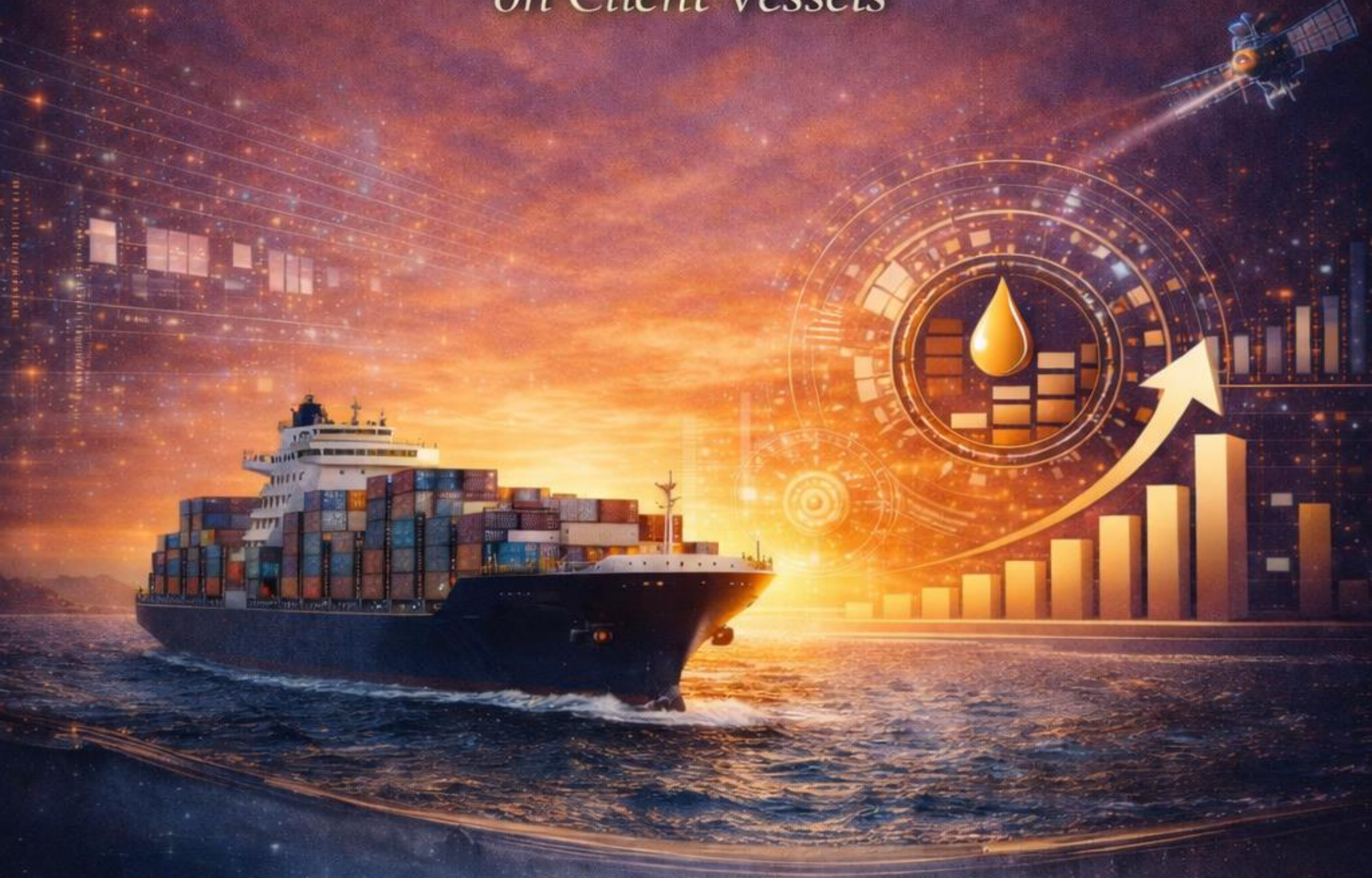
MONOGRAPH

Digitalization of Technical Operations

Implementation of Electronic Checklists, Remote Monitoring, and Fuel Data Analytics on Client Vessels



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Digitalization of Technical Operations:

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Abstract. In the context of profound structural transformation of the maritime industry driven by the implementation of the Industry 4.0 concept and the consistent tightening of environmental requirements by the International Maritime Organization (IMO), the digital modernization of fleet technical operation processes becomes strategically critical and becomes a key prerequisite for maintaining the long-term competitiveness of shipping companies. The study focuses on assessing the effectiveness of integrating digital solutions across the full spectrum of operations: from the transition to electronic watchkeeping logs and intelligent checklists to the implementation of predictive analytics systems aimed at optimizing fuel efficiency and monitoring the technical condition of heat-exchange equipment. The methodological basis of the work relies on a system analysis of empirical data for 2024–2025, drawing on reports of leading classification societies (DNV, Lloyd’s Register), design and operational documentation from manufacturers of marine equipment, as well as a current corpus of scientific publications. Based on the analysis performed, it is substantiated that the transition from fragmented paper-based document management to integrated digital ecosystems makes it possible to reduce the number of human-factor-related errors by 70–80%, which fundamentally increases the reliability of technical operation procedures. It is shown that the use of machine learning (ML) algorithms for continuous monitoring of operating parameters of heat exchangers and separators provides the possibility of abandoning the traditional model of planned preventive maintenance (PPM) in favor of the condition-based maintenance (CBM) concept. Such a transformation of maintenance strategies leads to a reduction in total operating costs and a decrease in the vessel’s carbon footprint, ensuring alignment with regulatory requirements for the Carbon Intensity Indicator (CII) and the Energy Efficiency Existing Ship Index (EEXI). Particular emphasis is placed on the analysis of mandatory requirements for the digitalization of bunkering operations entering into force in Singapore in 2025, which establish a new global benchmark in the field of transparency, traceability, and verifiability of fuel operations and exert a catalytic influence on the formation of unified international standards for digital control of fuel logistics.

Keywords: Digitalization of shipping, electronic logs (eLogs), predictive maintenance (PdM), digital twins, fuel efficiency, mass flow meters (MFM), heat exchangers, machine learning, decarbonization, IMO, CII, human factor.

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Introduction

Global shipping has entered a phase of unprecedented structural transformation driven by the so-called twin transition, combining accelerated digitalization and decarbonization. According to the Global Maritime Trends Barometer 2025 report, even with visible progress, the current trajectory of industry development remains insufficient to achieve the net-zero emissions target by 2050 [1]. Given that more than 80% of global trade is carried by sea, the effectiveness of managing vessel and infrastructure assets attains the status of a critical parameter not only for the economic profitability of shipping companies but also for the resilience of global supply chains [2].

The traditional model of fleet technical management, based on disparate paper reports, periodic crew submissions, and rigidly fixed calendar maintenance schedules, demonstrates its limitations under new regulatory requirements. The indices of energy efficiency of existing ships (EEXI) and carbon intensity (CII) introduced by the International Maritime Organization form a demand not merely for formal reporting, but for continuous optimization of vessel operational profiles on the basis of high-frequency data and analytics. The DNV Maritime Forecast to 2050 emphasizes that the service life and commercial attractiveness of vessels increasingly depend not on the physical characteristics of the hull and propulsion plant, but on the ability of management to build effective data governance, predictive analytics, and emissions metrics [2].

At the core of contemporary technical operation lies the phenomenon of island automation. Shipboard systems, from main engines to separators and boilers, generate significant volumes of telemetric information that often remain confined within local control loops or are manually duplicated into spreadsheet editors (Excel), which inevitably leads to an increase in errors, delays in decision-making, and a reduction in the responsiveness of technical management [2]. Fragmentation manifests at several interrelated levels. At the operational level, crews are forced to expend substantial time resources filling in paper logs and forms, which distracts from core duties and increases the risk of administrative errors that may entail penalty sanctions from Port State Control (PSC) [3]. At the technical level, monitoring of critical equipment, including heat exchangers, often relies on indirect diagnostic indicators (temperature, pressure) that do not always adequately reflect the degree of fouling or wear, creating prerequisites either for premature maintenance or for emergency failures [5]. At the commercial level, the absence of transparent and verifiable data on bunkering and the actual fuel quality forms a basis for commercial disputes and leads to irrational expenditure of financial resources [7].

Under these conditions, an objective need is emerging to develop and implement an integrated digital platform for technical operation for the fleet of a specific shipowner.

The purpose of the study is to substantiate such a need and to propose a holistic strategy for digital transformation of operational processes. The study covers three interrelated domains: administrative digitalization, implying the implementation of electronic checklists and logs in order to minimize the influence of the human factor; fuel analytics, oriented toward a transition to end-to-end digital monitoring of fuel quality and quantity along the entire path from bunkering to injection into the cylinders; and predictive diagnostics, including the use of digital twins and machine learning methods to service heat-exchange equipment and separators according to the actual technical condition.

Scientific novelty lies in the fact that, for the first time, the work proposes and substantiates an end-to-end model of a digital ecosystem for the technical operation of a vessel, which integrates eLogs/smart checklists, remote monitoring, and predictive analytics of fuel and heat-exchange/separation equipment into a unified loop for managing risks, costs, and CII/EEXI indicators.

The author’s hypothesis is reduced to the assumption that if fragmented paper procedures and island automation are replaced by an integrated digital platform (eLogs + smart checklists + sensors/MFM + ML/digital twins), then it is possible simultaneously to reduce human-factor errors by 70–80% and to shift maintenance from PPM to CBM/PdM, which results in a measurable decrease in OPEX and carbon intensity while concurrently reducing commercial disputes related to bunkering.

Materials and Methods

The study is based on a comprehensive analysis of industry reports, technical standards, and peer-reviewed scientific publications for the period 2024–2025. As the primary empirical and regulatory framework, materials from leading classification societies (Lloyd's Register, DNV, ABS), the analytical agencies Riviera Maritime and Maritime Gateway, as well as articles from the scientific journals IEEE Access, MDPI Energies, and the Springer publishing house were used. The key dataset includes statistics on the implementation of electronic logs and a detailed analysis of the causes of human errors in maintaining operational documentation [3]; technical regulations of the Maritime and Port Authority of Singapore (MPA) related to digital bunkering and the SS 648 standard defining requirements for the measurement and verification of fuel operations [7]; results of experimental studies on the application of machine learning algorithms for forecasting heat-exchanger fouling and optimizing separator operating modes [10]; as well as economic assessments of losses caused by heat-exchange equipment fouling performed within the framework of fouling cost analysis [6]. The combined use of these sources provides both a regulatory-legal and a techno-economic foundation for subsequent modeling and substantiation of the proposed solutions.

The methodological framework of the study is of a combined nature and integrates several analytical approaches. Comparative analysis is used to compare traditional analog operating methods and digital solutions according to the criteria of labor intensity, data accuracy and completeness, as well as total life cycle cost

(Life Cycle Cost, LCC), which makes it possible to quantify the effect of digitalization. Data-driven modeling is applied to analyze the applicability of artificial intelligence algorithms, including long short-term memory (LSTM) neural networks and multilayer perceptrons (MLP), to the task of predicting the remaining useful life (RUL) of equipment and developing predictive maintenance strategies. In addition, causal analysis is used based on J. Reason’s Swiss cheese model, which makes it possible to assess how the implementation of digital checklists and regulated electronic procedures contributes to reducing the probability of emergency incidents by decreasing the number of organizational and human errors that accumulate unnoticed. Such a methodological synthesis provides the necessary depth of consideration of both technical and behavioral aspects of the digital transformation of the technical operation of vessels.

Results and Discussion

The human factor continues to remain the dominant cause of accidents at sea: according to Allianz Global Corporate & Specialty and a number of other studies, from 75% to 96% of marine incidents are to some extent attributable to personnel errors [13]. Administrative control instruments, which conceptually are intended to act as a protective barrier, traditional paper logs and checklists, in practice often degrade into a formal procedure of the tick-box exercise type and cease to perform the function of a real risk management mechanism.

An analysis of surveys conducted by ABS Wavesight and other organizations demonstrates systemic limitations of paper media. More than half of respondents (51%) indicate incompleteness or absence of part of the records, 49% note their inaccuracy, and 42% encounter illegibility of handwritten text [3]. Additionally, 48% of respondents report cases of loss or damage of logs, which, under conditions of tightening inspections by supervisory authorities, creates direct risks of vessel detention in port. A substantial consequence is also the growth of administrative burden: 62% of chief engineers note that completion of paper reporting takes a disproportionately large amount of time and distracts from immediate maintenance tasks [3].

These qualitative deficiencies are transformed into direct financial losses. Approximately 60% of companies have faced vessel delays in ports for reasons associated with non-conformities or problems in logkeeping, and 49% have faced penalties [4]. Particularly indicative is the contrast between organizations fully dependent on paper and users of digital solutions: in the first group, 88% of respondents report delays in ports, whereas among companies that have implemented electronic systems, similar cases are recorded significantly less frequently [4]. Thus, the paper document management model acts not only as a source of operational inefficiency, but also as a factor increasing regulatory and commercial risks.

Against this background, the digitalization of reporting is moving from an experimental stage to a phase of large-scale implementation. In the period 2024–2025, 72% of maritime organizations already use electronic logs (eLogs) in one format or another; however, a complete abandonment of paper has been implemented in only 28% of companies [3]. At the same time, the highest degree of maturity is demonstrated by management companies, among which the share of fully digitalized processes reaches 48%, whereas among traditional shipowners the same indicator is only 23% [3]. This asymmetry reflects differences in institutional readiness to adopt digital technologies and in the priorities of management models.

Modern eLogs systems (including NAVTOR, NAPA, ABS solutions) are not merely electronic analogues of paper forms, but integrated intelligent platforms. An important element of their architecture is input data validation: the entered parameters are automatically checked for compliance with permissible ranges (for example, exhaust gas temperature, GPS coordinates, or operating mode values), which reduces the probability of input errors; this advantage is noted by 37% of users [3]. An equally critical functional requirement, cited by 64% of operating organizations, is the capability for instant replication of data ashore, providing technical departments with access to a single version of truth and enabling rapid detection and analysis of anomalies [3]. Integration of eLogs with navigation and automated control systems results in up to 50–60% of fields being populated automatically (coordinates, engine revolutions, weather parameters), which radically reduces the volume of routine operations and frees crew resources for core tasks.

When transitioning from logs to checklists, the functional role of digital instruments also shifts. If logs primarily record events that have already occurred, then checklists are oriented toward incident prevention. In digital form, checklists cease to be static lists of actions and become dynamic safety algorithms, ensuring sequential execution of critical procedures, elimination of omissions, and increased reproducibility of operations. In this way, smart checklists form an active risk management loop, embedding into the overall digital ecosystem of technical operation and strengthening its preventive component (see Table 1).

Table 1. Comparison of functional capabilities of traditional and digital control instruments (compiled by the author based on [3-7]).

Characteristic	Paper checklist	Digital smart checklist
Relevance	Often outdated versions of forms	Instant fleet-wide updating from the office
Execution control	Possibility to tick boxes retroactively	Timestamps at each step
Evidentiary basis	Signature only	Photo/video documentation of the condition of components
Analytics	Data are dead, stored in folders	Automated analysis of trends and bottlenecks

Table 2 summarizes the effects discussed above into a single KPI framework. This consolidation is required because the benefits of eLogs/checklists, digital bunkering, and PdM for thermal and separation equipment are often evaluated separately, while in practice they act as coupled layers of the same risk–cost–compliance loop. The matrix also highlights the key trade-off: integration increases value but expands the cyberattack surface, making security controls a necessary condition for sustaining the operational gains.

Table 2. Consolidated KPI matrix of digitalization effects across technical operation domains (compiled by the author based on [3–7; 10–12; 19, 25]).

Domain / process	Baseline issue (paper / island automation)	Digital enabler	KPI / metric	Reported / estimated effect (from cited sources in text)	Operational implication
Logkeeping & reporting compliance	Incomplete/inaccurate/illegible records; lost logs; high admin load	eLogs + auto-population + validation + shore replication	Data completeness/accuracy; admin time	51% incomplete, 49% inaccurate, 42% illegible, 48% lost/damaged; senior officers report admin burden (62% C/E) — motivation for digital shift	Lower PSC/ISM non-conformities, faster audits, fewer detentions/penalties
Port risk (PSC, delays, penalties)	Delays and penalties linked to logkeeping non-conformities	eLogs + traceability + “single source of truth”	Share of companies experiencing port delays/penalties	~60% delays; ~49% penalties; 88% delays in “paper-dependent” group vs markedly lower among digital users	Reduced off-hire/port costs; improved compliance readiness

Checklist execution quality	“Tick-box exercise”, retroactive ticks, weak evidence	Smart checklist with timestamps + photo/video + logical constraints	Procedure compliance; omission rate; evidence quality	Digital checklists prevent retroactive completion; timestamps and media evidence strengthen audit trail	Lower human-factor incidents; higher reproducibility of critical procedures
Bunkering transparency & disputes	Non-verifiable quantity/quality; dispute risk	e-BDN + MFM + real-time data capture	Measurement accuracy; dispute frequency proxy	MFM mass measurement error <0.5%; mandatory e-BDN in Singapore from 1 Apr 2025	Reduced quantity disputes; improved trust/traceability
Bunkering admin efficiency (port ecosystem)	Manual paperwork overhead	Digital bunkering platform	Admin labor	Up to ~40,000 person-days/year saved at Port of Singapore scale	Faster turnaround, lower transaction friction
Separation efficiency; oil losses; sludge volume	Fixed-throughput logic inefficient at low loads; timer-based desludging losses	Flow optimization + ML-based desludging triggers	Separation efficiency; oil losses; sludge volume	ML/CFD models show predictive capability (e.g., $R^2 \approx 0.74+$ in cited study context) enabling condition–triggered cycles	Better cat-fine removal, lower abrasion risk, less recoverable fuel loss
Heat exchanger fouling detection	ΔT/ΔP ambiguous under varying load/seawater temp	Digital twin + real-time Rf estimation	Early warning lead time; fuel penalty reduction	Fouling can drive up to ~3% fuel consumption increase; DL models report high classification accuracy (e.g., 0.9942 in cited study context)	Shift to PdM; avoid slowdowns; schedule cleanings economically
Maintenance strategy	Calendar PPM causes over/under-maintenance	CBM/PdM with ML + twin	Unplanned downtime; maintenance cost	PdM enables earlier warnings (reported up to months, incl. “up to nine” in platform use-case)	Lower failure probability, fewer emergency repairs

Integrated ecosystem	Fragmented subsystems; weak cross-correlation discovery	Data lake + event linking + workflow triggers	Decision latency; root-cause quality	Qualitative: enables intersystem correlation discovery and automated work request creation	Faster diagnosis, more consistent risk/cost control
Cyber resilience (trade-off)	OT connectivity increases attack surface	Security-by-default (gateways, auth, segmentation)	Residual risk management in SMS	Must align with IMO cyber risk management requirements	Reduces likelihood of data tampering / unsafe remote influence

Studies in adjacent highly regulated domains, such as medicine and aviation, demonstrate that the transition from paper procedures to digital checklists leads to a substantial increase in compliance with regulations and a decrease in the probability of omitting critically important operations [16]. In the maritime industry, the use of electronic checklists on wearable devices (tablets, smartphones) applied directly in the vicinity of the equipment rather than at a central control station ensures more accurate and context-linked execution of inspection procedures and, as a consequence, an improvement in the quality of technical inspections [17]. An additional advantage is the possibility of implementing the principle of foolproofing: software-logical constraints do not allow completion of the engine start-up preparation checklist until normal values of key parameters have been confirmed, for example oil pressure or the position of the turning gear [18].

The fuel segment in the structure of a vessel's operating costs remains dominant, accounting for up to 50–60% of operating expenses. Digital transformation in this area covers the entire value chain, from fuel procurement and acceptance to its preparation, purification, and subsequent conversion into useful mechanical or electrical energy. A characteristic example is regulatory and technological development in the bunkering sector. From 1 April 2025, Singapore, the world's largest bunkering hub, introduces mandatory use of electronic bunker delivery notes (e-BDN) for all fuel supply operations [7]. This measure, based on the SS 648 and SS 709 standards, effectively concludes the era of paper-based document circulation and significantly limits opportunities to apply non-transparent schemes during bunkering.

The technological core of the new system is constituted by Coriolis mass flow meters (MFM). Unlike traditional volumetric measurements that are sensitive to temperature variations and fuel aeration effects, MFM record mass directly with an error of less than 0.5%. The integration of such flow meters with digital platforms forms a transparent measurement loop: the bunkering profile, flow rate, density, and temperature are recorded and transmitted in real time, and any attempt at external interference (for example, the use of magnets) leaves a digital trace and is subject to subsequent analysis. Increasing the degree of document workflow automation at the scale of the Port of Singapore makes it possible to save up to 40,000 person-days per year [7]. In addition, reducing the verification frequency of flow meters from two to one time per year, driven by the high reliability of digital monitoring and data traceability, yields industry savings on the order of 300,000 United States dollars annually [19]. For a shipowner, implementing comparable solutions on the receiving manifolds of its own vessels, including regions outside Singapore, practically eliminates quantitative disputes during bunkering and increases assurance of the actual receipt of the paid fuel volume.

The transition of the global fleet to very low sulfur fuel oil (VLSFO) and the growing share of biofuels are accompanied by increased variability of fuel operational characteristics, including viscosity, density, and compatibility parameters. Traditional viscosity control systems often prove insufficiently sensitive to dynamic changes in the properties of blended fuels. Modern intelligent viscometers (for example, Viscomaster, Rivertrace Smart Visco) provide measurement not only of kinematic but also of dynamic viscosity, as well as density, directly in the flow at high operating temperatures [20]. Integrating data from these sensors with engine operating parameters forms the basis for predictive analytics of combustion processes. In such systems, the Calculated Carbon Aromaticity Index (CCAI) can be computed in real time, which makes it possible to identify fuel with unsatisfactory ignitability indicators in a timely manner before the onset of detonation phenomena or thermal overloads. At the same time, maintaining viscosity within a narrow optimal range, typically 10–15 cSt, contributes to the formation of a favorable spray structure, increases combustion completeness, and reduces specific fuel oil consumption (Specific Fuel Oil Consumption, SFOC) [22].

A key element of protecting a ship power plant from contaminated fuel remains fuel separators. At the same time, the traditional operating mode, assuming operation at a fixed throughput calculated for 100% engine load, proves inefficient under sustained operation at reduced regimes. Dynamic flow optimization technology, implementing automatic adjustment of fuel supply through separators in accordance with current engine consumption, makes it possible to increase the residence time of fuel in the zone of centrifugal forces, which qualitatively improves the removal of catalytic fines, the main abrasive factor that accelerates destruction of the cylinder-piston group [23]. Additional application of machine learning methods to vibration and turbidity data makes it possible to optimize sludge discharge cycles. Instead of timer-based regulation (for example, every 2 hours), which often leads to the discharge of a significant volume of fuel that has not yet been fully purified together with the sludge, algorithms initiate desludging upon the actual accumulation of sediment. It has been shown that neural network models can predict the efficiency of the separation process with a coefficient of determination on the order of R2 ≈ 0.74 and higher, which makes it possible simultaneously to reduce oil losses and decrease the volume of sludge sent for disposal [11].

Heat exchanger fouling constitutes a latent but significant driver of increased operating costs of power systems. Estimates indicate that total losses from fouling of heat-exchange equipment can reach approximately 0.25% of gross domestic product in industrially developed countries [6]. For marine vessels, this manifests as an increase in fuel consumption of up to 3% due to increased back pressure and degradation of thermodynamic cycle parameters, in particular in the case of deterioration of charge air cooling, as well as an increase in costs for maintenance and cleaning, including the use of chemical reagents and labor costs for dismantling apparatuses, and also in the risk of forced power reduction (slow down) when limit temperature setpoints are reached [12]. At the same time, the traditional approach to monitoring based on controlling temperature differences (ΔT) and pressure drops (ΔP) often leads to incorrect conclusions because changes in these parameters may be caused by changes in engine load or seawater temperature rather than by fouling itself.

One of the most effective tools for solving this diagnostic task is the application of thermodynamic digital twins of heat-exchange equipment. A digital twin in this context is a physical-mathematical model that calculates the expected behavior of a clean heat exchanger under current boundary conditions, namely coolant flow rates and inlet temperatures [25]. The primary diagnostic parameter is the fouling thermal resistance coefficient Rf, computed in real time according to the expression

$$R_f(t) = 1/U_{actual}(t) - 1/U_{clean}(t) \quad (1),$$

where Uactual is the actual heat transfer coefficient determined on the basis of current measurements, and Uclean is the reference value specified by the digital twin model [24, 26]. This approach makes it possible to detect degradation of heat-transfer surfaces at early stages, when control temperatures have not yet reached emergency setpoints, and, consequently, to plan interventions before critical states occur.

Contemporary research works show that deep learning methods demonstrate substantial superiority over simple regression models in predicting the condition of plate heat exchangers [10, 21]. Hybrid architectures combining a multilayer perceptron (MLP) and long short-term memory (LSTM) recurrent networks are capable of accounting for the inertia of thermal processes and complex nonlinear relationships among parameters. In one study, the MLP+LSTM hybrid model achieved a condition classification accuracy at the level of 0.9942 [10, 15]. Training the model on time series of operational data (temperatures, pressures, flow rates) makes it possible to predict the time of reaching a critical fouling level weeks before the actual occurrence of the event. This creates a basis for implementing a maintenance strategy according to technical condition (Predictive Maintenance, PdM), when cleaning of heat exchangers, from sea chests to central coolers, is planned precisely in those intervals when it is economically justified, while simultaneously preventing both excessive interventions (dismantling an apparatus that is practically clean) and prolonged operation in an inefficient mode. The integration of such models into fleet management platforms, such as XMPro iBOS, makes it possible to generate warning signals about the probability of failure months, up to nine, before a potential incident [25]. Figure 1 below presents a framework that links electronic logbooks and intelligent checklists with sensor telemetry (including fuel cell and fuel condition monitoring), analytics (machine learning and digital twins) and automated maintenance workflows within an SMS-aligned cyber-monitoring framework.

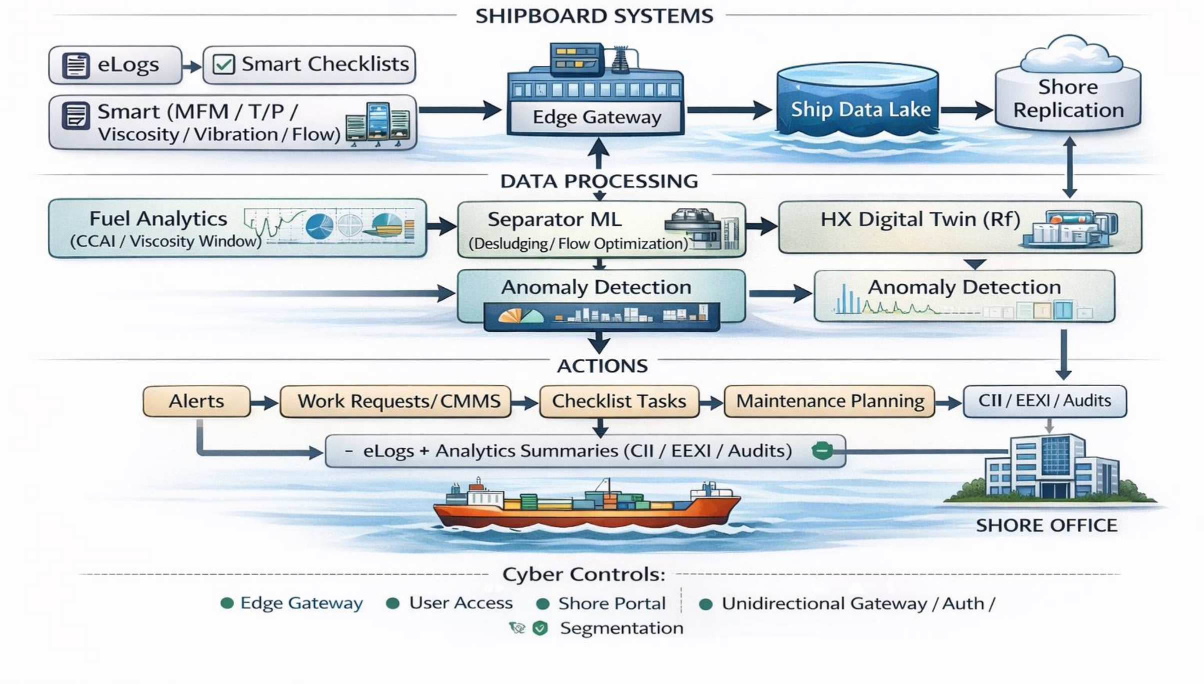

Fig.1. End-to-end integrated digital ecosystem for vessel technical operations (author's model)

Further improvement of the effectiveness of digitalization of ship technical systems is possible only by overcoming fragmentation of individual subsystems and forming a unified information loop. Data from electronic ship logs recording, for example, a switch to heavy fuel oil should be used automatically when interpreting separator monitoring signals (increased vibration), and the results of predictive analytics of heat exchanger condition should initiate the creation of corresponding work requests in the digital checklist system. The creation of a single data lake makes it possible to identify hidden intersystem correlations. Thus, persistent exceedance of fuel temperatures recorded by intelligent viscometers may correlate with accelerated fouling of heaters according to the digital twin data, which indicates incorrect operation of the steam supply regulator and is practically not detectable under separate analysis of these subsystems [8, 9].

At the same time, as the degree of integration increases, the cyberattack surface inevitably expands. Increased connectivity of ship systems makes operational technology (OT) a potential target for malicious actors. Compromise of a monitoring system may lead to substitution of data on the condition of mechanisms, masking of real problems, or, in the extreme case, remote influence on critically important systems, including their forced shutdown [14, 27]. In accordance with IMO resolution MSC.428(98), cyber risks are subject to management within the existing Safety Management System (SMS), and contemporary digital solutions must be designed in the security-by-default paradigm. This implies the use of unidirectional gateways when transmitting data ashore, strict user authentication mechanisms when working with electronic checklists, and other embedded measures to ensure the cyber resilience of shipboard information and control systems [28].

Conclusion

The digital transformation of fleet technical operation has lost the status of a futurological scenario and has moved into the category of an objective production necessity for operators oriented toward compliance with the regulatory and market requirements of the 2025 horizon. The results of the study demonstrate that the formation of a comprehensive digital ecosystem provides a quantitatively measurable effect across all key aspects of the functioning of shipboard and shore-based services.

Within the administrative domain, the replacement of paper ship logs and traditional checklists with intelligent electronic log systems (eLogs) and smart checklists leads not only to a reduction in time expenditure of senior officers by up to 50%, but also to a decrease in the risk of operational delays and penalty sanctions through the creation of a transparent, continuous digital trace of all regulated actions. In the field of fuel management, the integration of mass flow meters with predictive analytics of fuel quality and characteristics makes it possible to minimize commercial losses at the bunkering stage, optimize the combustion process, and, as a consequence, reduce the carbon burden generated by vessel operation. The application of digital twins and machine learning algorithms, in particular LSTM and MLP architectures, for diagnostics of heat-exchange equipment and fuel separators ensures a transition to a full-scale condition-based maintenance concept, which makes it possible to prevent emergency downtime and reduce total operating costs by approximately 15–20%.

At the same time, the effectiveness of digitalization is determined not only by the level of deployed technologies. The key limiting factor remains the integration of disparate data sets into a unified platform for decision-support and automation, as well as the provision of an adequate level of cyber resilience. For a shipping company, strategic fleet modernization programs should include not only the installation of sensor systems and specialized software, but also targeted investments in the development of personnel competencies and the adaptation of existing management processes to new digital models of organizing technical operation.

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