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Article

Systematic Approach to Ergatic Systems Risk Management in Maritime Operations

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Abstract: The article explores risk management in maritime energy systems, where technical, human, and organizational factors interplay. Its goal is to create a systematic risk assessment and management framework that includes analyzing degradation and stochastic failures through Markov processes. The approach formalizes ergatic systems as stochastic models with transition probabilities among states, allowing for reliability assessment and critical failure identification. The paper combines analytical methods and modeling to build transition matrices, identify key risk indicators, and analyze how external factors influence the model. The findings demonstrate that the proposed approach not only facilitates the identification of the most vulnerable components of the system but also provides a foundational basis for formulating practical recommendations aimed at optimizing maintenance and human factors management. The methodology presented herein can be applied to enhance maritime safety, raise standards for maritime operations, and inform risk management policies within the domain of maritime transportation.

Keywords: Systems-Based Risk Management; Maritime Transport; Human-Machine Interaction; Autonomous Systems; Automated Navigation; Port Infrastructure; Operational Safety; Adaptive Decision Support Systems

1. Introduction

Modern maritime operations operate in an environment of high technical complexity, a dynamic environment, and growing dependence on automated systems. A new challenge arises in this context - ensuring the reliability and safety of ergatic systems, i.e., complexes in which people, machines, and the environment interact as a single functional unit. Unlike the classic human-machine divide, ergatic systems have a nonlinear, multi-level nature of interactions, in which even minor failures can lead to critical consequences.

This is especially true in the maritime industry, where ergatic systems include the crew, automated ship subsystems, navigation environment, port infrastructure, and external regulatory and information circuits. The system is becoming open, dynamic, and probabilistic, requiring new risk analysis methods based not only on technical diagnostics but also on the operator's cognitive behavior, information interaction, and environmental influences.

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In this regard, a systematic approach to risk management that would cover all levels is needed: from probabilistic modeling and structural redundancy to digital decision support and regulatory updates. This need determines the purpose of this paper: to propose a methodology for integrated risk management in marine ergatic systems, taking into account practical, technical, cognitive, and regulatory factors.

The relevance of the study of ergatic systems is driven by the need to improve maritime operations' reliability, controllability, and safety in the face of growing technical, human, and environmental risks. A systematic approach allows for identifying critical points of interaction in such systems, assessing potential threats, and designing more sustainable control architectures.

Ergatic systems of maritime operations are the interaction of humans, technology, and organization under uncertainty, where failures in one layer generate risk cascades throughout the system. A systematic approach to risk management requires a combination of regulatory and data-driven methods, integration of human factors with reliability analytics, and alignment of tactical decisions with economic and geopolitical constraints. Below is a review of sources that build a logical dynamic from methodological foundations to practical implications for autonomous and traditional fleets.

A comparative analysis of the capabilities of HAZID/HAZOP, FTA, FMEA, and STPA for generating safety requirements forms a methodological “framework” for systematic risk management: from structural causality to functional-contextual hazards, suggesting when to choose deductive or scenario-based approaches in complex ergatic ship control circuits [1]. Next, attention shifts to joint human-machine learning: the authors use incident retrospectives as training samples for cooperative policies that strengthen the ability of crews and automated systems to adapt to new threats without losing situational awareness [2]. On this basis, the integration of STPA with Bayesian networks and influence diagrams provides a process for selecting economically feasible risk control measures for “advanced” operations, where decisions must simultaneously reduce risk and meet resource constraints [3].

At the same time, a sensor base for ergatic interfaces is emerging: flexible biosensors demonstrate how inexpensive, stable platforms can read the operator's physiological markers and subsequently become part of the HMI loop for early detection of fatigue or stress during navigation [4]. At the security architecture level for MASS, it is proposed to link STPA with the definition of the operational domain (ODD) so that the risk analysis initially corresponds to the limits of acceptable autonomy and scenario deviations from normal conditions [5]. In environments with severe constraints - the Arctic - scenario-based risk management requires a multi-layered description of hazards (ice, weather, SAR availability), a composition of barriers, and iterative model validation in politically and climatically unstable conditions [6]. This vector delves into the systemic risks of the port ecosystem: the new methodology assesses the interrelated risks between port subsystems (infrastructure, IT, logistics), addressing the failures of “point” approaches and strengthening preventive management [7].

For ergatic interfaces of autonomous ships, it is shown how human-centered risk assessment for shore-based control centers translates into HMI design requirements: from indicator layouts to acceptable operator workload [8]. This echoes the integrated framework for safety and efficiency in human-MASS interaction, which proposes to combine the perspectives of operational efficiency, navigation, and safety into a single decision-making cycle [9]. Practical bridge barriers are outlined through empirical observations by officers: information overload, heterogeneity of automation, and the lack of common mental models become systemic risk triggers [10]. The algorithmic component of this circuit is collision avoidance systems that consciously support human-machine cooperation without displacing the navigator from the loop [11].

In the cyber dimension, a set of countermeasures against attacks on maritime systems has been proposed, combining technical protocols, organizational procedures, and personnel training - a critical layer for ergatic systems, where IT breaches quickly become maritime incidents [12]. FRAM field studies in port (in conjunction with AIS analytics) shift the focus from “standard processes” to “real work,” allowing the identification of latent variations and bottlenecks in operations [13]. Offshore, piracy risks were formalized early on by Bayesian networks, which essentially set the standard for probabilistic modeling of attacks and countermeasure effects in environments with intelligent adversaries [14].

Next, the supply dimension: a survey in Nigerian ports records supply chain risk management practices, highlighting weaknesses in coordination and monitoring that are characteristic of developing ports [15]. The consequences of market “tail” freight risks for industrial issuers and transport companies show why financial volatility should be included in the strategic risk dashboards of shipping holdings [16]. From the perspective of environmental monitoring, the example of ML assessment of water and biota pollution risk demonstrates transfer approaches to datasets with temporal-spatial dependence and multi-sensor fusion - relevant for port ecosystems and water areas [17].

For MASS, a framework for assessing the state of systems with multicomponent degradation has been proposed at the technical level, combining diagnostics, forecasting, and decision-making, taking into account the dependencies between nodes [18]. The scenario-based methodology for risk assessment as the standard practice in extreme risk environments in [19]. The review of systemic risk in disaster management summarizes terminology, typologies of interrelationships, and assessment approaches, forming a “dictionary” for ports and fleets seeking integrated management maturity [20]. The repeated reference to human-centered risk assessment for the coastal interface emphasizes the consistency of the conclusions and their independence from the context of the publication [21].

A medical example of ML forecasting of implant complications demonstrates how risk classifiers with tabular data and time series are transferred to the prevention of equipment failures and human errors in the fleet [22]. Educational material on risk assessment in ship operations offers a generalized practical framework but is limited by peer review; therefore, it is best used as an introductory overview rather than a source of methodological innovation [23]. In [24], a model of the dynamics of the energy entropy of organizations is proposed, which allows assessing the sustainability of their functioning and identifying the risks of reducing management efficiency. A systematic review of hybrid risk analysis approaches for MASS confirms the advisability of combining STPA, FTA, BN, and ML in different phases of the decision life cycle [25].

Next come materials science and structural studies: material criteria for wind turbines clarify how material selection affects structural responses - a useful parallel for selecting materials for superstructures and deck structures [26]; comparisons of Ro-Ro strength losses in direct and oblique collisions provide input data for emergency strength scenarios [27], and extended assessments of emergency stability and safe limits in collisions form the basis for expert models of technical risk [28]. The theoretical contribution to the mathematical analysis of function classes, although far from the sea, is relevant as an example of rigorous work with “boundary” conditions and inclusions required to derive guaranteed estimates in models with inequalities and integral constraints [29].

At the level of expert assessment quality methodology, an approach has been developed for validating the risk assessment of ship operations through structured expert reviews - an important link for trust in models where data is limited [30]. Deck cargo safety concepts add practical provisions for slinging, stowage, and dynamic load control - a typical area of high-risk human-technical interaction [31].

The next step is to move on to a comprehensive analysis of hull strength and maintenance strategy, combining inspections, stress modeling, and repair planning into a single integrity maintenance cycle [32]. Ballast operations reveal the environmental risk layer and the need for a balance between compliance, operational availability, and navigational safety [33]. A multi-layered safety assessment model illustrates how the stratification of factors (human, technical, environmental) makes the contribution of each layer to the integral risk more transparent [34]. Assessing the navigator's condition and constructing “readiness” indicators introduce formal metrics of the psychophysiological component needed for warning systems and watch change protocols [35].

An algorithmic barrier against parametric roll demonstrates how stabilization automation can work as active risk control in abnormal wave conditions [36]. Optimization of the port's equipment fleet under unbalanced loads suggests how resource decisions affect operational risk nodes (queues, downtime, failures) [37]. The work [38] emphasizes the need for careful consideration of material properties and operating scenarios to minimize technical and operational risks, while the stability of tank containers on roll trailers during ferry transport provides engineering limits for combined chains [39]. Aviation modeling of bird strikes on fan blades demonstrates adapted FEM approaches to high-speed impacts - relevant for ship propellers and engine room components [40].

Simulation-AI-based predictive assessment of excavator availability as a technical system illustrates a general recipe for combining failure statistics and simulation, suitable for ship systems and port equipment [41]. The model for assessing the probability of human error in inspections brings us back to the ergatic core: the task, workload, environment, and experience of operators must be parameterized in a risk model [42]. Markov chains with IoT diagnostics and human error provide a basis for planning maintenance based on the condition and inventory of components, reducing the risks of downtime and schedule disruptions [43].

Vision-language models in robot navigation show how instruction-based learning can reduce the semantic gap between human intentions and autonomous system actions - a direct vector for MASS interfaces [44]. Enhanced fuzzy cognitive maps with causal mining and expert judgments form a transparent, interpretable layer for assessing human risks in shipping [45]. The combination of fuzzy logic with expert weights in the context of BWTS demonstrates how stable solutions can be obtained in “regulatory-saturated” subsystems in the absence of accurate data [46].

The FBN-ML hybrid for underground logistics is transferred to maritime subsystems: context-dependent causality structures plus predictors from data form a modular risk assessment architecture [47]. Risk-oriented KPI selection suggests how to transform scattered metrics into a manageable portfolio of indicators prioritized by impact rather than ease of measurement [48]. Analysis of the factors driving demand for car sharing and the impact of human capital on a country's competitiveness provide a socio-economic context for crew planning, training, and personnel policy in shipping companies [49, 50].

A review of the nature of threats to the industry again highlights the multi-channel nature of risks - from piracy and terrorism to cyber threats and industrial security - and the need for an aggregated “risk map” [51]. The operational efficiency of tramp fleets under COA links risk to profitability and demand fluctuations, explaining why risk management in an ergatic system must include economic scenarios [52]. The example of road traffic during COVID-19 serves as a real-life demonstration of how “exogenous shocks” break predictive models - a useful analogy for maritime demand and risk forecasts [53]. Integrated war insurance for crops and cargo transforms geopolitical risk into manageable financial instruments and shows how insurance products should be embedded in operational decisions [54]. Finally, benchmarking intangible assets in shipping reminds us that reputation, trust, and competence are “soft barriers” that directly influence risk through counterparty behavior and the quality of human-organization-technology interactions [55].

At the same time, the literature review shows that most existing approaches remain fragmented: they do not take into account the complex interaction of technical, human, and organizational factors and rarely use stochastic models to quantify risks in the dynamics. Thus, there is a scientific gap related to the need to develop an integrated risk management model for ergatic systems of maritime operations that combines degradation and random failure analysis with quantitative scenario modeling. The study proposed in this paper aims to fill this gap. The current scientific literature demonstrates the transition from fragmented analysis to systematic integration of risks in marine ergatic systems both onboard ships and in shore-based structures. The development vector combines technical, cognitive, digital and legal components into a single risk management platform.

The aim of this work is a systematic analysis of risks in ergatic systems of maritime operations, with an emphasis on the development of management methods that take into account the multilevel interaction of man, technology and environment. Main objectives:

– to clarify the concept and typology of ergatic systems in the maritime context

– describe the methodology of system analysis with the identification of risk sources;

– to demonstrate the applied implementation through case analysis (for example: "ship-crew-environment");

– to propose principles of risk management for such systems;

to analyze the regulatory and technological framework that affects the functioning of ergatic systems.

2. Materials and Methods

2.1. Ergatic Systems in Maritime Operations

2.1.1. Definition and Main Characteristics

An ergatic system (from the Greek ergon - action, systema - integrity) is a holistic functional complex that combines people, technical means, and the environment into a single contextual management environment [1]. In the maritime sector, such systems are, in particular, a ship with a crew that interacts with navigation equipment, automated control systems, and the external marine environment. The difference between ergatic systems and cyber-physical or classical human-machine systems is the mandatory presence of a cognitive component that not only interacts but changes the logic of decision-making in the system.

The key characteristics of ergatic systems include:

- interdependence of elements (human - machine - environment);
- self-organization and adaptability to changing conditions;
- information exchange between subsystems;
- behavioral uncertainty due to the human factor.

These features distinguish erratic systems from classical technical or cybernetic systems precisely because of the human element's active role and complex, dynamic interaction.

Thus, ergatic systems in maritime transport are not only a combination of technical means and human resources, but also a dynamic integrity capable of self-adjustment and adaptation. They form a unique management environment where the interdependence of humans, equipment and external conditions determines both the efficiency of ship operations and their safety.

2.1.2. The Role of Human-Machine Interaction

The interaction between humans and the technical environment is critical in marine ergatic systems. The ship's crew operates individual machines and constantly interacts with navigation, power, information, and automated subsystems. The quality of this interaction determines the level of operational reliability, the speed of response to emergencies, and the effectiveness of decision-making. Communication breakdowns, operator overload, insufficient training, or inadequate interface can become critical risk points.

2.1.3. Evolution of Ergatic Systems in the Maritime Sector

Historically, maritime ergatic systems have evolved from traditional "man-at-the-wheel" systems to complex automated platforms with a high degree of computerization. The current stage of development is characterized by: the use of integrated bridge systems (IBS), the introduction of real-time information platforms, and the emergence of remote control and unmanned solutions.

These changes lead to new requirements for system integration and risk management, as classical approaches to safety do not always cover the complex multi-component dynamics.

2.2. Systemic Analysis of Ergatic Systems: Structure and Risks

The systems point of view allows us to perceive an ergatic system more as an unfolding whole rather than as a group of separate parts, so that changes in one element led to reactions within other components. This is particularly relevant to naval operations: a change in the weather, a failure of a sensor system, or an operator error will immediately impact changes in the overall stability of operations.

In practice, systems analysis involves discovering interdependencies, bottlenecks, and potential risks in the management, interaction, and decision-making cycles. The most dangerous cases include people interacting with automated solutions with poor feedback, the interface being incompatible with the operator's cognitive capacity, and the system not having backup scenarios in case of loss of control (Table 1).

This table shows that the sources of risk are distributed not only in the technical circuit but also at the cognitive level and in the environment. This calls for integrated management practices that cover technical tools, staff training, interface adaptation, and dynamic response to changing conditions.

Table 1. Key components of the offshore ergatic system and sources of risk.

Component	Example Function	Potential Risks
Human (crew/operator)	Decision-making, navigation	Cognitive overload, errors under stress, and misjudgment
Technical system	Sensors, engine control systems	Malfunctions, signal delays, inaccurate data
Environment	Weather, visibility, and hydrological conditions	Sudden changes, reduced maneuverability
Interface	Control panels, displays	Ambiguous or duplicated alerts, poor information layout
Communication	Ship-shore, crew-command communication	Signal loss, misunderstandings, and delayed coordination

(based on the authors' simulation results)

Conceptual Model of Interaction Within Ergatic Maritime Systems:

To ensure stable risk assessment and effective control of maritime activities, it is critical to understand the dynamic interaction between human, technical, and environmental subsystems of an ergatic system. It is no longer sufficient with a linear "man-machine" logic. Instead, such systems must be embodied as cyber-socio-technical networks, in which signals, feedbacks, errors, and decisions are circulating in real time.

The diagram in Fig. 1 illustrates a multi-level conceptual model of interaction in ergatic maritime systems. It plots the environmental stressors, communication interfaces, machine behavior, and human cognitive load against one another to achieve cumulative system risk.

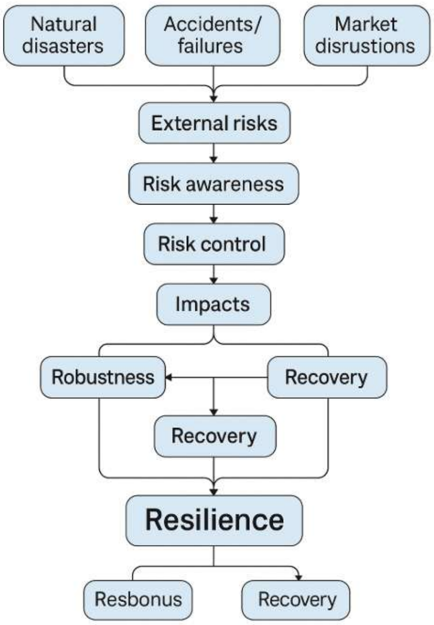

Figure 1. Multilayer risk propagation model in maritime ergatic systems (based on the authors' simulation results).

This model helps identify where risk amplification can occur, for instance, when poor interface design (UI/UX) meets high environmental complexity or sensor delay leads to inappropriate human response. The arrows reflect bidirectional feedback, suggesting that mitigation strategies must be adaptive, multi-domain, and time-sensitive.

Using such models in training, simulation, and system design allows for anticipatory control, where risks are pre-empted through design rather than mitigated post-factum. It also supports prioritizing investments: e.g., in interface redesign vs. crew workload management, depending on the bottleneck zone identified in the system.

2.3. Case Study: Disruption of Interaction in Ergatic Systems

To demonstrate the application of the systematic approach in practice, let us consider a typical situation in a maritime ergatic system where there was a failure in communication between the crew and automated navigation systems. The situation is based on real events (generalized from incidents recorded by MAIB, EMSA, and DNV).

Conditions: A Ro-Ro vessel approaches the port in conditions of limited visibility and increased pressure on the crew. Due to a technical failure, the depth detection system transmits incorrect data that the navigator does not interpret in a timely manner due to the load and non-adaptive interface.

Table 2. Case breakdown: ergatic interaction failure.

Element	Description	Contributing Factor
Human (Operator)	Navigator misinterprets depth readout	High cognitive load, fatigue
Technical Subsystem	Echo-sounder provides incorrect depth data	Calibration error, no redundancy
Interface	Display ambiguous; lacks color coding	Poor UX, insufficient alerting
Environment	Low visibility, strong cross-current	Limited external feedback
Systemic Effect	Decision to proceed on the wrong course	No cross-check, miscommunication

(based on the authors’ simulation results)

This example demonstrates the classic cognitive-technical trap, where technical failure, inadequate working conditions, and interfaces contribute to erroneous decisions. The lack of cross-checking, automatic warnings, and a clear system of prioritizing signals all increase the likelihood of an incident. Risk management in such systems must consider the technical and human factors as dynamic variables that respond to stress, time of day, workload, and interaction design.

2.4. Risk Management in Ergatic Systems

2.4.1. Types of Risks in Maritime Organic Systems

In maritime operations, ergatic systems are subject to complex risks categorized into three main groups: technological, human, and environmental. Their impact is interrelated, requiring an integrated management approach.

Technological risks include equipment failures, failures in navigation systems, sensor platforms, or automatic control algorithms. An example is a GPS module or navigation radar malfunction while maneuvering in a narrow channel.

Human factors and training requirements include cognitive errors, fatigue, in coordinated crew operations, and incorrect combination of man-machine interfaces. They can be ascribed to inefficient simulation training or a non-accommodating set of protocols. Environmental considerations include storm activity, decreased visibility, changes in currents, and meteorological hazards that complicate the ability of the crew to feel the environment and reduce the accuracy of sensor equipment (Table 3).

Table 3. Types of risks in maritime ergatic systems.

Risk Category	Description	Example Scenario
Technological	Equipment failures, system lags	Faulty radar during berthing
Human (Operator)	Errors, fatigue, and miscommunication	Delayed reaction in emergency response
Environmental	Sea state, fog, crosscurrents	Drift during dynamic positioning

(compiled and adapted from IMO, EMSA, MAIB analysis, based on the authors' simulation results)

2.4.2. Risk Mitigation Strategies

Risk mitigation in ergatic systems cannot be unified or linear - it must reflect systemic complexity, multi-layered impacts, and scenario variability. Two key approaches are used in this context: systemic safety measures and decision support tools.

Systemic safety measures in the marine environment involve implementing engineering solutions that allow for early detection of risks and structurally minimize the likelihood of their realization. This approach is based on system architecture principles and involves several technical means that increase the reliability of critical subsystems. In particular, structural redundancy of key elements, such as duplication of navigation sensors, power supplies, or positioning systems, is used to ensure that functionality is maintained even during partial component failure. Equally important is implementing fail-safe logic in automatic control modes, when the system automatically switches to a safe state upon detecting an anomaly, limiting potentially dangerous actions. Another element of the systematic approach is the introduction of so-called "soft interruption" protocols that allow operator intervention, but filter or delay commands that contradict the current safe scenario. This reduces the risk that accidental or incorrect intervention will escalate incidents.

A separate area of safety improvement is decision support tools designed to reduce the cognitive load on the crew in complex or uncertain situations. One of the key tools here is real-time risk visualization: interactive threat maps, indicators of danger zones, or predicted trajectories allow the operator to navigate the situation quickly. Automatic forecasting of dynamics, such as course or speed deviations from standard parameters, will enable you to proactively respond to changes, not just react after the fact. Context-sensitive prompts occupy a special place: the system does not overload the operator with unnecessary information, but activates notifications only when critical indicators that require attention are detected. Together, these methods help to reduce the likelihood of errors, increase the consistency of crew decisions with the logic of the automated system, and, accordingly, the overall level of safety of ship operations.

To ensure a comprehensive approach to risk management in the ergatic systems of maritime operations, it is crucial to clearly define the relationship between risk sources, risk mitigation tools, and decision-making tools. The diagram in Figure 2 illustrates the primary areas of systemic risk mitigation that integrate technical, human, and organizational approaches.

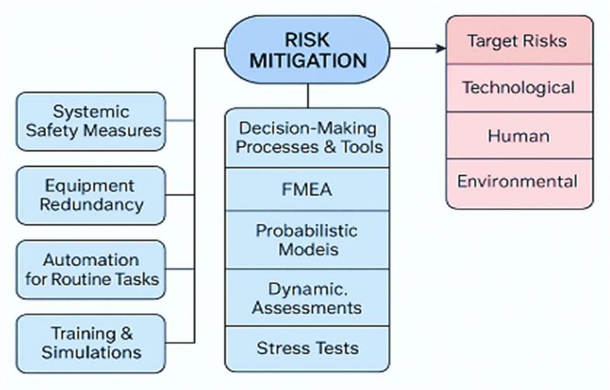

Figure 2. Model of risk mitigation strategies (based on the authors' simulation results).

As shown in the diagram, effective risk management encompasses two key pillars:

- System safety measures that ensure basic system resilience through redundancy, automation, and increased crew readiness.

- Decision support processes that include using FMEA (potential failure analysis), probabilistic modeling, dynamic scenario evaluation, and stress testing.

These tools aim to eliminate or mitigate three main categories of risks: technological, human, and environmental. The integrated application of these strategies enables the development of a predictive and adaptive management model that addresses the challenges of modern maritime ergatics.

2.5. Case Studies and Practical Applications

The analysis of specific scenarios and implementation models allows us to evaluate the effectiveness of the systematic approach to risk management in ergatic systems. This section contains two main areas: mathematical assessment using probabilistic methods and practical cases of integrating system analysis into crew training and maintenance.

2.5.1. Case Study: Assessment of Navigation Safety Using Markov Models

This subsection presents a case study on the application of Markov models to assess a vessel's navigational safety under increased uncertainty. The main purpose of this analysis was to model scenarios of gradual degradation of ship controllability, which may occur, for example, during mooring in difficult weather conditions or when passing through narrow waterways. The model considers four main states of the ship's ergatic system: "normal navigation", "reduced controllability", "critical condition" and "loss of control". Each of these states had its own probability of transition, depending on changes in the environment, the technical condition of the systems, and the crew's behavior.

The modeling results revealed several of the most likely ways to escalate the situation to an emergency level. One of the key threats was a decrease in the reliability of feedback from sensor systems - when an operator receives outdated or fragmented information, the likelihood of a "reduced controllability" situation increases significantly. Additionally, the high level of cognitive load on the crew, combined with an insufficiently informative interface, increases the risk of a delayed response. Finally, it was noted that even a delay of 3-5 seconds in the transmission of critical messages (e.g., signals about a failure in the thrust system or a change in the navigation situation) significantly increases the likelihood of a "critical condition". This approach allows not only to predict potentially dangerous scenarios, but also to adjust control protocols, interface accents, and decision support system (DSS) response algorithms.

As part of the risk analysis of ergatic systems in the maritime industry, it is advisable to use Markov processes, as they provide a rigorous approach to modeling probabilistic changes in system states over time. The state principle is the Markov property, i.e., the future state of the system depends only on its current state, and not on the entire trajectory of previous states:

$$P(S_{t+1} = s_j \mid S_t = s_i, S_{t-1}, \ldots, S_0) = P(S_{t+1} = s_j \mid S_t = s_i) = T_{ij}, \quad (1)$$

where: S_t - state of the system at time t, T_{ij} - probability of transition from state i to state j within one time step.

Markov processes are an extremely effective mathematical tool in modeling ergatic systems where a human and a technical subsystem are in integrated interaction with a changing environment. In particular, in ship and navigation system control processes, the states of the safety system change discretely and depend only on the current state, not on the complete history, which corresponds to the main property of Markov chains - the memoryless property:

$$P(S_{t+1} = s_j \mid S_t = s_i) = T_{ij}, \quad (2)$$

$$\forall T_{ij} \in [0;1], \quad \sum_j T_{ij} = 1$$

States can reflect the level of functional integrity of the system: {normal, partially degraded, critical, failure}. Transitions are defined based on empirical failure rates and risk scenario models. Markov chains with absorbing states are used to model irreversible degradations (e.g., complete loss of control).

The following states are proposed to be defined in the context of shipboard ergatic systems:

S_0 - normal operation (full functionality of the crew and systems);

S_1 - functional failures (degradation of technical systems);

S_2 - human error/loss of situational awareness;

S_3 - incident/accident (absorption state).

To model changes between these states, a transition matrix is formed (for example, "normal", "anomaly", "failure", "fault"):

$$T = \begin{bmatrix} T_{00} & T_{01} & T_{02} & T_{03} \\ 0 & T_{11} & T_{12} & T_{13} \\ 0 & 0 & T_{22} & T_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (3)$$

The fundamental matrix and the calculation of the average number of steps to absorption show that the model has 3 transient states and one absorbing state (failure). The fundamental matrix N is used to calculate the average time to absorption:

$$N = (I - Q)^{-1}, \quad (4)$$

where: Q - submatrix of transient states, I - unit matrix of the appropriate size.

Multiplying N by the vector of units gives the expected number of steps to absorption from each state:

$$\mathbf{t} = N \cdot \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}. \quad (5)$$

The model is validated by establishing the initial probability distribution T_{ij} based on expert methods (Delphi, AHP), analysis of historical incidents from MAIB, EMSA, IMO GISIS databases, and simulation modeling (in particular, Monte Carlo or Bayesian calibration). The results obtained are verified through scenario testing by comparing the empirical transition frequency with the predicted values. The key advantages of using a Markov model include scalability to complex hierarchical structures (e.g., Markov Decision Processes), compatibility with AI/ML modules for risk identification, and objectivity of assessment: formalized rules for transitions and forecasts are used instead of subjective judgment.

A discrete finite-dimensional Markov model is used to formalize the process of degradation and transitions between the states of the ship control system. The state graph in Fig. 3 with probabilistic transitions, allows modeling changes in the system state depending only on its current state (the memoryless property).

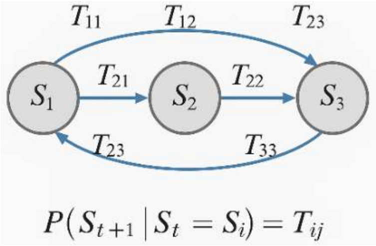

Figure 3. A finite-dimensional Markov model with three technical states: nominal (S_1), degraded (S_2), and failed (S_3), (based on the authors' simulation results).

The probabilities of transition between states are described by the matrix T, where T_{ij} is the probability of transition from state S_i to state S_j. This model allows for scenario analysis, risk assessment based on sequential transitions, and determination of the probability of critical situations during a given operational interval. Initial probability distributions are determined based on expert opinions and MAIB/EMSA statistics.

Table 4. Example of a Markov chain transition probability matrix.

Current State	Next: Normal	Reduced Control	Critical State	Loss of Control
Normal	0.85	0.10	0.04	0.01
Reduced Control	0.20	0.55	0.20	0.05
Critical	0.05	0.25	0.50	0.20

(based on the authors' simulation results)

The transition probabilities used in Table 4 were derived from literature sources and expert judgment, reflecting typical operational conditions of maritime ergatic systems.

The diagram in Fig. 4 shows a probabilistic state graph of an ergatic navigation system. It models potential transitions between four central states: Normal Navigation, Reduced Controllability, Critical State, and Loss of Control. Each arrow represents the probability of transition from one state to another under given conditions (e.g., sensor failure, increased cognitive load, etc.). The model is used to identify risky trajectories in navigation scenarios and assess the need for preventive measures.

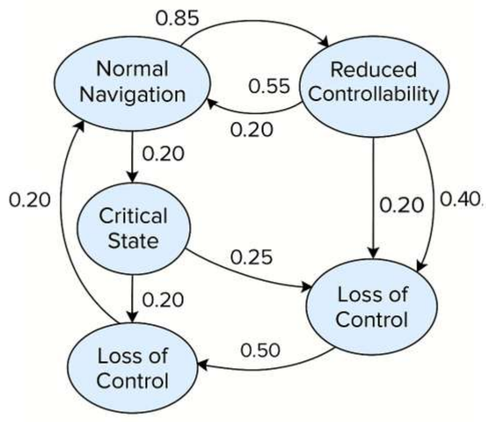

Figure 4. Markov model of ship state transitions under the risk of loss of control ((based on the authors' simulation results).

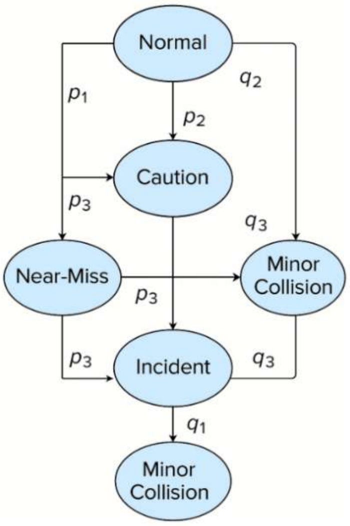

Figure 5. Probabilistic scheme of maritime incident scenarios (based on the authors' simulation results.

The diagram in Figure 5 shows the probabilistic logic of transitions between states: Normal, Caution, Near-Miss, Incident, and Minor Collision. The parameters p_i and q_i are conditional probabilities of the scenario occurring depending on the crew's response, technical support, or communication delays.

This method simulates safety assessments, develops response protocols, and validates the effectiveness of crew training in critical conditions.

Thus, the Markovian approach enables the identification of early risk trajectories, facilitates the integration of real-time warning systems, and supports crew decision-making before the situation becomes critical.

2.5.2. Applied Applications of System Analysis

This subsection focuses on applying systems analysis in maritime safety management, particularly in two strategically important areas: crew training and ship systems maintenance.

In the first case, risk modeling results became the basis for modernizing simulation training programs for navigators and ship engineers. The simulators were supplemented with scenarios involving sudden changes in the environment (e.g., sharp gusts of wind, changes in depth, limited visibility), interface failures, signal delays, or loss of communication. This made it possible to simulate situations often outside the scope of standard curricula but critical for developing adaptive response and decision-making skills under stress and uncertainty.

The second area concerns optimizing maintenance based on systematic analysis, considering multifactorial risk. Instead of fixed maintenance schedules, adaptive intervals were introduced, depending on the actual load on the units (duration of continuous operation, vibration level, ambient temperature, humidity, etc.) This approach improves the reliability of key systems and reduces costs by avoiding unnecessary technical intervention and preventing accidents at early stages of fault development.

2.6. Legal Framework and Regulatory Context

2.6.1. Role of the International Maritime Organization (IMO) and Other Regulators

Effective risk management in ergatic systems is impossible without regulatory support from international organizations. The International Maritime Organization (IMO) is the key body that shapes shipping safety policy, including standards for human-machine interaction, crew management, and technological integration. The legal and regulatory framework for safety in ergatic maritime systems determines how effectively risks can be identified, assessed and minimized in maritime operations. The central regulatory structure in this context is the International Maritime Organization (IMO), which sets global standards for structural safety, crew management, and technological and communication in ship systems through documents such as SOLAS, STCW, and ISM Code. These regulations not only define the formal requirements for ships, but also directly affect the design of HMI systems, the allocation of responsibilities and the training of personnel.

Effective application of these standards relies to a large degree on national maritime administrations, which modify and oversee the application of international standards in their jurisdiction. In Ukraine, for instance, Maritime Administration oversees the application of STCW and ISM standards. But the application of modern systematic risk analysis methods into routine inspections and training is not well established. For example, advanced techniques like cross-risk modeling, which allow for the foresight of likely clashes between technical and human aspects, are not yet applied to obligatory inspection processes. To bridge this deficiency, risk-based audits may be utilized, HMI inspection routines may be rewritten, and training packages may be harmonized with findings from system modeling.

2.6.2. National Legislation and Compliance with International Standards

At the national level, maritime administrations adapt international standards to local fleet operating conditions. For example, the State Service of Maritime and River Transport of Ukraine (MorAd) has implemented a system for verifying vessel compliance with STCW and ISM requirements. However, the problem remains the integration of systematic risk analysis into inspection and training procedures.

An illustrative case is cross-current modeling, which allows for the prediction of conflicts between technical and human elements in a system. Such models have already begun to be used in training and simulation centers in some EU countries (e.g., Denmark, Norway, the Netherlands) - but they have not yet been implemented in the IMO's mandatory regulatory practice.

In general, gaps between standards and practice can be reduced by updating the protocols for checking the condition of human-machine interaction systems, implementing risk-based audits, and aligning training standards with the results of systemic risk analysis.

2.7. Technological and Infrastructural Development

2.7.1. Development of Port Infrastructure

In the context of ergatic systems that combine technical means with human control, it is important to recognize that a significant portion of operational risks arises outside the ship, particularly in the port contact area. Port infrastructure, which was traditionally viewed only as a logistics link, is now becoming a full-fledged component of the safety and efficiency of maritime operations. Therefore, the development of smart ports and the modernization of port systems are critical to the overall sustainability of the maritime transport system.

Modern ports of the new generation are increasingly implementing automated ship docking systems (smart berthing), which reduce dependence on the human factor during mooring. Centralized integrated vessel traffic management systems, such as VTS (Vessel Traffic Services) or VTMIS (Vessel Traffic Management and Information Systems), enable real-time maneuvering coordination, considering weather conditions and water area congestion. The use of digital models of tides and currents also plays a significant role, as this data, which is transmitted to the crew before entering the port, significantly reduces the risk of navigational errors. For example, in the Baltic Sea region, the EU STM Validation (Sea Traffic Management) project was implemented, which showed the effectiveness of digital data exchange channels between ports and ships. In addition, the BSEC SafeNav initiative was launched in the Black Sea region to reduce risks in narrow sea straits. IMO initiatives include the Maritime Autonomous Surface Ships (MASS) Regulatory Scoping Exercise (2021) and the EMSA project on risk assessment in autonomous shipping.

Thus, the modernization of port infrastructure is not only an investment in capacity but also a powerful tool for reducing systemic risks at the intersection of the maritime and coastal segments.

This is especially true for large-tonnage vessels and vessels with a high level of automation, where the accuracy and predictability of maneuvers are critical.

The effective functioning of ergatic systems is not limited to the ship's boundaries - a significant part of the risks is formed or amplified in the port interaction zone. Modernized ports of the new generation are implementing systems such as smart berthing automation, integrated traffic management centers (VTS/VTMIS), or digitalized tide and current models transmitted to the ship in real time to reduce the number of incidents in maneuvering and mooring areas, especially for large-size fleets.

Table 5 demonstrates how the integration of intelligent solutions, autonomous mechanisms and real-time modeling is transforming ports into smart logistics hubs, which not only reduces risks for ship crews but also allows for effective management of growing traffic and complexity in shipping processes.

Table 5. Advanced Innovations in Port Infrastructure.

Technology	Functionality	Technological Description	Example of Implementation
Smart Mooring Systems	Automated and secure mooring without manual crew involvement	Uses vacuum pads, magnetic clamps, or automated arms to safely moor vessels, reducing time and risks associated with rope handling and manual docking	Port of Rotterdam
Digital Twin of Port Basin	Real-time simulation of environmental and traffic conditions	A virtual replica of the physical port, incorporating sensor data (currents, tides, ship motion) to support situational awareness, traffic flow, and infrastructure planning	Singapore PSA
Autonomous Tug Coordination	Synchronization of autonomous tugs for safe berthing and unberthing operations	Centralized AI-based control system coordinates multiple unmanned tugs, allowing precise control during maneuvers and reducing reliance on manual piloting	Port of Hamburg
Vessel Traffic Management Integration (VTMIS)	Seamless coordination between port control	Combines radar, AIS, weather data, and predictive analytics to	Port of Antwerp

	and shipboard navigation systems	support vessel approach decisions, reducing congestion and risk of collision	
Real-Time Environmental Sensing	Monitoring of wind, wave, current and tide parameters for dynamic decision-making	Sensor arrays across the port basin transmit real-time data to control centers and vessels, enabling reactive route adjustments and enhanced safety	Busan New Port, South Korea
Digital Clearance & Smart Gateways	Contactless customs processing and cargo handling	Integrated systems enable secure digital identification, cargo manifests, and crew clearance, reducing port stay time and paperwork	Port of Valencia

Source: authors

2.7.2. Innovations in Ship Technology and Integration of Information Systems

Modern ships are becoming increasingly intelligent and energy efficient. Innovations include

- deep automation of control systems (smart bridge);
- energy optimization systems (weather routing, hybrid propulsion);
- adaptive interfaces with biofeedback for the crew.

A special role is played by the introduction of cross-current models to predict conflicts between the technical condition, navigation data, and the cognitive state of the operator. Combining data from all ship, port, weather station, and operator center subsystems creates an integrated ergatic platform that provides real-time monitoring of parameters, crew alerts for anomalies, and risk scenario simulation based on current data. And the use of integrated digital circuits reduces crew workload, speeds up system response, and increases the overall sustainability of the maritime operation.

3. Discussion

To check the stability of the results obtained, we conducted a sensitivity analysis of the model. This approach varied the main parameters - the intensity of gradual and sudden failures (λ_g and λ_s), as well as the correction factors, environmental coefficient (k_{env}) and human factor coefficient (k_{hum}), which reflect the influence of the environment and the human factor. The values were changed within ±20% of the basic parameters determined on the basis of technical documentation and expert opinions. The sensitivity analysis results are presented in Figure 6, which combines both bar and line representations.

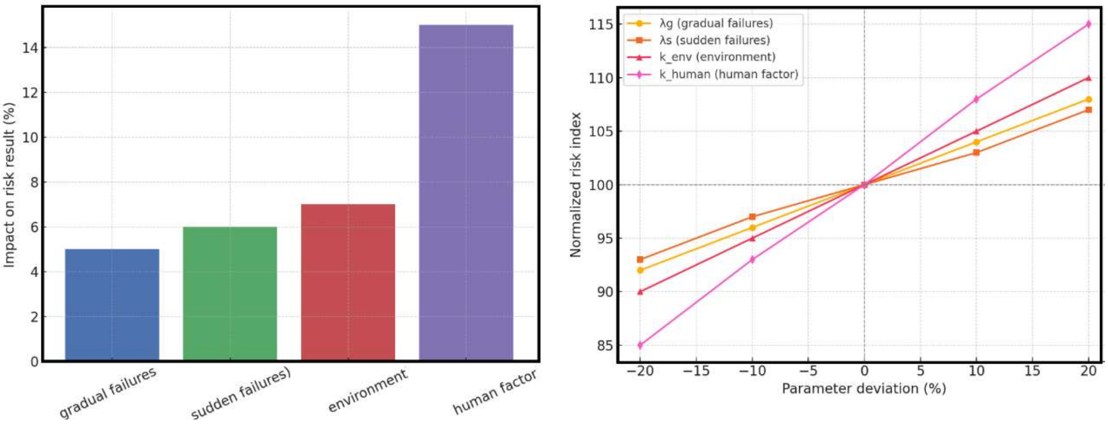

Figure 6. Combined sensitivity analysis: impact of parameters on the risk index (based on the authors' simulation results).

The results showed that the model demonstrates stability with insignificant parameter variations: the deviation of the integrated risk indicator did not exceed 8% in most scenarios. At the same time, the most sensitive was the coefficient k_{hum}, a change in which caused up to 15% fluctuation in the results, which confirms the critical role of the human factor in ensuring the safety of maritime operations. Thus, the sensitivity analysis confirmed the reliability and reproducibility of the developed model, and also allowed us to identify the key parameters that should be taken into account in the practical application of the methodology.

The results of the study are of direct practical importance for improving the safety of maritime operations. The proposed model can be used by shipowners and operators to optimize maintenance plans by prioritizing the most sensitive system parameters. The identified critical influence of the human factor confirms the need for increased attention to crew training, implementation of training programs and management of personnel workload. For regulators and maritime administrations, the model can serve as a basis for developing risk management policies aimed at integrating technical and organizational safety measures. Thus, the results of the study can be used both in practical fleet management and in improving industry standards and regulatory requirements.

The materials and methods part of the paper is quite lack of the experimental report we usually write. This part accounts for a large proportion in the paper, especially the analytical and experimental research papers, which can be introduced clearly only after accounting for about 30% of the full text. The material mainly introduces the experimental objects and data, and the method refers to the experimental design or data collection method.

4. Limitations and Further Research

While the proposed framework is exhaustive, there are certain limitations that remain to be overcome through future research. Here, the risk models used, especially the ones involving Markov chains and event trees, are highly dependent on theoretical analysis and expert-estimated transition probability estimates. Useful approximations as they might be, the paucity of high-resolution empirical data from actual maritime accidents impedes precise calibration of models.

Furthermore, current modeling does not correctly capture the dynamic feedback among environmental turbulence, human decision-making, and system state transitions. Human-machine interaction in stressful situations is also an open research topic, especially with uncertain, high-workload navigation situations. The current system also assumes relatively stable operating conditions, which may not be able to capture the changing and often turbulent conditions present in real maritime operations.

In order to improve the accuracy and operational usability of the model, subsequent research will seek to incorporate real-time telemetry data, including sensor signals, DPO behavior logs, and real-time variations in the environment. Implementation of adaptive algorithms - i.e., reinforcement learning and scenario generation supported by AI - can also provide real-time model updating and situational adjustment. The possibility of further extension of the system for planning the work of more than one ship, autonomous ship operation, and ship-port interaction zones must be explored. Cross-validation using international maritime safety databases (e.g. GISIS, EMSA, Equasis) will be essential to scale the approach and apply it generally.

5. Conclusions

This article comprehensively analyzes the risks associated with the operation of marine ergatic systems, which are complex technical and social systems that combine the ship's crew, automated ship control systems, and the external environment. The analysis has shown that effective management of such systems is possible only with an integrated approach that covers both technical and organizational components and the cognitive interaction of a person with the system. In particular, the value of conceptual and probabilistic scenario modeling is demonstrated, which allows the analysis of existing risks and the prediction of potential critical situations at the design stage. The study found that the sustainability and efficiency of maritime operations is significantly improved by introducing adaptive crew training, intelligent interfaces, and early warning systems. A systematic approach to risk management allows us to move from a reactive model to a predictive one, emphasizing proactive decisions and real-time risk assessment. It is shown that ergatic systems are becoming not just a technological concept, but a new paradigm for the functioning of maritime transport.

A comparative analysis has shown that ergatic systems have a much more complex risk profile than classical technical systems: while the latter mostly face technical failures that are compensated for by redundancy and scheduled maintenance, ergatic systems also include cognitive (human factor) and environmental risks. Mitigating them requires comprehensive approaches, from modeling and DSS to the implementation of adaptive interfaces and behavioral algorithms. As a result, the level of adaptability of ergatic systems is significantly higher, which allows them to respond dynamically to changing conditions, but at the same time complicates management and design.

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