major thematic clusters and research trends, offering a clearer view of how current studies are structured and where important gaps

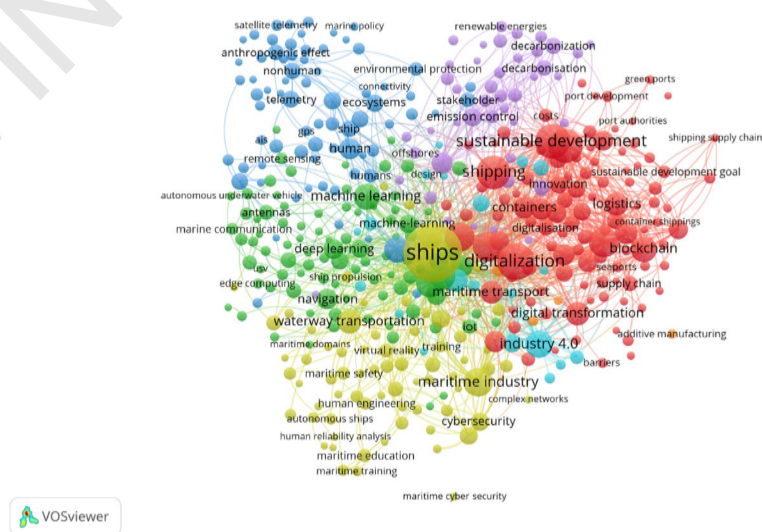


Fig. 5 Co-occurrence network in full counting.*Source* Authors

remain.[2] Mapping keyword relationships allows for a comprehensive overview of the domain, revealing not only the most frequently discussed topics but also how these topics interconnect (Bukar et al. 2025; Ichimura et al. 2022).

The keywords and search terms used, such as digitalization, telemetry, shipping, ship, and vessel, were selected based on their theoretical and practical significance in the maritime digital transformation domain (Gong and Riviere 2021; Ichimura et al. 2022). These terms reflect central concepts widely recognized in previous studies and industry reports as key to understanding the adoption and impact of digital technologies on maritime operations (Mouschoutzi and Ponis 2022; Cao et al. 2023). The search query was designed to capture literature explicitly linking digitalization efforts to maritime vessels, consistent with theoretical frameworks on technology diffusion and innovation adoption (Gong and Riviere 2021).

In the resulting network visualization, the distance between keywords indicates the strength of their co-occurrence relationships, while the size of each keyword reflects its frequency in the dataset (Gursel et al. 2025).

Among the most frequent terms are “ships”, “digitalization”, “shipping”, “supply chains”, and “sustainable development”. A prominent pattern observed -and triggered this research—is the close association between “digitalization” and “ships”, highlighting the increasing application of digital technologies in vessel operations. This strong linkage suggests that digital tools such as telemetry, predictive maintenance, and AI-driven monitoring systems are being integrated to enhance operational efficiency, improve safety, and ensure regulatory compliance.[3] These technologies also help minimize unnecessary maintenance costs by ensuring critical systems remain functional and compliant (Zonta et al. 2020).

These patterns highlight the need for a clear theoretical lens to explain how digitalization interacts with regulatory expectations and operational performance across the maritime sector.

Port state control (PSC)

The discussion of digitalization would be incomplete without considering regulatory oversight mechanisms such as PSC, which plays a critical role in ensuring vessel compliance and operational safety. Digital technologies, particularly telemetry, predictive maintenance, and automated inspection support, are increasingly being integrated to address many of the same deficiencies that are regularly identified during PSC inspections (Fan et al. 2022). Theoretically, this connection aligns with institutional theory, which posits that organizational practices, including technology adoption, are influenced by regulatory and compliance pressures (Wang et al. 2025). Empirically, numerous studies have

[2] In the network visualization, items are represented by their label and, by default, are also depicted within a circle. The size of an item's label and circle is proportional to its weight meaning that the greater the weight, the larger the label and circle. The colour of the item is assigned based on the cluster it belongs to. Regarding the full counting method, the link between two keywords has a strength of 2. This indicates that both keywords have co-occurred in 2 documents. This visualization tool is used to extract and visualize the co-occurrence networks of authors’ keywords from studies included in the review. The VOS method relies on mapping and clustering based on the same fundamental principle, which is a weighted and parameterized variant of modularity function (Bukar et al. 2025).

[3] The following query was used to retrieve results for Fig. 3: digitalization OR digitalisation OR telemetry AND maritime OR shipping AND ship OR vessel AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2023) OR LIMIT-TO (PUBYEAR, 2024)).

shown that maintenance deficiencies, poor recordkeeping, and equipment failures are among the most common PSC findings and are often precursors to accidents (Yang et al. 2024). Therefore, analysing PSC outcomes provides a concrete and measurable lens through which the impact of digitalization on safety and maintenance performance can be evaluated.

PSC serves as a control mechanism established to prevent the operation of substandard vessels that fail to comply with international maritime standards from navigating globally (Sanlier 2020).

The objective of PSC inspections is to improve the maritime safety standards of the global trade fleet by eliminating substandard vessels (Kara 2022). During a PSC inspection, any onboard conditions that fail to meet the requirements are identified as deficiencies which require rectification (Wang et al. 2019). Should there be significant deficiencies that render a ship unfit for navigation, the PSC officer has the authority to detain the ship and mandate the rectification of subject deficiencies prior departing. Ship detention is the most serious decision made during an inspection and can be regarded as the most severe result of PSC inspection. Ship detention not only indicates poor ship condition and increases the risk of future incidents but may also result in considerable delays of the vessel and economic losses (Yan et al. 2021).

Maintenance and spare parts cost

Given that many deficiencies identified during PSC inspections stem from poor maintenance practices, the economic dimension of maintenance becomes critical. Inadequate management not only increases the risk of deficiencies and ship detentions but also raises operational costs. These costs, particularly those associated with major interventions like drydocking or hull repairs, often lead shipowners to delay necessary maintenance, especially when inspections do not immediately enforce corrective action. Such delays compromise vessel safety and contribute to recurring PSC deficiencies (Yang et al. 2018). Analysing maintenance and spare parts costs, therefore, provides key insight into how digital technologies such as predictive maintenance and telemetry can support compliance, reduce costs, and enhance operational safety.

Maintenance refers to the upkeep of ship systems and machinery to ensure reliability and safety (Dereci and Tuzkaya 2024). As vessels become increasingly complex, the consequences of delayed or inadequate maintenance grow more severe. Optimized maintenance improves system availability, reduces downtime, and lowers lifecycle costs (Karatuğ et al. 2023). One widely employed strategy in the maritime sector is Time-Based Maintenance, a form of predictive maintenance based on scheduled service intervals (Karatuğ et al. 2023).

Spare parts management is a critical component of effective maintenance. Mouschoutzi and Ponis (2022) define a spare part as an interchangeable item kept in inventory for maintenance purposes. A common approach is "repair-in-replacement," whereby faulty components are replaced with ready-to-use spares to minimize downtime (Mouschoutzi and Ponis 2022). However, this method depends heavily on the availability and timely delivery of parts, an ongoing challenge for globally operating vessels, particularly tramp ships. Thus, planning spare parts logistics and maintaining service levels are therefore vital, as stock-outs can have serious financial and operational consequences (Mouschoutzi and Ponis 2022).

Theoretical framework: linking digitalization, regulatory pressure, and operational performance

The maritime sector's digital transformation goes beyond mere technological advances. It is deeply influenced by institutional and environmental forces shaping how organizations behave. Two theories help explain why shipping firms adopt digital tools like telemetry, and how these tools impact operations: Institutional Theory and the Technology-Organization-Environment (TOE) framework.

Institutional Theory suggests firms embrace new practices due to three main pressures: coercive, normative, and mimetic (Kuo et al. 2022). In maritime contexts, regulations and international conventions exert coercive pressure, pushing companies to adopt digital solutions to meet transparency and safety standards. Normative pressure arises from bodies such as professional associations and port authorities endorsing standardized procedures. Meanwhile, mimetic pressure comes into play as companies follow competitors who have gained market advantages through digitalization (Kuo et al. 2022). Studies reinforce that these sector-wide expectations strongly influence digital adoption (Jović et al. 2022).

The TOE framework complements this by highlighting how technology readiness, organizational capabilities, and external environment interact. For instance, digital skills, system complexity, funding, and management support shape whether firms succeed in implementing digital technologies. Recent research confirms that these factors collectively determine digital transformation outcomes in shipping (Jović et al. 2022; Nguyen 2024).

Together, these two frameworks offer a clear rationale for this study's hypotheses. Telemetry adoption reflects firms responding to external expectations, regulatory and competitive, while relying on internal resources to implement effectively. Such digital tools improve PSC compliance and operational efficiency by enhancing monitoring and reducing uncertainty. This alignment between external pressures and organizational capabilities is key to reducing maintenance issues and spare parts costs through data-driven decision-making.

Methodology

To examine the proposed research questions, this study adopts a data driven methodological approach grounded in real fleet operations. The overall process consists of the following steps:

- *Step 1:* Raw data were collected from a single shipping company, including PSC inspection reports and internal financial records covering maintenance and spare parts expenditures over a six-year period.
- *Step 2:* Vessels equipped with telemetry systems were identified, and both inspection and cost data were categorized into two distinct periods, before and after the implementation of telemetry.
- *Step 3:* For each vessel, average values of the selected key performance indicators, PSC deficiencies, maintenance cost, and spare parts cost, were calculated for both timeframes to enable direct comparison. These averages were computed over the same 3 years' operational period for each vessel before and 3 years after the implementation of digitalization.

- *Step 4:* The dataset was refined to include only vessels with complete and reliable telemetry records, thereby ensuring consistency, comparability, and analytical robustness (see Sect. "Data collection and processing" for details for data validation and reliability checks).
- *Step 5:* Shapiro–Wilk test and Tukey Fence Method were applied to confirm normality and exclude outliers, justifying the use of the Paired Sample T-Test.
- *Step 6:* Statistical analysis was performed using the Paired Sample T-Test.

Sections "Data collection and processing" and "Data description" provide a detailed explanation of the data collection procedures, and a description of the key variables and metrics used in the analysis.

Data collection and processing

To address the research hypotheses outlined earlier, this study employed real case empirical data from real-time sources. It analyzed PSC inspection reports collected over six years from a sample fleet of bulk carriers operated by a shipping company. Additionally, economic data, specifically maintenance and spare parts expenses, were sourced from the company's archives for the same vessels and timeframe.

To ensure the reliability of the data used in the analysis, several validation steps were applied across all datasets. For PSC records, consistency checks were conducted by cross-verifying deficiency entries with the official inspection dates and ship identifiers, while duplicated or incomplete inspection reports were removed. Maintenance and spare parts cost data were also screened for missing monthly entries, internal inconsistencies, and unrealistic cost fluctuations. For the telemetry data, which served only to classify vessels into pre- and post-implementation periods, completeness checks were performed to confirm uninterrupted sensor coverage throughout the three-year windows before and after installation. Vessels showing systematic mismatches, irregular patterns, or extended gaps attributable to sensor malfunction or transmission errors were excluded. Only vessels passing all reliability checks were retained in the final dataset.

This integrated approach provides access to operational information that is often absent from standard databases and enables a more detailed understanding of PSC performance patterns. By combining raw PSC report data with financial records, the study delivers a more nuanced understanding of PSC reporting systems, emphasizing the key factors behind deficiencies and detentions. The overall data processing workflow adopted in this research is illustrated in Fig. 6.

Specifically, this analysis covered 234 PSC inspection reports documenting 750 deficiencies and detentions. Most vessels in the fleet are equipped with telemetry and high-frequency data collection systems. Initially, the analysis was conducted at the individual vessel level, comparing periods before and after telemetry implementation. Since installation dates varied across vessels, the average value of each measured parameter for the pre- and the post-digitalization period was calculated. This method allowed for a more effective fleet-level analysis.

Subsequently, after removing outliers, vessels lacking digital equipment, and those with incomplete reports or data, the dataset was refined to 98 PSC inspection reports, documenting 263 deficiencies and detentions from 23 bulk carriers. This study focused on this subset of digitally equipped vessels to provide targeted insights.

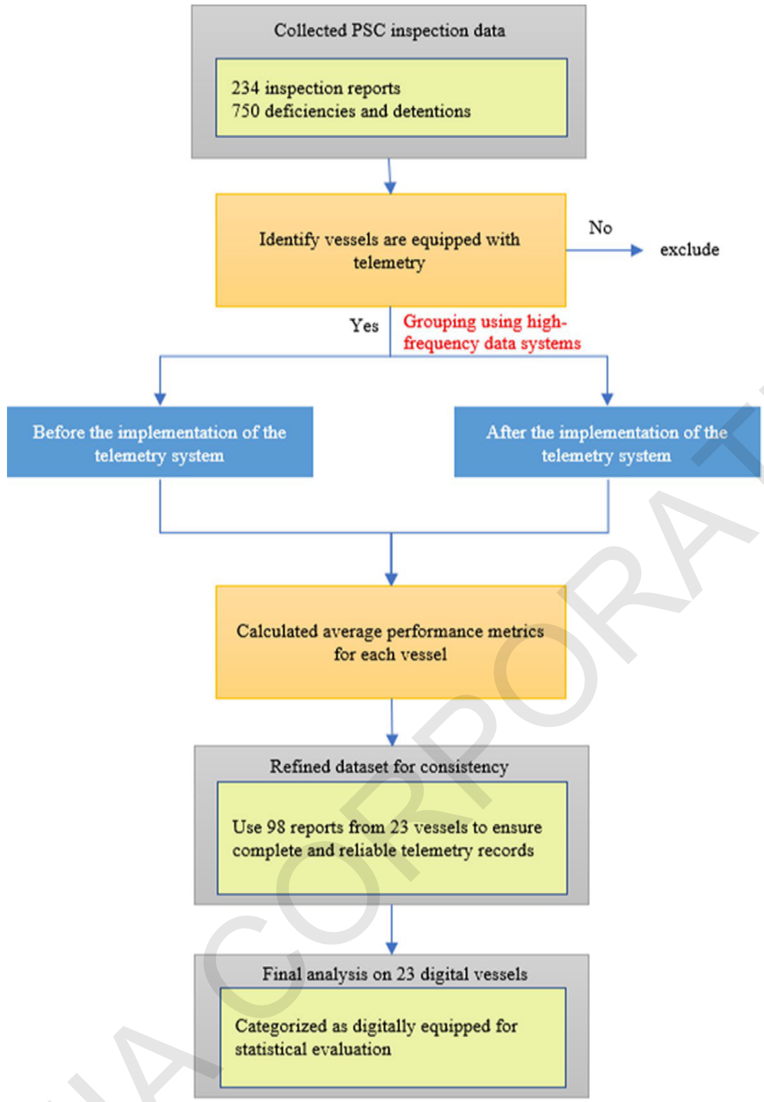


Fig. 6 The flowchart of data processing.*Source* Authors

Data description

The vessels were built between 2010 and 2021, with an average year built of 2015 (SD = 3.38). The descriptive analysis shows clear variation in PSC deficiencies, maintenance costs, and spare parts expenditure across vessel types and years. For example, Mini Cape vessels recorded the highest deficiency levels in some years, peaking at 18 deficiencies in 2018, whereas Newcastlemax and Capesize vessels reported near-zero deficiencies in multiple years. In terms of costs, Panamax vessels consistently recorded the highest maintenance spending, reaching over $2.1 million in 2021, followed closely by Post Panamax vessels at around $1.29 million in 2020. Spare parts expenditure was also largest for Panamax vessels, peaking at $2.16 million in 2021, with Post Panamax vessels and Ultramax vessels also showing high annual totals. When adjusting costs per deficiency, volatility becomes more pronounced. For instance, the cost-per-deficiency for Capesize vessels in 2020 exceeded $80,000 for maintenance and $81,000 for spare parts, while in some years it was effectively zero due to no recorded deficiencies. Across the fleet, average maintenance cost per deficiency peaked at $105,599 in 2020, and spare

Table 1 Descriptives for PSC deficiencies

	N	Mean	Median	SD	SE
PSC deficiencies before telemetry	23	1.92	1.75	1.63	0.34
PSC deficiencies after telemetry	23	0.71	0.66	0.71	0.15

Source Authors

Table 2 Descriptives for maintenance and spare parts cost

	N	Mean	Median	SD	SE
Maintenance cost ($) before telemetry	23	94,810.1	92,110.4	44,405.9	9259.3
Maintenance cost ($) after telemetry	23	72,262.8	73,849.2	31,032.6	6470.7
Spare parts cost ($) before telemetry	23	105,480.4	116,090.1	48,654.9	10,145.2
Spare parts cost ($) after telemetry	23	83,690	92,285.6	43,522.9	9075.1

Source Authors

parts cost per deficiency peaked at $108,014 in the same year, likely reflecting pandemic-related operational disruptions.

Three key patterns emerge:

1. *Performance disparities*: Certain vessel classes, such as Mini Capes, have persistently higher deficiency counts, while others maintain consistently low rates.
2. *Cost concentration:* Panamax and Post Panamax vessels account for the largest share of total maintenance and spare parts expenditure, highlighting where efficiency gains from telemetry could have the biggest financial impact.
3. *External volatility:* The years 2020–2021 saw sharp spikes in cost-per-deficiency across all vessel types, underscoring the influence of global disruptions like COVID-19 on cost-effectiveness and compliance.

These patterns provide a robust baseline for evaluating whether the adoption of telemetry systems leads to measurable improvements in both regulatory compliance and cost efficiency.

The descriptives for PSC deficiencies are presented in Table 1 while the descriptives for Maintenance and Spare Parts Cost are presented in Table 2.

Methods

First, the normality of the sample was examined using Shapiro–Wilk normality test with a significance level of $\alpha = 0.05$. The Shapiro–Wilk test is widely recommended (Monter-Pozos and Gonzalez-Estrada 2024), as it allows for using small sample sizes (< 50 samples). The Shapiro–Wilk test on the differences in PSC deficiencies before and after the implementation of telemetry indicated that the assumption of normality, $W(23) = 0.9678$, $p = 0.6361 > 0.05$ cannot be rejected. The test statistic falls within the 95% region of acceptance [0.9142, 1], supporting the conclusion that the data are normally distributed. Similarly, for the differences in Maintenance Cost, the Shapiro–Wilk test yielded $W(23) = 0.9678$, $p = 0.1593 > 0.05$, indicating that the assumption of normality cannot be rejected. Regarding the differences in Spare Parts Cost, the test produced $W(23) = 0.9719$, $p = 0.7354 > 0.05$, also suggesting normality of the data.

In addition, to identify any potential outliers, the Tukey Fence method, which uses the interquartile range (IQR), was applied (Dastjerdy et al. 2023). This method allowed the assessment of whether any of the 23 difference values (after–before) were extreme enough to potentially distort the results of the paired samples t-test. Using the standard threshold of k = 1.5 and considering that the minimum and maximum values in the PSC deficiencies dataset were 1.000 and -3.889 respectively, the minimum and maximum values in the Maintenance Cost dataset were \$56,488.9 and \$120,718.8 respectively, and the minimum and maximum values in the Spare Parts Cost dataset were \$81,422.6 and -\$116,968.3 respectively, all data points fell within the calculated bounds for PSC deficiencies: Lower fence = –0.48688 and Upper fence = 2.5213, for Maintenance Cost: Lower fence = -\$163,759.8 and Upper fence = \$130,255.9 and for Spare Parts Cost: Lower fence = –\$163,030.2 and Upper fence = \$130,265.9. Therefore, no outliers were detected, supporting the assumption of no extreme outliers and confirming the appropriateness of the paired t-test for this analysis.

To evaluate the differences in key performance metrics before and after telemetry implementation basis on the hypothesis that PSC deficiencies, Maintenance and Spare Parts Cost decrease after adopting digital tools, a left-tailed Paired Sample T-Test (Langenberg et al. 2023) was applied to conduct the paired analysis of the two samples.

Interpretation follows Cohen's general guidelines (Langenberg et al. 2023):

- $|d| \approx 0.10$: small effect
- $|d| \approx 0.30$: medium effect
- $|d| \geq 0.50$: large effect

This approach provides both statistical significance and a meaningful measure of the practical impact of digitalization.

Results

The number of PSC deficiencies was compared before and after the installation of telemetry. The median number of deficiencies before telemetry (Mdn = 1.75) was higher than after telemetry (Mdn = 0.66). A left-tailed paired sample t-test showed that this reduction was statistically significant, t(22) = –4.64, $p < 0.001$, with the test statistic falling below the critical value ($t_{critical} = -1.717$), indicating strong evidence of improvement after telemetry. The detailed statistical results are presented in Table 3.

Maintenance costs were also compared before and after telemetry installation. The median maintenance cost before telemetry (Mdn = \$92,110.40) was higher than after telemetry (Mdn = \$73,849.20). A left-tailed paired t-test revealed a statistically significant reduction, t(22) = –2.01, p = 0.028, again with the test statistic below the critical threshold ($t_{critical} = -1.717$).

Similarly, spare parts costs decreased after telemetry was implemented. The median cost before telemetry (Mdn = \$116,090.10) was greater than after telemetry (Mdn = \$92,285.60). A left-tailed paired t-test confirmed this reduction to be statistically significant, t(22) = –1.93, p = 0.033, with the test statistic also below the 95% critical value ($t_{critical} = -1.717$), providing moderate evidence for a cost-saving effect. A summary of these results is shown in Table 4.

Discussions and implications

This study offers rare empirical evidence from the maritime sector showing that telemetry-based digitalization improves PSC compliance, maintenance efficiency, and spare parts expenditure. By comparing equivalent pre- and post-implementation periods within the same fleet, the analysis isolates the effect of telemetry more clearly than cross

Table 3 Left-tailed paired sample T-test for PSC deficiencies

							95% confidence interval		
		t-crit95%	t-statistic	*p*-value	Mean difference	SD difference	Lower	Upper	Cohen's effect size
PSC deficiencies before telemetry	PSC deficiencies after telemetry	− 1.717	− 4.6375	0.0000636	− 1.2154	1.2569	− 4.869	2.521	0.97

Note H_a $\mu_{After-Before} \neq 0$

Source Authors

sectional approaches that may be affected by variations in management practices, crew culture, or vessel employment patterns.

All three hypotheses are supported. For Hypothesis 1, the significant reduction in PSC deficiencies after telemetry installation aligns with earlier studies showing that many deficiencies stem from undetected machinery deterioration or delayed corrective actions (Fan et al. 2022; Yang et al. 2024). For Hypotheses 2 and 3, the observed decreases in maintenance and spare parts costs indicate that real-time monitoring improves diagnostic accuracy and resource allocation, supporting fewer unplanned failures and more efficient use of resources (Karatuğ et al. 2023; Liang et al. 2024). These cost reductions contribute directly to operational profitability by lowering unexpected expenditures and stabilizing maintenance budgets.

The mechanism behind these improvements is evident in operational practice. Figure 7 illustrates a case where the exhaust gas temperature of a single cylinder trended upward toward the alarm threshold. Because the system detected the deviation early, the crew inspected and cleaned a fouled injector before the next port call, avoiding what would likely have emerged as a machinery related deficiency during inspection. In another instance, combining route information with sensor data made it possible to schedule maintenance and arrange spare parts in advance, preventing a repeat deficiency previously caused by a repair delay. These examples show how telemetry converts emerging faults into timely corrective actions, reducing the likelihood of PSC findings.

The implications are relevant for several stakeholder groups. For shipowners and technical managers, telemetry reduces operational uncertainty, enhances maintenance predictability, and limits avoidable expenditure. Ports and PSC authorities benefit indirectly, since vessels with fewer latent technical issues reduce inspection burdens and minimize operational delays. Technology providers can use these insights to refine monitoring tools that directly support compliance readiness.

The applicability extends beyond bulk carriers. Tankers can employ telemetry for pumps and cargo handling systems, container ships for reefer units and auxiliary machinery, and passenger vessels for accommodation, ventilation, and safety related equipment. Across segments, early detection of anomalies reduces machinery failure probability and supports smoother PSC outcomes.

The findings also connect to broader sustainability and resilience objectives. Preventive maintenance reduces unnecessary component replacement, minimizes waste, and lowers emissions associated with corrective repair work. More stable machinery performance enhances operational resilience by reducing unplanned downtime and improving the ability to absorb disruptions during periods of supply chain or staffing constraints. These outcomes align with current policy goals promoting safe, efficient, and environmentally responsible maritime transport.

Overall, the results show that telemetry enabled digitalization delivers tangible compliance, economic, and environmental benefits. The study offers evidence-based guidance for policy makers, managers, and technology developers, and highlights the wider value of expanding digital monitoring practices across the maritime sector.

Table 4 Left-tailed paired sample T-test for maintenance and spare parts cost

							95% Confidence Interval		
		t-crit95%	t-statistic	*p*-value	Mean difference	SD difference	Lower	Upper	Cohen's Effect Size
Maintenance cost ($) before telemetry	Maintenance cost ($) after telemetry	− 1.717	− 2.0136	0.028	− 22,547.3	53,700.4	− 163,759.8	130,255.9	0.42
Spare parts cost ($) before telemetry	spare parts cost ($) after telemetry	− 1.717	− 1.9275	0.033	− 21,790.4	54,217.0	− 163,030.2	130,265.9	0.40

Note H_a $\mu_{After-Before} \neq 0$

Source Authors

Limitations and directions for future research

As with any academic research, this study also encounters certain limitations. The primary constraint lies in the fact that the data was sourced from a single shipping company, which may constrain the generalizability of the findings. Future scholars should endeavour to mitigate this limitation by acquiring data from a broader sample that includes multiple shipping companies. Expanding the dataset in this manner would enhance the generalizability and reliability of the results, thereby contributing to a more comprehensive understanding of the subject.

Secondly, it is important to acknowledge two significant limitations in the scope of this research. First, this analysis is limited to a dataset that spans merely a six-year timeframe, thereby constraining the temporal dimension of this analysis. This temporal limitation hampers the capacity to identify long-term patterns and variations in the data, potentially resulting in an incomplete representation of the phenomenon under investigation. Additionally, by focusing solely on one vessel type, bulk carriers, this study does not capture the diversity and variability present across the wider maritime industry. Therefore, to enhance the comprehensiveness of future research, it would be beneficial to prolong the data collection period, enabling a more in-depth exploration of long-term trends as well as incorporating data from various types of vessels to reflect the inherent heterogeneity within the industry. This would enable researchers to achieve a more holistic and robust understanding of the factors influencing the performance and dynamics of the maritime sector.

Thirdly, some vessels have installed their digitalization system during 2022. For future research, refining further the same dataset, either by excluding these vessels or by defining better the period prior- and post-digitalization implementation could enhance the accuracy of the results.

Conclusions

This study examined whether telemetry-based digitalization can meaningfully improve vessel compliance and operational performance, using a rare longitudinal dataset that compared equivalent pre- and post-implementation periods within the same fleet. The results demonstrate that digital monitoring contributes to fewer PSC deficiencies, lower maintenance expenditure, and reduced spare parts consumption, confirming all three hypotheses. These improvements stem from earlier fault detection and more accurate maintenance planning, which reduce the likelihood of equipment related non-conformities during inspection.

Beyond the measured outcomes, the study shows that digital tools can reshape operational practices by enabling more timely intervention and supporting a shift toward predictive rather than reactive maintenance. The findings also indicate that the benefits extend across different stakeholder groups, from ship operators seeking more reliable performance, to ports and authorities aiming for more efficient inspection processes, and to technology providers refining monitoring systems that support regulatory readiness.

The evidence suggests that telemetry supports broader sectoral priorities related to safety, sustainability, and resilience. By reducing unnecessary component replacement, limiting unplanned failures, and improving the stability of onboard systems, digital

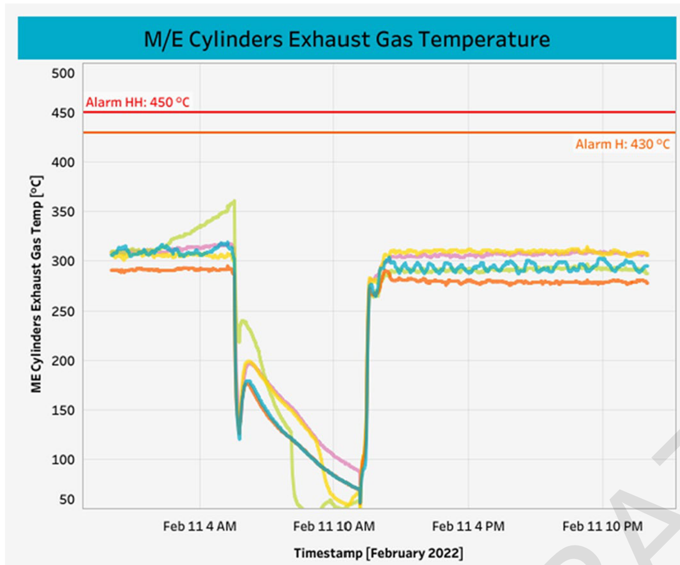


Fig. 7 Main engine cylinder exhaust gas temperatures recorded by the telemetry system, showing early detection of a rising temperature trend.*Source* Authors

monitoring contributes to more efficient resource use and strengthens the fleet's capacity to manage operational disruptions.

Overall, the study highlights the role of telemetry as a practical and effective component of maritime digitalization. While the analysis focuses on bulk carriers, the mechanisms identified are applicable to other vessel types, providing a foundation for further research and wider industry adoption.

Abbreviations

AI	Artificial Intelligence
N	Number
PSC	Port State Control
p-value	Probability Value
SD	Standard Deviation
SE	Standard Error
TOE	Technology-Organization-Environment
W	Shapiro-Wilk test statistic

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Author contributions
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Availability of data and materials
The data used in this study include confidential operational records and therefore cannot be publicly shared. Aggregated or anonymized data may be made available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
This study did not involve human or animal experiments requiring formal ethics committee approval. Informed consent was obtained from all individual participants involved in the study.

Consent for publication
All authors give their consent for the publication of identifiable details that may appear in the manuscript, provided that these are relevant to the study and essential for its understanding.

Competing interests

The authors declare that they have no competing interests relevant to the content of this article.

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References

Al Hanbali A, Saleh H, Alsawafy O, Attia A, Ghaithan A, Mohammed A (2022) Spare parts supply with incoming quality control and inspection errors in condition-based maintenance. Computers Ind Eng 172:108534. https://doi.org/10.1016/j.cie.2022.108534

Ametepey S, Aigbavboa C, Addy H, Thwala W (2024) A bibliometric review of the trends of construction digitalization research in the past ten years. Buildings 14(9):2729. https://doi.org/10.3390/buildings14092729

Bukar U, Sayeed M, Amodu O, Razak S, Yogarayan S, Othman M (2025) Leveraging VOSviewer approach for mapping, visualization, and interpretation of crisis data for disaster management and decision-making. Int J Inf Manage Data Insights 5(1):1003145. https://doi.org/10.1016/j.jjimei.2024.10031

Cao Y, Wang X, Yang Z, Wang J, Wang H, Liu Z (2023) Research in marine accidents: a bibliometric analysis, systematic review and future directions. Ocean Eng 284:115048. https://doi.org/10.1016/j.oceaneng.2023.115048

Cariou P, Wolff F (2015) Identifying substandard vessels through port state control inspections: a new methodology for concentrated inspection campaigns. Mar Policy 60:27–39. https://doi.org/10.1016/j.marpol.2015.05.013

Cirillo V, Evangelista R, Guarascio D, Sostero M (2021) Digitalization, routineness and employment: an exploration on Italian task-based data. Res Policy 50(7):104079. https://doi.org/10.1016/j.respol.2020.104079

Dabbous A, Barakat K, Krau S (2023) The impact of digitalization on entrepreneurial activity and sustainable competitiveness: a panel data analysis. Technol Soc 73:102224. https://doi.org/10.1016/j.techsoc.2023.102224

Dagkinis I, Psomas P, Platis P, Dragović B, Nikitakos N (2023) Modelling of the availability for the ship integrated control system sensors. Cleaner Logist Supply Chain 9:100119. https://doi.org/10.1016/j.clscn.2023.100119

Dastjerdy B, Saeidi A, Heidarzadeh S (2023) Review of applicable outlier detection methods to treat geomechanical data. Geotechnics 3(2):375–396. https://doi.org/10.3390/geotechnics3020022

Dereci U, Tuzkaya G (2024) An explainable artificial intelligence model for predictive maintenance and spare parts optimization. Supply Chain Analytics 8:100078. https://doi.org/10.1016/j.sca.2024.100078

Elsisi M, Amer M, Su C, Aljohani T, Ali M, Sharawy M (2025) A comprehensive review of machine learning and Internet of Things integrations for emission monitoring and resilient sustainable energy management of ships in port areas. Renew Sustain Energy Rev 218:115843. https://doi.org/10.1016/j.rser.2025.115843

Fadiga A, Ferreira L, Bigotte J (2024) Decarbonising maritime ports: a systematic review of the literature and insights for new research opportunities. J Clean Prod 452:142209. https://doi.org/10.1016/j.jclepro.2024.142209

Fan L, Zhang M, Yin J, Zhang J (2022) Impacts of dynamic inspection records on port state control efficiency using Bayesian network analysis. Reliab Eng Syst Saf 228:108753. https://doi.org/10.1016/j.ress.2022.108753

Farzadmehr M, Carlan V, Vanelslander T (2025) AI project portfolio ranking in port and maritime industries: a novel framework for assessing deployment complexity. Transp Eng 21:100370. https://doi.org/10.1016/j.treng.2025.100370

Garg N, Neeraj C, Priyanka D (2025) Digital technologies' impacts on alleviation of poverty: a bibliometric review. J Strateg Manag 18(1):205–223. https://doi.org/10.1108/JSMA-07-2023-0195

Gong C, Riviere V (2021) Developing a unified definition of digital transformation. Technovation 102:102217. https://doi.org/10.1016/j.technovation.2020.102217

Gursel E, Madadi M, Coble J, Agarwal V, Yadav V, Boring R, Khojandi A (2025) The role of AI in detecting and mitigating human errors in safety-critical industries: a review. Reliab Eng Syst Saf 256:110682. https://doi.org/10.1016/j.ress.2024.11068

Ichimura Y, Dalaklis D, Kitada M, Christodoulou A (2022) Shipping in the era of digitalization: mapping the future strategic plans of major maritime commercial actors. Digital Business 2(1):100022. https://doi.org/10.1016/j.digbus.2022.100022

Jalali M, Tei A (2025) Maritime technology attention trends: buzzwords, stability, and emerging patterns. Environ Innov Soc Trans 57:101035. https://doi.org/10.1016/j.eist.2025.101035

Jović M, Tijan E, Vidmar D, Pucihar A (2022) Factors of digital transformation in the maritime transport sector. Sustainability 14(15):9776. https://doi.org/10.3390/su14159776

Kara G (2022) Determination of maritime safety performance of flag states based on the port state control inspections using TOPSIS. Mar Policy 143:105156. https://doi.org/10.1016/j.marpol.2022.105156

Karatuğ C, Arslanoğlu Y, Guedes Soares C (2023) Design of a decision support system to achieve condition-based maintenance in ship machinery systems. Ocean Eng 281(1):114611. https://doi.org/10.1016/j.oceaneng.2023.114611

Kuo H, Chen T, Yang C (2022) The effects of institutional pressures on shipping digital transformation in Taiwan. Marit Bus Rev 7(2):175–191. https://doi.org/10.1108/MABR-04-2021-0030

Langenberg B, Janczyk M, Koob V, Kliegl R, Mayer A (2023) A tutorial on using the paired t test for power calculations in repeated measures ANOVA with interactions. Behav Res Methods 55:2467–2484. https://doi.org/10.3758/s13428-022-01902-8

Liang Q, Knutsen K, Vanem E, Aesoy V, Zhang H (2024) A review of maritime equipment prognostics health management from a classification society perspective. Ocean Eng 301:117619. https://doi.org/10.1016/j.oceaneng.2024.117619

Lin B, Dong X (2023) Ship hull inspection: a survey". Ocean Eng 289:116281. https://doi.org/10.1016/j.oceaneng.2023.116281

Liu C, Zheng P, Xu X (2021) Digitalisation and servitisation of machine tools in the era of Industry 4.0: a review. Int J Prod Res 61(12):1–33. https://doi.org/10.1080/00207543.2021.1969462

Lopes L, Nabais J, Pinto C, Caldeirinha V, Pinho T (2025) Essential competencies in maritime and port logistics: a study on the current needs of the sector. Sustainability 17(6):2378. https://doi.org/10.3390/su17062378

Ma L, Ma X, Wang T, Chen L, Lan H (2024) On the development and measurement of human factors complex network for maritime accidents: a case of ship groundings. Ocean Coast Manag 248:106954. https://doi.org/10.1016/j.ocecoaman.2023.106954

Monter-Pozos A, Gonzalez-Estrada E (2024) On testing the skew normal distribution by using Shapiro-Wilk test. J Comput Appl Math 440:115649. https://doi.org/10.1016/j.cam.2023.115649
Mouschoutzi M, Ponis S (2022) A comprehensive literature review on spare parts logistics management in the maritime industry. Asian J Shipp Logist 38:71–83. https://doi.org/10.1016/j.ajsl.2021.12.003
Nguyen T (2024) Investigating driving factors of digital transformation in maritime enterprises: TOE framework based. SAGE Open 14(4). https://doi.org/10.1177/21582440241301 21
Niu Y, Fan Y, Ju X (2024) Critical review on data-driven approaches for learning from accidents: comparative analysis and future research. Saf Sci 171:106381. https://doi.org/10.1016/j.ssci.2023.106381
Peng P, Xie X, Claramunt C, Lu F, Gong F, Yan R (2025) Bibliometric analysis of maritime cybersecurity: research status, focus, and perspectives. Transp Res Part E 195:103971. https://doi.org/10.1016/j.tre.2025.103971
Proksch D, Rosin A, Stubner S, Pinkwart A (2021) The influence of a digital strategy on the digitalization of new ventures: the mediating effect of digital capabilities and a digital culture. J Small Bus Manag 62(1):1–29. https://doi.org/10.1080/00472778.2021.1883036
Puisa R, McNay J, Montewka J (2021) Maritime safety: prevention versus mitigation? Saf Sci 136:105151. https://doi.org/10.1016/j.ssci.2020.105151
Sanlier S (2020) Analysis of port state control inspection data: the Black Sea Region. Mar Policy 112:103757. https://doi.org/10.1016/j.marpol.2019.103757
Senarak C (2024) Port cyberattacks from 2011 to 2023: a literature review and discussion of selected cases. Marit Econ Logist 26:105–130. https://doi.org/10.1057/s41278-023-00276-8
Tombak M, Zetterman B, Tapaninen U (2025) Cybersecurity risks at port. Transp Telecommun 26(3):276–291. https://doi.org/10.2478/ttj-2025-0021
Wang M, Wang Y, Feng C (2025) Artificial intelligence, institutional environment, and corporate green transformation: evidence from China's resource-based sector. Int Rev Econ Finance 103:104473. https://doi.org/10.1016/j.iref.2025.104473
Wang S, Yan R, Qu X (2019) Development of a non-parametric classifier: effective identification, algorithm, and applications in port state control for maritime transportation. Transp Res Part B 128:129–157. https://doi.org/10.1016/j.trb.2019.07.017
Xu J, Yu Y, Zhang M, Zhang J (2023) Impacts of digital transformation on eco-innovation and sustainable performance: evidence from Chinese manufacturing companies. J Clean Prod 393:136278. https://doi.org/10.1016/j.jclepro.2023.136278
Yan R, Wang S, Cao J, Sun D (2021) Shipping domain knowledge informed prediction and optimization in Port State Control. Transp Res Part B 149:52–78. https://doi.org/10.1016/j.trb.2021.05.003
Yang K, Yang T, Yao Y, Fan S (2021) A transfer learning-based convolutional neural network and its novel application in ship spare-parts classification. Ocean Coast Manag 215:105971. https://doi.org/10.1016/j.ocecoaman.2021.105971
Yang Z, Yu Z, Yang Z, Wan C (2024) A data-driven Bayesian model for evaluating the duration of detention of ships in PSC inspections. Transp Res Part E Logist Transp Rev 181:103371. https://doi.org/10.1016/j.tre.2023.103371
Yang Z, Wan C, Yu Q, Yin J, Yang Z (2023) A machine learning-based Bayesian model for predicting the duration of ship detention in PSC inspection. Transp Res Part E 180:103331. https://doi.org/10.1016/j.tre.2023.103331
Yang Z, Yang Z, Yin J, Qu Z (2018) A risk-based game model for rational inspections in port state control. Transp Res Part B 118:477–495. https://doi.org/10.1016/j.tre.2018.08.001
Zeng F, Chen A, Xu S, Chan H, Li Y (2025) Digitalization in the maritime logistics industry: a systematic literature review of enablers and barriers. J Mar Sci Eng 13(4):797. https://doi.org/10.3390/jmse13040797
Zhang M, Taimuri G, Zhang J, Zhang D, Yan X, Kujala P, Hirdaris S (2025) Systems driven intelligent decision support methods for ship collision and grounding prevention: present status, possible solutions, and challenges. Reliab Eng Syst Saf 253:110489. https://doi.org/10.1016/j.ress.2024.110489
Zhang M, Tsoulakos N, Kujala P, Hirdaris S (2024) A deep learning method for the prediction of ship fuel consumption in real operational conditions". Eng Appl Artif Intell 130:107425. https://doi.org/10.1016/j.engappai.2023.107425
Zonta T, Da Costa C, Da Rosa Righi R, De Lima M, Da Trindade E, Li G (2020) Predictive maintenance in the Industry 4.0: a systematic literature review. Computers Ind Eng 150:106889. https://doi.org/10.1016/j.cie.2020.106889

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