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Maritime decarbonisation and resilience: A research agenda for green shipping corridors

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Keywords

Maritime decarbonisation; Maritime resilience; Green shipping corridors; Alternative fuels; Policy/transition research

Abstract

Decarbonising maritime transport requires technological innovation and the rapid diffusion of low-carbon solutions across complex value chains involving multiple stakeholders. This extended abstract synthesises two complementary reviews: a bibliometric analysis of renewable-energy technological innovation in transport and logistics, and another on maritime transport resilience. Both research streams have expanded rapidly since 2010, although collaboration among researchers and institutions remains fragmented. Key themes include climate change mitigation, hydrogen and electrification technologies, vulnerability and adaptation strategies, and port resilience. The synthesis is situated within major policy developments shaping maritime decarbonisation. These include the International Maritime Organisation's 2023 greenhouse gas reduction strategy, which targets the uptake of zero- and near-zero-emission fuels by 2030 and a global net-zero framework for shipping. It also reflects the extension of the European Union Emissions Trading System to maritime transport, including methane and nitrous oxide emissions from 2026, and the FuelEU Maritime regulation, which requires well-to-wake emissions reductions and zero-emission technologies at berth from 2030. Considering the Global Maritime Forum's portfolio of 84 green shipping corridor initiatives, this study proposes six research directions to advance resilient, low-carbon maritime transport systems.

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Resilience-based Port Integrated Scheduling Incorporating Uncertain Equipment Failure, Operations and Maintenance Time

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Keywords

Port and terminals; Optimisation and control; Uncertainty and robustness evaluation; Scheduling resilience; Meta-heuristic algorithm;

Abstract

In real-world port operations, besides the fluctuations in operation time, unexpected equipment failures often occur, causing complex scheduling challenges. Such uncertainty makes it very challenging to develop integrated scheduling of container port quay cranes, internal vehicles, and yard cranes. This study aims to develop a novel resilience-based scheduling method capable of addressing uncertainty in integrated container port operations. The proposed method introduces an enhanced anti-cascade effect and robustness evaluation index to assess schedule resilience. The index is then used to define gap time slots in a Gantt Chart as buffers to absorb uncertainty. For the first time, the proposed index considers the positions of these buffer slots together with fluctuations in operation times, equipment failure probabilities, and the potential maintenance durations associated with the activities adjacent to each slot. These factors directly influence the schedule's anti-cascade capability and overall robustness. The method incorporates prior knowledge, including the probability distributions of uncertain parameters. The scheduling model is validated using *Gurobi*, and the most suitable solution-based on the developed evaluation index- is identified through a meta-heuristic algorithm. The findings reveal the method's effectiveness in handling large-scale cases with a high level of uncertainty. Furthermore, the proposed model achieves reasonable computation time, notably outperforming compared methods in efficiency.

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Assessing Cybersecurity Resilience in Digital Ports: A Bayesian Network-FAIR Integrated Framework

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Keywords

Digital Ports;
Cybersecurity Risk Assessment;
Bayesian Network;
FAIR Model;
Maritime Infrastructure Resilience

Abstract

The digitalisation of seaports has improved operational efficiency while increasing exposure to cyber–physical disruptions that threaten transport continuity and supply chain reliability. This study develops an integrated risk assessment framework that combines Bayesian Networks (BN) with the Factor Analysis of Information Risk (FAIR) model to quantify cybersecurity risks in digital port systems. The framework captures interdependencies across six domains—cyber layer, physical layer, interconnection layer, organisational, external threat, and individual—enabling probabilistic analysis of interdependent vulnerabilities. Based on expert elicitation, the model identifies key risk drivers, including legacy software, unpatched systems, hardware failures, and limited cybersecurity awareness. Sensitivity analysis is used to evaluate critical risk drivers and estimate the financial consequences of disruption events. The results indicate that integrating probabilistic causal modelling with financial quantification enables more transparent and decision-relevant risk assessment. The proposed BN–FAIR approach provides a structured basis for cybersecurity risk assessment in digitally enabled port infrastructures.

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Type-Aware Predictive Normality Learning for AIS Trajectory Anomaly Detection

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Keywords

AIS trajectory anomaly detection;
vessel-type-specific modelling;
sequence prediction;
temporal attention;
data quality awareness

Abstract

Automatic Identification System (AIS)-based anomaly detection is increasingly used for maritime safety monitoring, yet many existing methods still assume a shared normality model across heterogeneous vessel categories and insufficiently account for unreliable AIS observations. This study proposes a vessel-type-specific and quality-aware framework for short-term AIS trajectory anomaly detection. A quality-aware dual-attention sequence-to-sequence predictor is developed to learn nominal short-term motion dynamics separately for different vessel categories, where observation-quality indicators modulate historical inputs and dual attention captures both feature relevance and temporal dependence. Multi-step prediction discrepancies are aggregated into anomaly scores and calibrated through vessel-specific quantile thresholds, yielding category-specific operating boundaries. Experiments on six major vessel categories show that operating boundaries implied by nominal prediction errors, dominant anomaly-driving features, and anomaly-to-boundary separability differ systematically across vessel types. These findings indicate that AIS abnormality should not be assessed under a shared global error scale. A representative anomalous case further provides qualitative support by linking local trajectory deviation to heading-related inconsistency and concentrated temporal response. Overall, the results support a vessel-aware, prediction-based anomaly detection paradigm for AIS screening and maritime safety monitoring under realistic and imperfect observation conditions.

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Error Propagation and Correction in MASS Team Tasks: A Task Interdependence Analysis Based on the SIR Model

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Keywords

Maritime Autonomous Surface Ships;
Task interdependence;
Susceptible-Infected-Recovered model

Abstract

In real-world scenarios, the progression of team tasks is not always smooth, as task execution is often disrupted by multiple factors. To examine how task progression of Maritime Autonomous Surface Ships (MASS) operational teams is hindered, a simulation based on Susceptible-Infected-Recovered (SIR) model is conducted. A quantitative evaluation model of task interdependence is developed across three dimensions, integrating modularity theory and propagation costs. The infection and recovery probability of the SIR model are set according to the quantified value of task interdependence and task complexity to simulate information flow. The model outputs four key indicators reflecting the delay, scope, and intensity of fault propagation. Results indicate that shore-based operators exhibit lower fault correction capabilities compared to onboard operators, primarily due to limited perception. While shore-based systems exhibit capacity for anomaly detection and correction, but their effectiveness is constrained by the predefined software performance. Through modelling the dynamics of error diffusion and correction, a novel approach to understanding MASS team resilience is provided.

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Development Status and Future Trends of Large Language Model-Driven Fault Diagnosis Methods for Mechanical Equipment

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Keywords

Large Language Models; Mechanical Equipment; Fault Diagnosis; Intelligent Agents; Industrial Operation and Maintenance

Abstract

The in-depth advancement of Industry 4.0 and intelligent manufacturing has driven mechanical equipment toward precision-oriented, complexity-increased, and systematisation-driven development. As the core component of equipment predictive maintenance, fault diagnosis has become crucial for ensuring the safe and efficient operation of industrial systems. Traditional fault diagnosis methods face key challenges such as small sample sizes, distribution shifts across operating conditions, single-modality limitations, and a lack of interpretability. In contrast, Transformer-based large language model technology, with its powerful general representation capabilities, few-shot learning, and cross-modal reasoning abilities, has brought about a paradigm shift in mechanical equipment fault diagnosis. This paper systematically reviews the technological evolution and development context of large language models as well as their basic theoretical framework, and conducts an in-depth analysis of their application progress and core research methods in the field of mechanical equipment fault diagnosis. It also examines the existing academic controversies and common problems in this domain. By integrating the trend of large language models evolving towards intelligent agents and practical industrial needs, this paper proposes future development directions, providing theoretical reference and practical guidance for constructing the next-generation industrial fault diagnosis systems with higher robustness, interpretability, and generalization ability.

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Barriers to Decarbonisation Investment in Maritime SMEs: Evidence from an International Survey

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Keywords

Decarbonisation;
Maritime SMEs;
Barriers;
Empirical study;
Comparison analysis

Abstract

Maritime decarbonisation is essential for achieving global net zero targets, yet small and medium-sized enterprises (SMEs) face substantial barriers in adopting low-carbon technologies. This study identifies and evaluates key barriers influencing decarbonisation investment decisions in maritime SMEs. An initial set of 38 barriers was derived from a structured literature review and subsequently refined to 13 through a pilot survey and stakeholder workshop. A questionnaire survey (n=97) was conducted to assess the perceived importance of these barriers. Descriptive statistics were used to rank the barriers, while ANOVA and independent samples t-tests were applied to examine differences across company size and respondent background. The results indicate that economic barriers, particularly limited access to capital and external risks, are the most significant. Statistically significant differences are observed in information and policy-related barriers across groups. The findings provide empirical insights to support targeted policy and industry interventions.

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The Impact of Different Market-Based Measures on Shipping Firms' Emission Reduction Decisions

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Keywords

Carbon emission;
Market-Based Measures;
Game theory;
Shipping;
Welfare economics

Abstract

In recent years, growing concerns over climate change have drawn increasing attention to the shipping industry, a major contributor to global greenhouse gas emissions. China has set ambitious targets to achieve carbon peaking by 2030 and carbon neutrality by 2060. However, uncertainty remains regarding whether carbon tax or an emissions trading system (ETS) will dominate future policy design, creating challenges for shipping stakeholders. This study examines the interaction between government and shipping firms by developing a Stackelberg game model under both carbon tax and ETS regimes. It derives optimal strategies and systematically compares the impacts of these policy instruments on firms' emission reduction decisions. The results indicate that carbon tax is more effective in reducing emissions, whereas ETS performs better in maximising social welfare. In addition, shipping firms can enhance profitability by appropriately increasing their emission reduction intensity, and their decisions are highly sensitive to the carbon tax rate and initial allowance allocation. These findings provide important insights for policymakers and industry practitioners, offering policy implications for designing effective decarbonisation strategies in the shipping sector.

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Numerical Investigation of Crushing-Bending Failure Mode Transition of Ice Wedges with Varying Thickness under Fluid-Structure Interaction

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Keywords

Ice-structure interaction;
Arbitrary Lagrangian-Eulerian method;
Ice thickness;
Failure mode transition

Abstract

To investigate ice-induced effects on inclined structures in ice-covered regions, a Fluid-Structure Interaction (FSI) numerical model based on the Arbitrary Lagrangian-Eulerian (ALE) method is developed to systematically examine the evolution of failure modes during ice-structure interaction under varying ice thicknesses. The results indicate that the ice failure pattern exhibits a strong dependence on ice thickness. As the ice thickness increases, the dominant failure mode transitions from bending to crushing, while a mixed bending-crushing mode is observed at intermediate thicknesses. Bending failure is characterised by the initiation and rapid propagation of circumferential cracks in the bending zone, which eventually leads to global fracture and separation of the ice. In contrast, crushing failure is localised in the contact region and is associated with severe fragmentation and pronounced stress concentration. These findings highlight the governing role of ice thickness in controlling failure mechanisms.

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Safety Assurance of Shore-to-Ship Remote Takeover: STPA-BN-Based Risk Modelling for Autonomous Shipping

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Keywords

Maritime Autonomous Surface Ships;
Remote Takeover;
STPA-BN;
Leaky Noisy-MAX;
Dynamic Risk Assessment

Abstract

Remote takeover is a safety-critical operating mode for Maritime Autonomous Surface Ships (MASS), in which shore-based operators, communication links and shipboard control systems form a tightly coupled cyber-physical-human system. Conventional quantitative risk assessment methods are limited in representing control-logic conflicts, human-machine interaction failures and cascading uncertainty in such scenarios. This paper proposes a risk-informed STPA-BN framework incorporating Leaky Noisy-MAX dimensionality reduction and a system attenuation factor. First, System-Theoretic Process Analysis is used to decompose the shore-to-ship control loop and map unsafe control actions into Bayesian network nodes. Then, Leaky Noisy-MAX is introduced to reduce the exponential growth of conditional probability tables, while the attenuation factor calibrates probability propagation to avoid unrealistic risk amplification. For a six-parent node, the model reduces the parameter burden by approximately 89% and converges the model-based conditional probabilities of major loss events under remote takeover activation to about 1%. Sensitivity and stress-test results show that communication link quality becomes more critical than operator workload in remote takeover conditions. In addition, the failure of the command verification mechanism under a critical control-action omission may induce an additional risk increase of approximately 11%. These probabilities should be interpreted as conditional estimates generated by the calibrated BN model rather than empirically validated accident rates. The proposed framework provides engineering support for heterogeneous communication redundancy, delay-threshold design and dynamic risk warning in autonomous shipping.

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An Intelligent Ship Speed Optimisation Method for Safe Navigation under Meteorological Conditions

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Keywords

Ship speed optimisation; Weather routing; Navigation safety; Mixed-integer non-linear programming (MINLP); Fuel consumption

Abstract

To address ship speed decision-making under complex and variable meteorological conditions, this paper proposes a speed-optimisation method that jointly considers meteorological impacts and navigational safety constraints. Targeting realistic voyages in which wind, waves and currents act simultaneously, the proposed method takes the minimisation of voyage fuel consumption as its objective and incorporates the speed of each leg, the recursive voyage time and the feasible navigational time windows as decision variables, formulating a multi-constraint mixed-integer nonlinear programming model. Through piecewise linearisation, the model is reformulated as a mixed-integer linear programme that is solved efficiently by SCIP. Case studies based on Automatic Identification System data of a real ocean-going voyage show that, while satisfying both navigational safety and time-window constraints, the proposed approach produces smoother speed-control strategies, improves the rationality and flexibility of voyage planning and demonstrates clear practical potential in reducing voyage fuel consumption.

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Conditional Diffusion for Maritime Multi-Vessel Encounter Scenario Generation

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Keywords

Maritime scenario generation;
AIS data;
Conditional diffusion model;
Vessel encounter modelling

Abstract

Existing maritime testing scenario generation methods remain limited in generating complete, controllable, and interaction-consistent multi-vessel encounter processes. This paper proposes an own-ship-centric conditional diffusion framework for multi-target maritime encounter scenario generation. Each scenario is represented in a unified own-ship reference frame, and target vessels are described by structured encounter conditions, including appearance time, initial relative position, relative motion state, encounter type, and CPA-related attributes. Instead of directly generating absolute trajectories, the model generates relative motion increments and reconstructs complete target-vessel trajectories through anchor-based integration. To capture both temporal continuity and multi-vessel dependency, a temporal-interaction-aware denoiser is designed by combining per-target temporal modelling with graph-based interaction modelling. Experiments on AIS data from the Ningbo-Zhoushan Port area show that the proposed method achieves reasonable CPA-related consistency, scene-level realism, and interaction-level agreement with real AIS encounter distributions. Ablation results further demonstrate that temporal modelling improves motion realism, while graph-interaction modelling helps preserve multi-vessel conflict structures. The proposed framework provides a data-driven way to generate complete and condition-guided encounter scenarios for collision avoidance algorithm testing.

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Spatiotemporal Patterns and Predictive Risk Analysis of Maritime Accidents in UK Waters

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Keywords

Maritime accidents;
UK waters;
Spatial clustering;
Severity modelling;
Risk prioritisation

Abstract

Maritime accident analysis often treats hotspot detection and severity modelling as separate tasks. This extended abstract presents a cluster-first spatial-severity framework for Marine Accident Investigation Branch records in UK waters from 2013 to 2021. The study cleans 3,938 occurrence-level records, applies KDE and DBSCAN to coordinate-reliable ship-casualty records, and uses leakage-controlled machine-learning models to score severe-outcome risk. Cluster profiles integrate accident frequency, empirical-Bayes severe-rate estimates, predicted severe-risk scores, local mechanism evidence and temporal typologies. The results show that accident frequency is concentrated around major port and estuarine systems, but severe-outcome priority is not reducible to accident counts. Hull, London, Southampton and Liverpool emerge as strategic priority clusters, while several smaller coastal clusters require validation as severe-risk watchlist locations. The framework provides evidence for targeted traffic management, seasonal monitoring, inspection and emergency-response planning.

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Unlocking Maritime Data Value Through Trust: Lessons Learned from a Maritime Use Case

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Keywords

Data trustworthiness; Trust technologies; Lessons learnt

Abstract

This work focuses on how data trustworthiness influences the value of data-driven maritime applications using Vessel Technical Index (VTI) as a representative use case. VTI relies on operational data collected from onboard systems to assess vessel technical performance. The confidence of VTI depends directly on the trustworthiness of input data and unreliable data can lead to misleading VTI calculation and thereby resulting in inappropriate decisions. Building on our prior work, the paper reflects on practical experience by sharing several lessons learnt drawn from this use case regarding data trustworthiness, data manipulation risks, the necessity of verifiable data trustworthiness and the emerging challenges related to multimedia data.

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A Systematic Framework for Causation Correlation Analysis of Multiple Types of Maritime Traffic Accidents via Semantic Context Mining

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Keywords

Maritime traffic accidents; Causation correlation analysis; Semantic mining; HVMCE framework; Complex network; Accident prevention; Risk analysis

Abstract

Maritime traffic accidents pose significant threats to maritime transportation safety and supply chain resilience. This study constructs a systematic causation correlation analysis framework for maritime traffic accidents based on semantic context mining. By analysing 3,393 maritime accident reports from the GISIS database (1990-2022), we employ Latent Dirichlet Allocation (LDA) topic modelling and natural language processing techniques to extract semantic features and construct a factor network. The study reveals the complex causation mechanisms among Human, Vessel, Machinery, Cargo, and Environment (HVMCE) factors. Through complex network analysis and Louvain community detection, we identify key accident causation chains and critical nodes. The empirical results demonstrate that environmental factors serve as primary triggers, propagating through equipment failures to human errors, forming the core transmission path of "Environment → Machinery → Human". This research provides theoretical foundations for maritime accident prevention and contributes to the digital transformation of maritime transportation safety management, enhancing supply chain resilience in the maritime sector.

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"So it's all about making money": A Critical Review of Higher Level Authorities and Their Perceptions on the Reporting Culture within the Realms of Maritime industry

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Keywords

Reporting;
Safety;
Risk;
Maritime

Abstract

Maritime reporting practices are necessary to learn from operations and to understand how and why accidents occur, thereby improving prevention and mitigation, yet persistent fragmentation, limited data standards, underreporting, blame culture, and conflicting business priorities indicate that this potential is not fully realised. This paper argues that the way operational realities are interpreted by higher-level authorities, such as classification societies, maritime administrations, port state authorities, and insurers, limits what the industry can learn from reported operational data. Using 11 focus group interviews analysed through a Grounded Theory approach, the study identifies, through participants' interpretations, mechanisms that contribute to a reporting culture that underperforms in supporting knowledge about accident prevention and mitigation. The findings show that the stakeholders broadly recognise that the current operational reporting is a lost learning opportunity, and that compliance-driven practices are perceived as poorly suited to capturing operational realities. These mechanisms are interpreted as driven by fragmentation and powerful business processes, which contribute to a blame culture and thereby reinforce underreporting. This shows why reporting is perceived as ineffective for learning from maritime operations and argues for a broader discussion of risk management approaches that better align reporting practices with the operational realities on board vessels.

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Analysing Port Congestion Based on Vessel Stay Behaviour Recognition

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Keywords

Port congestion analysis;
Vessel stay behaviour;
Speed-Spatial Gating Transformer;
AIS data

Abstract

Existing port congestion indicators are mostly used to characterise congestion states, but they remain limited in explaining the formation and manifestation of congestion through specific vessel behavioural processes. To address this limitation, a port congestion analysis framework centred on vessel stay behaviour recognition is developed in this study. Within this framework, a Transformer architecture incorporating a Speed-Spatial Gating module is designed to strengthen spatial feature representation under low - speed stay conditions and improve the identification of anchoring and berthing patterns. The recognition results are subsequently used to construct behaviour-based congestion indicators, and vessel size is introduced to examine heterogeneous congestion characteristics across vessel classes. Using cargo vessel AIS data from the Los Angeles - Long Beach port complex in 2021 as a case study, the results show that the proposed model can accurately identify anchoring and berthing behaviours. The analysis further reveals that larger cargo vessels exhibit more pronounced congestion characteristics. The findings provide an analytical basis for berth resource allocation, arrival traffic organisation, and the improvement of port operational efficiency.

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Digital Twins for Offshore Wind and Marine Protection: Stakeholder Perspectives from Nova Scotia, Canada

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Keywords

Offshore Wind;
Digital Twin;
Maritime Management;
Maritime Risk;
Maritime Governance

Abstract

Nova Scotia currently plans extensive offshore wind infrastructure developments, raising urgent questions about how renewable energy development can proceed without compromising marine ecosystems. Digital Twin (DT) technology, virtual replicas that integrate data, models, and visualisation, has been proposed as a tool to support marine spatial planning, environmental impact assessment, and maritime risk management. This presentation reports findings from a mixed-methods study that explored stakeholder perspectives on the value, feasibility, and governance requirements of DTs in the Nova Scotia context. Drawing on a multi-sector technical workshop and follow-up expert interviews, the study shows broad support for DTs as decision-support tools for environmental monitoring and predictive "what-if" scenario analysis. However, participants also identified significant barriers, including data fragmentation, high costs, institutional silos, and risks that complex models may become opaque "black boxes". The results highlight that technical capability alone is insufficient: social legitimacy depends on transparency, open data practices, and inclusive governance. The study suggests that small pilot projects offer a pragmatic pathway to test DT applications while building trust and capacity.

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Enhancing Maritime Safety: A ST-VAE-GAN Framework for Ship Collision Accident Scenario Generation and Risk Analysis

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Keywords

Ship collision;
Risk analysis;
ST-VAE-GAN model;
Accident data generation

Abstract

Marine collision accident data often suffer from issues such as small sample sizes, discrete features, and sparse high-risk patterns, which severely constrain the accurate identification and effective intervention of risk via data-driven methods. To overcome data limitations, we propose a conditional variational autoencoder-generative adversarial network (ST-VAE-GAN) model that incorporates maritime domain knowledge to generate data, based on historical collision accident data from IMO statistics. Empirical results indicate that the synthetic data exhibit high consistency with the original data in statistical characteristics, including mean and correlation (achieving 100% feature coverage), and demonstrate strong performance in downstream prediction tasks (the XGBoost model trained on synthetic data attains an AUC-score of 0.86). The model successfully captures complex interaction effects among factors such as flag, vessel type, and age. SHAP analysis identifies accident-prone waters, vessel malfunctions, flag, hull type, and age as the top five critical risk factors. This study confirms that the ST-VAE-GAN model effectively generates ship collision data suitable for maritime safety analysis, offering a reliable solution to the small-sample problem.

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A dynamic ship domain-based method for quantifying the traffic flow saturation in restricted waters

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Keywords

Waterway transportation; Ship traffic management; Dynamic ship domain; Traffic flow analysis

Abstract

With the increase in ship traffic volume and the trend toward larger ship dimensions, traffic congestion frequently occurs in restricted waters, leading to a significant rise in the risk of maritime accidents. This study develops a calculation method for waterway traffic flow saturation based on a dynamic ship domain model. By integrating environmental variables, waterway configurations, and real-time traffic states, the proposed approach enables a quantitative, high-fidelity evaluation of traffic saturation. Taking the Sutong Yangtze River Highway Bridge as a case study, the traffic flow saturation for this water area in June 2023 was calculated. The results indicate that the average saturation levels for upstream and downstream traffic were 11.94% and 15.27%, respectively, with maximum values reaching 93.34% and 99.95%. The results were then validated using Heinrich's Law and maritime accident statistics for the investigated area. The findings of this research can provide a reference for enhancing maritime safety management capabilities.

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Model of maritime traffic flow in the approaching waterways

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Keywords

Safety of navigation;
Maritime traffic flow;
Safety function;
Approaching waterways

Abstract

The significant increase in maritime traffic volume over the past decade, together with its concentration on specific routes, has directly highlighted the need to improve the maritime traffic organisation. In this context, the organisation of maritime traffic in restricted areas, such as port approaching waterways, starting points of maritime routes, or areas of high traffic density, has become particularly important. Accordingly, the purpose of this research is to propose a model for the organisation of the maritime traffic flow in the approaching waterways. The research analyses maritime traffic flow with the aim of quantifying the safety of navigation. Maritime traffic flow is defined by a model in which the safety of navigation is represented by a safety function. The research results demonstrate that a model can be used to measure the safety-of-navigation value of maritime traffic flow in a particular navigation area, and to support planning procedures to improve the safety of navigation.

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Digital Maritime Reporting Systems: Risk and Resilience Implications of the NEMO System

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Keywords

Maritime Single Window;
Digital transformation;
Change management;
Risk and resilience;

Abstract

Maritime logistics is currently experiencing a significant shift as digital solutions, such as Maritime Single Window (MSW) systems, are introduced to streamline reporting processes. These systems aim to improve efficiency, data quality, and coordination between stakeholders. At the same time, they change how maritime operations depend on information systems, which can introduce new types of operational risk. This study examines the Finnish Maritime Single Window system, NEMO, from a risk and resilience perspective. A structured Key Performance Indicator (KPI) framework, together with stakeholder analysis, is used to evaluate system performance, data reliability, and organisational readiness. The results show that digitalisation can reduce administrative workload and improve transparency, but it also introduces challenges related to data accuracy, system interoperability, and differences in stakeholder readiness. As operations become more dependent on centralised digital systems, risks related to system disruptions, coordination issues, and human adaptation become more visible. The findings suggest that resilience in digital maritime systems is a technical issue and depends on how well organisations manage change, align stakeholders, and develop necessary skills. Overall, the study highlights the need to view MSW systems as critical infrastructure and provides practical insights into safety, reliability, and resilience.

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Port Contracting and Capacity Reservation for Liner Carriers under Geopolitical Disruptions

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Keywords

Port contracting and capacity reservation;
Two-stage stochastic programming;
Liner shipping resilience;
Geopolitical disruptions;
Benders decomposition

Abstract

Geopolitical disruptions increasingly expose liner shipping networks to corridor blockages, port-capacity degradation and congestion propagation. This study develops a resilience-driven two-stage stochastic programming model for liner carriers. In the first stage, the carrier selects contracted ports and reserves priority-handling capacity before disruption realisation. In the second stage, scenario-dependent container flows are reallocated across feasible routes and ports subject to disrupted arc and port capacities, service-level requirements and limited unmet-demand recourse. To improve scalability, a Benders decomposition framework is combined with a path-based column-generation procedure for scenario subproblems. A Hormuz-centred case study is constructed from the LINERLIB benchmark and a corridor-based geopolitical stress ladder. The proposed strategy is compared with no-contract and minimum-reservation benchmarks. Results show that optimised preparedness reduces expected system cost by about 36% relative to the purely reactive benchmark and performs particularly well under severe disruptions. Resilience metrics further confirm that the proposed strategy delivers stronger service robustness, port-side redundancy and contracted-port support. The findings provide decision support for liner carriers seeking to balance ex-ante preparedness and ex-post adaptive routing under geopolitical uncertainty.

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Life-Cycle Economic Viability and Carbon Reduction Pathways of Alternative Fuels for Inland Waterway Vessels

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Keywords

Inland Waterway Vessels; Alternative Fuels; Life-Cycle; Economic Viability; Carbon Reduction Pathways

Abstract

Against the backdrop of the global shipping industry's transition towards green and low-carbon operations, this paper takes the route from Taiping Port to Zhenjiang Port on the Grand Canal as a case study. It constructs a four-tier progressive model encompassing cost, effectiveness, emissions, and pathways to assess the life-cycle economic viability and carbon-reduction potential of five alternative fuels: LNG, lithium-ion batteries, hydrogen, methanol, and ammonia. The results indicate that in the short term, LNG and lithium-ion batteries offer the best economic performance, with lithium-ion batteries achieving the lowest unit transport cost and LNG exhibiting the shortest payback period. In the medium term, hydrogen and methanol demonstrate significant potential for large-scale deployment, while in the long term, ammonia fuel offers the greatest promise for carbon neutrality but remains prohibitively costly. Based on these findings, a phased implementation carbon-reduction pathway is proposed, providing a decision-making reference for the green transition of inland waterway shipping.

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Evaluating the Resilience of Liner Shipping Networks from a Port Redundancy Perspective

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Keywords

liner shipping network; vulnerability analysis; port redundancy; maritime resilience

Abstract

Liner shipping networks (LSNs) are exposed to many types of disturbance such as regional conflicts, financial crises, and transport accidents, leading to service disruption. This study develops a vulnerability-based assessment framework that combines weighted network efficiency with liner service route outage rates and evaluates redundancy-port strategies for rerouting cargo when critical ports become unavailable. Using the China-Europe route during COVID-19 as a case, the analysis examines temporal changes in network vulnerability and compares alternative redundancy schemes. The results show that vulnerability increased markedly during periods of severe blank sailings and that targeted redundancy at key hub ports can partially restore network performance, although substitute ports do not fully replicate the operational role of failed hubs. The framework provides a practical basis for contingency planning and resilience assessment in maritime transport.

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Simulation Study on Ship Collision Risk at the Crossing Waterway of Port

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Keywords

Crossing waterway;
Ship collision;
Risk analysis;
System simulation

Abstract

Aiming at the problem of ship collision risk analysis in crossing waterways, this paper combines a risk assessment model, ship navigation rules, and system simulation technology to conduct simulation experiments and verifications for the crossing waterway of port and analyse the risk of ship collision. Firstly, the factors affecting ship collision are analysed, including natural environment factors, ship characteristics, management factors, and the characteristics of the crossing waterway. Then, the simulation modelling process of ship collisions at crossing waterways based on the risk assessment model, ship navigation rules, and system simulation technology is introduced in detail. A ship arrival simulation model is designed, the navigation process of ships is simulated, and a waterway system simulation model is constructed. The simulation modelling process comprehensively considers the key factors of ship navigation, such as waterway geographical environment, waterway layout, and ship behaviour, and evaluates the collision risk through the risk assessment model. Finally, the risk patterns of ship collisions in the crossing waterway of Yangshan Port are analysed through simulation experiments, providing a scientific basis and practical guidance for waterway management and ship navigation safety.

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Research on Communication Demand Analysis and Construction for Intelligent Safety Management of Coastal Ships

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Keywords

Communication Private Network;
Ship-to-Shore Communication;
Intelligent Management of Ship Safety;

Abstract

Aiming at the requirements for intelligent safety management of ships in complex coastal navigation scenarios, this study focuses on improving navigation safety, emergency response efficiency and all-domain supervision capability for coastal vessels. By systematically analysing ship-to-shore information interaction demands for safety management, this paper addresses the prominent problems of current ship-to-shore communication, including insufficient bandwidth, poor stability and high cost. A dedicated ship-to-shore communication private network is constructed in key coastal waters, and a series of high-quality information interaction tests are carried out. Test results show that the proposed private network can provide real-time, reliable and high-bandwidth communication support for coastal ship safety management, and effectively satisfy the application requirements of intelligent navigation supervision and emergency disposal. This work offers a practical communication solution for the construction of a new-generation intelligent maritime traffic management system.

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A Spatio-Temporal Analysis Framework for Ice Navigation Using AIS and Metocean Data: A Case Study of Arctic LNG Transportation

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Keywords

Arctic LNG transportation; ice navigation; AIS data; Metocean data; LNG carriers

Abstract

In recent years, the strategic importance of Arctic shipping routes has surged due to their potential for shorter transit times and access to untapped resources, making safe navigation of liquefied natural gas (LNG) carriers in ice-covered waters critical for polar transportation and the global energy supply chain. This study investigates ice navigation behaviour in Arctic LNG transportation using multi-source data, AIS data with meteorological and oceanographic (Metocean) data. First, extensive AIS data in Arctic waters are processed, which involves cleaning, interpolation, and compression to ensure optimal data quality. Second, AIS and Metocean data are spatiotemporally fused to create a multidimensional dataset that captures both environmental and navigational dynamics. Based on this, the ice navigation speed and route selection behaviour of LNG carriers are analysed across different Arctic seas under seasonal and directional conditions. The findings highlight adaptive variations in ship speed and route choices under diverse environmental conditions, providing theoretical support for risk identification, route optimisation, and navigation decision-making.

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Design and Implementation of "One Policy for One Route" Intelligent Supervision System for Ro-Ro Passenger Transport in Qiongzhou Strait

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Keywords

Qiongzhou Strait;
ro-ro passenger transport;
one policy for one route;
intelligent maritime;
data integration;

Abstract

Qiongzhou Strait is a strategic channel supporting the construction of Hainan Free Trade Port and a key area of China's national maritime safety supervision. Aiming at the prominent problems of insufficient multi-dimensional perception, serious data islands, lagging risk early warning, and insufficient emergency collaboration in traditional supervision mode, this paper designs and implements an intelligent supervision system for ro-ro passenger transport based on microservice architecture and domestic information technology infrastructure. The system is deeply integrated with the intelligent maritime supervision platform, VTS system and maritime supervision application, and constructs five core modules: all-round visual perception, transport capacity monitoring, route management, intelligent control and intelligent emergency response. The system realises full-domain situation monitoring, multi-dimensional risk early warning, dynamic capacity analysis, one-key route control and intelligent matching of emergency resources for large-scale personnel transfer scenarios. Engineering application shows that the system can significantly improve the efficiency of maritime supervision, optimise the organisation of cross-strait navigation, and enhance the ability of emergency support. It provides a replicable and promotable technical solution for refined and intelligent supervision of ro-ro transport in key waters.

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A COLREGs-Compliant AI Framework for Mixed Autonomous and Conventional Vessel Traffic Management

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Keywords

Maritime Autonomous Surface Ships (MASS); COLREGs; Structural Risk Nodes; AIS Spatial Analysis; Maritime AI Governance;

Abstract

The integration of Maritime Autonomous Surface Ships (MASS) into conventional traffic lanes presents a fundamental regulatory challenge: the 1972 COLREGs were designed for human navigators, yet their application to autonomous decision-making systems remains undefined. This paper proposes a COLREGs-compliant AI framework for Vessel Traffic Services (VTS) operating in mixed-traffic environments. Using historical Automatic Identification System (AIS) data from the high-density approaches of Yangshan Deepwater Port – comprising 14.64 million records (January 2025 - May 2026) from 15,041 unique vessels – we apply macro-spatial density analysis to identify high-probability COLREGs encounter zones, termed Structural Risk Nodes. The empirical distribution shows Rule 15 Crossing scenarios dominate (65.47%), followed by Rule 13 Overtaking (22.25%) and Rule 14 Head-on (12.28%). We propose a structured three-layer AI decision architecture mapping COLREGs Rules 13, 14, 15 to measurable spatial-traffic parameters, enabling VTS operators to maintain legal oversight while leveraging AI-assisted traffic orchestration. The framework advances maritime safety governance by bridging international regulations and emerging autonomous navigation technology, with direct implications for the IMO's ongoing MASS regulatory scoping exercise.

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Multi-objective dynamic route planning and speed optimisation for ships under typhoon conditions

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Keywords

Ship route optimisation; Multi-objective optimisation; NSGA-III algorithm; Typhoon avoidance

Abstract

Effective typhoon-avoidance routing is essential for maritime safety, yet conventional methods often decouple optimisation objectives or fail to provide a unified dynamic assessment. A multi-objective route optimisation framework is developed to integrate multi-source environmental data, waypoint sequences, and segment speeds. A cost model encompassing navigation risk, duration, and fuel consumption is established and solved via an enhanced NSGA-III algorithm. Results demonstrate that the proposed method effectively generates diverse Pareto-optimal solutions, with the compromise route exhibiting the most balanced performance. The Pareto front reveals a fundamental trade-off between voyage duration and fuel economy, while elucidating that risk is jointly driven by trajectory geometry, velocity profiles, and environmental exposure duration. Sensitivity analysis confirms that optimisation outcomes are more susceptible to energy-related parameters than to individual environmental risk weights. This study provides a robust quantitative basis for dynamic maritime decision-making and supports high-precision safety management in transoceanic shipping.

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Quantifying Food Supply Chain Resilience of Import-dependent National Using Bayesian Networks: Insights from Singapore

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Keywords

Food supply chain; Resilience assessment; Bayesian networks; Sustainable development; Dempster-Shafer evidence interval theory

Abstract

The food supply chain (FSC) is essential for global food security but is increasingly vulnerable to disruptions such as natural disasters, geopolitical conflicts, and economic instability. These disturbances threaten not only food availability but also broader economic stability and public health. Given their unpredictability, enhancing FSC resilience has become a critical priority. However, existing research remains fragmented and predominantly qualitative, often focusing on isolated components such as logistics or trade. Quantitative approaches are limited and rarely address resilience holistically at the national level, particularly under uncertainty. To address this gap, this study proposes a Bayesian network (BN)-based quantitative framework for assessing FSC resilience at the country level. The BN approach enables probabilistic modelling of complex interdependencies, integrating empirical data with expert knowledge and supporting reasoning under uncertainty. Singapore, a highly import-dependent country, is used as a case study. By incorporating data on trade, shipping networks, and economic conditions, the model evaluates resilience dynamics and identifies key influencing factors through sensitivity and inference analyses. Results highlight the importance of trade diversification and reliable logistics systems. The study provides actionable policy recommendations, including diversifying import sources and strengthening infrastructure, offering a robust foundation for improving FSC resilience and informing future research.

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Training for Wind-Assisted Ship Propulsion (T-WASP): A Competency Framework and STCW Gap Analysis

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Keywords

Wind-Assisted Ship Propulsion; STCW; Competency Framework; Systematic Review; Maritime Training

Abstract

Wind-Assisted Ship Propulsion (WaSP) technologies are entering commercial service at pace, driven by the IMO's 2023 net-zero strategy and tightening regulatory frameworks including the Carbon Intensity Indicator and FuelEU Maritime. By the end of 2024, 54 large commercial vessels were operating with WaSP systems installed, with a further 80 on the orderbook. Despite this growth, no standardised training framework exists for deck officers operating these systems, and the STCW Code contains no WaSP-specific provisions. This paper develops a competency framework for deck officers operating WaSP systems and assesses the adequacy of current STCW provisions against those requirements. A systematic literature review following PRISMA guidelines screened 297 records from Scopus and Web of Science, yielding 20 papers from which 172 raw competency statements were consolidated into a 30-item framework across seven operational domains. Each competency was mapped against STCW Tables A-II/1, A-II/2, and A-II/3 using a two-tier coverage classification. Gap analysis found that most of competencies lack adequate STCW coverage, with six of seven operational domains showing complete regulatory gaps. The framework provides a foundation for STCW amendment proposals and IMO Model Course development.

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The Role of Maritime Economics and Maritime Law in Data-Driven Leadership: A Comparative Analysis of Traditional and Autonomous Shipping Companies

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Keywords

Autonomous; MASS-Code; Maritime Law; Leadership; Maritime Economics

Abstract

The maritime industry is undergoing a profound transformation driven bydigitalisation, automation, and the emergence of autonomous vessels. As shipping companies navigate this transition, data-driven leadership has become a central strategic capability. This essay examines the role of maritime economics and maritime law in data-driven leadership shipping companies and compares their functions in transformation from traditional shipping to autonomous shipping. This transformation period is expected to last for some time as shipping is capital demanding industry. The change management based on maritime economics and maritime law will be in transition period for some time and knowledge based management will be essential in maritime businesses giving them competitive advantages. Comparison can be made to the transformation period in the 1850-1920 when wooden sailing ships were used effectively by same companies until 1920's. The IMO's voluntary MASS-code was finalised in May this year. This makes international autonomous shipping finally regulated. There are several companies around the world which are already prepared to start traffic. They are ready to introduce their mixed fleet, and the new technological transition is about to evolve.

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Challenges in Identifying Biofouling-Induced Ship Performance Loss from Real Operational Data

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Keywords

Biofouling impact;
Ship performance monitoring;
Added resistance;
ISO 19030;
Condition-based maintenance

Abstract

Biofouling-induced performance degradation is commonly assessed using indirect indicators from ship operational data, such as added resistance (AR). However, the extent to which these indicators reliably capture fouling effects in real-world conditions remains unclear. In parallel, experimentally derived, physics-based biofouling growth models have been widely developed. This study investigates the discrepancy between such models and real operational data, as well as the challenges of identifying biofouling-related performance loss. The analysis is based on industrial data from 39 vessels. The dataset and a biofouling-induced AR (BIAR%) indicator, defined as the percentage added resistance after ISO 19030-inspired corrections, originate from an industrial-grade monitoring system. A representative time dependent growth model is used as a physical reference. Results show that strict ISO filtering leaves only a small fraction of usable data, while the remaining data exhibit substantial noise and uncertainty. BIAR% retains strong dependence on speed and draft, and maintenance records are uncertain, with 20% of dry-docking transitions followed by increased resistance. Significant discrepancies are observed between theoretical expectations and real data. These findings highlight a fundamental challenge in linking noisy performance signals with complex fouling processes, suggesting that more robust and bias-aware methods are required for reliable biofouling assessment.

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Remote Lookout: Screen-Based Watchkeeping, Situational Awareness, and Workload in Remote Operation Centre Operators

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Keywords

Remote Operation Centre (ROC);
Watchkeeping;
Situational awareness;
Window wiper scan;
MASS

Abstract

The transition to Maritime Autonomous Surface Ships (MASS) has created the Remote Operation Centre (ROC) as the main workplace for qualified seafarers who monitor and control autonomous vessels from shore. Unlike conventional bridge watchkeeping, ROC operators rely mainly on screen-based visualisation, with limited direct physical cues from navigation, machinery, and the surrounding environment. This paper examines how prolonged screen use affects ROC operators' lookout performance, situational awareness, and workload. ROC operators are expected to retain watchkeeping responsibility for maintaining a proper lookout in line with COLREGs Rule 5. Drawing on eye-tracking research from ship bridges and simulators, the review identifies three main problems: reduced time spent on external lookout, increased fixation on displays, and attentional tunnelling. It proposes adapting the Window Wiper Scan (WWS) method, originally developed for bridge watchkeeping, to the ROC environment and introduces a Centre Console Display (CCD) concept inspired by aviation's six-pack to reduce information overload and visual clutter.

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Digital Fuel Passport: Addressing the Trust Gap in Green Maritime Fuels

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Keywords

Fuel Traceability;
Blockchain;
Sustainability;
Product Passport;
Supply Chain

Abstract

Maritime transport accounts for 90% of global merchandise trade and faces growing regulatory pressure to reduce greenhouse gas emissions. The transition to sustainable marine fuels complicates verification of fuel authenticity and lifecycle emissions across complex, multi-actor, multimodal supply chains prone to data fragmentation and greenwashing. This paper proposes the Digital Fuel Passport (DFP) as a tamperproof, lifecycle-oriented representation of maritime fuel batches. Rather than treating fuel as a static commodity, the DFP models each batch as a persistent digital entity that accumulates provenance, verification evidence, and emissions attributes throughout the supply chain. DFP relies on a blockchain-based trust infrastructure that records immutable digital representations of green fuel batches as non-fungible tokens on a permissioned ledger. Modular smart contracts govern lifecycle events and compliance logic, while blockchain oracles anchor certified physical marker and sustainability data. Privacy-preserving off-chain storage addresses data sensitivity and scalability. To support operational flexibility, the system incorporates a book-and-claim mechanism that decouples environmental attribute ownership from physical fuel custody while preserving auditability and preventing double counting. The approach complements emerging regulatory frameworks, including the European Union's Union Database for Biofuels (UDB), and provides a practical digital foundation for regulation-aligned maritime fuel traceability.

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Balancing Conflicts between Growth & Development and Protection of Environment in Ship Building and Ship Repair Industry

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Keywords

Shipbuilding and Ship Repair (SBSR);
Green Shipbuilding Industry;
Balanced Scorecard (BSC);
Analytic Hierarchy Process (AHP);
Sustainability in the Maritime Industry

Abstract

The shipbuilding and ship repair (SBSR) industry faces significant challenges in balancing economic growth with environmental protection. This study presents an integrated framework combining the Balanced Scorecard (BSC) and Analytic Hierarchy Process (AHP) to address these challenges. The BSC framework evaluates shipyard organisational performance across four key perspectives: financial, customer, internal processes, and learning and growth, while AHP prioritises these perspectives and their associated criteria. Drawing on insights from Malaysia's Green Shipbuilding and Ship Repair (Green SBSR) industry, the study identifies customer satisfaction as the most critical factor, followed by financial performance, internal processes, and learning and growth. Key recommendations include enhancing customer-centric strategies, investing in green technologies, building organisational capacity, and strengthening regulatory compliance. This integrated approach provides a robust model for achieving sustainable growth in the SBSR industry while aligning with global environmental stewardship goals.

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A three-layer approach to strategic risk assessment in maritime transportation

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Keywords

Strategic risk assessment;
Maritime safety;
Safety of navigation;
Ship collisions;
Maritime traffic hotspots

Abstract

Maritime transport is fundamental to global trade, yet ensuring navigational safety remains a major challenge, especially as vessel traffic, ship size, and offshore infrastructure continue to increase. Although operational maritime risk assessment has been widely studied, strategic risk assessment remains less developed and often relies on simplified geometric models and subjectively selected causation factors. This study proposes a three-layer framework for strategic ship collision risk assessment based on historical AIS data and first-principles logic. The framework integrates: i) encounter geometry between two vessels, expressed through a Collision Potential Index (CPI) derived from COLREGs-based assumptions and proximity indicators such as CPA; ii) the complexity and dynamics of surrounding traffic, assessed using the covariance matrix of nearby vessels' velocity vectors; and iii) human performance, represented by a Bayesian-inspired hybrid network with deterministic functional nodes based on the NARA framework and expert elicitation. The model produces a total CPI for each vessel and time step, which is then aggregated spatiotemporally for regional risk analysis. The framework was validated using AIS data from the Gulf of Gdansk (Poland). Results were compared with IWRAP Mk2 outputs, indicating that the proposed approach can support hotspot identification, capture temporal dependencies, and provide broader insights into collision-prone areas.

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From Prediction to Interpretation: An Ensemble Learning Method for Ship Fuel Consumption Analysis

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Keywords

Maritime transport;
Ship fuel consumption prediction;
Feature selection;
Ensemble learning;
Interpretability analysis

Abstract

Accurate prediction and interpretation of ship fuel consumption is essential for energy savings, emissions reduction, and intelligent transformation in the shipping industry. However, operational data's high dimensionality, nonlinearity, and multi-feature coupling of operational data pose challenges for accurate modelling using traditional methods. This study proposes a fuel consumption prediction framework integrating feature selection, ensemble learning models, and interpretability analysis. Using the Recursive Feature Elimination (RFE) method with Random Forest and cross-validation, a 10-dimensional optimal feature subset was selected from 36 initial features, reducing model complexity while enhancing predictive accuracy. Comparative analyses of three single machine learning models and three ensemble models identified the Stacking model as the best performer, achieving a test set R^2 of 0.9351, a 1.69% improvement over the top single model LightGBM, and a 10.15% reduction in RMSE. SHAP and partial dependence analysis further reveal nonlinear influence patterns of key features like Daily voyage hours and Draught, supporting ship energy efficiency and operational optimisation decisions.

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Promoting green shipping transformation: Innovative models for waterborne transport organisation and operations

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Keywords

Full-Voyage Optimisation;
Collaborative Operations;
Green and Low-Carbon Transition;
Integrated Waterborne Traffic Organisation;

Abstract

Driven by the International Maritime Organisation's (IMO) emission reduction targets, the transition of the shipping industry toward green development is not merely a matter of technological advancement, but also a fundamental restructuring of transport organisation. Typical phenomena such as "sailing fast and then waiting" demonstrate that local optimisation often undermines overall system efficiency, resulting in unnecessary energy consumption and carbon emissions. Against this background, we propose a new model for waterborne traffic organisation from a full-voyage perspective, aiming to shift from segmented and localised decision-making toward a systematic operational mode involving the coordinated participation of ships, ports, and relevant operating stakeholders. By integrating voyage planning, speed control, fleet organisation, and port scheduling into a unified decision-making process, and by leveraging multi-source data fusion and intelligent decision-making methods for dynamic optimisation, this approach establishes a more flexible and efficient operational framework. Building on this model innovation, the presentation will further draw on representative Chinese practices in smart port and green shipping development, including smart port rating, integrated traffic organisation at Yingkou Port, and integrated traffic management in the Qiongzhou Strait.

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COLREG decision complexity metrics for autonomous navigation

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Keywords

COLREG;
Autonomous navigation systems;
Vision Language Model (VLM);
Decision Complexity Estimation

Abstract

Autonomous navigation systems are rapidly advancing maritime operations. These systems must make reliable decisions that not only comply with the International Regulations for Preventing Collisions at Sea (COLREG) under well-defined situations but also handle the full spectrum of real-world complexity. Existing collision risk metrics focus primarily on proximity and urgency between ships but do not explicitly capture the decision-making complexity when interpreting rules, resolving interactions, and selecting feasible manoeuvres are all simultaneously being executed by autonomous systems. This paper introduces a structured metrics for estimating COLREG decision complexity by distinguishing between COLREG-independent and COLREG-dependent factors. Together, these factors provide a semantic representation of decision complexity that be used for decision making. Two complementary data sources are used to validated the proposed metrics. Synthetic encounter scenarios generated by a rule-based scenario generator are used to analyse and validate COLREG-independent complexity in a controlled setting, demonstrating their suitability for decision-support and scenario-based testing applications. The results highlight how the decision complexity provides additional insight into situations that are difficult to manage despite moderate risk levels. And it establishes a foundation for complexity-aware simulation-based testing and digital assurance of autonomous navigation systems.

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Fatigue-Induced Cognitive Drift in Bridge Watchkeepers: A Workload-Window Analysis of Decision Latency in Near-Miss Reports

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Keywords

Maritime fatigue; Bridge watchkeeping; Situational awareness; Bayesian Network; Decision latency

Abstract

Bridge watchkeeping near-misses are commonly attributed to fatigue, situation awareness loss, and workload, yet existing probabilistic models typically treat these factors as static categorical inputs and rely on accident rather than near-miss data. This paper presents a Bayesian Network (BN) model of decision latency in maritime bridge near-miss events, structured in three tiers in which temporal and operational exposures act through cognitive mediators on response performance. The network was built using a hybrid approach of combining domain theory and structured expert elicitation, parameterised in GeNIe Modeller using the Expectation–Maximisation algorithm, and applied to 350 narratives compiled from MAIB, NTSB, and IMO GISIS records. Ten-fold cross-validation produced AUC values of 0.855, 0.802, and 0.892 for the Immediate, Delayed, and Failed states of decision latency. Diagnostic inference identifies high fatigue and lost situation awareness as the dominant antecedents of response failure, with junior experience and high workload during late-night watches amplifying this effect. Three scenario simulations show how response failure probability rises from 17% under low-risk conditions to 35% under compound overload. The framework offers a transparent decision-support structure for watch-rotation scheduling and bridge resource management.

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Rapid prediction of ship fire scenarios using a GAN-based data-driven model

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Keywords

Ship fire simulation;
Generative adversarial network;
Passenger ship;
Fire dynamics;
Temperature field prediction.

Abstract

Prediction of ship fire scenarios is of significant importance for improving onboard fire safety and emergency preparedness. However, conventional fire simulation methods based on Computational Fluid Dynamics (CFD) are characterised by high computational cost and long simulation times. These limitations restrict their applicability in rapid assessment and real-time scenarios. To address these issues, a ship fire scenario prediction method based on a Generative Adversarial Network (GAN) is proposed in this study. Based on the "Ocean Jewel" passenger ship, a multi-scenario fire database is constructed using the Fire Dynamics Simulator (FDS), and the simulation data are subsequently preprocessed. Then, a GAN model is developed, in which ship layout, fire source location, and fire development time are used as inputs to enable rapid prediction of the temperature field. The research findings show that the proposed GAN-based method reduces computational cost while maintaining high accuracy, showing strong potential for rapid ship fire simulation and supporting safety assessment and evacuation decision-making.

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Effects of Panic Propagation on Human Evacuation from Passenger Ships: An Agent-Based Simulation Study

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Keywords

Maritime safety;
Emergency evacuation;
Passenger ships;
Panic propagation;
AnyLogic

Abstract

Efficient human evacuation from passenger ships is critical to maritime safety. During emergency evacuation, close-range interpersonal interactions, including panic propagation and crowd jostling, may aggravate congestion, falls, and secondary injuries. To address these challenges, a simulation model for human evacuation from passenger ships under panic conditions is developed to dynamically represent the evacuation process under the complex ship layouts. First, the personality model is integrated with the transmission model to develop a Panic Emotion Propagation Model (PEPM), through which passenger heterogeneity, behavioural differences, and panic propagation within the crowd are characterised. Second, the PEPM is embedded into a simulation environment constructed from the actual spatial layout of a passenger ship, so that the dynamic evolution of panic during evacuation can be reproduced in a realistic setting. Finally, the effects of panic propagation on evacuation performance are comprehensively evaluated using multiple evacuation indicators. The simulation results show that panic significantly disrupts the evacuation process by intensifying local congestion and passage conflicts, prolonging total evacuation time, and producing a pronounced "faster-is-slower" effect. This study provides theoretical support and practical guidance for emergency evacuation planning on passenger ships.

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How Do Markets, Ships, and Prices Co-Evolve? A Data-Calibrated Oil Market-Vessel Equilibrium Simulation Framework for Global Crude-Oil Shipping

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Keywords

Crude-oil shipping;
Agent-based simulation;
Market-logistics equilibrium;
AIS

Abstract

More than 78% of global oil trade is transported by tanker, so disruptions in major export regions and maritime chokepoints can propagate quickly through crude sourcing, fleet deployment, and freight markets. This extended abstract presents DOMES, a Data-Calibrated Oil Market-Vessel Equilibrium Simulation framework for crude-oil tanker networks. DOMES integrates AIS trajectories, tanker registry information, energy statistics, freight benchmarks, and event records to initialise a daily multi-agent simulation linking exporters, importers, and vessels. The framework combines an empirical calibration layer, a cargo-allocation layer, and a vessel-execution layer in which spot procurement, scarcity premia, freight formation, route choice, port queues, vessel speeds, and inventories co-evolve. Stable-year reconstruction, Russia-Ukraine war reproduction, and Strait of Hormuz stress tests show that DOMES captures route-level tanker-capacity and freight patterns and produces interpretable disruption-response dynamics. The results indicate that severe chokepoint closures mainly prolong elevated freight and longer voyage-distance conditions rather than proportionally increasing peak freight levels.

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Experimental Study on Bottom-Vented Combustion Behaviour of Ternary Lithium-ion Batteries in Ro-Ro Ship

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Keywords

Battery electric vehicle;
Ro-Ro ship;
Thermal runaway;
Lashing hole;
Solutions for Maritime.

Abstract

With the rapid growth of Battery Electric Vehicle (BEV) transport by Roll-on/Roll-off (Ro-Ro) ships, battery thermal runaway risk has become a critical maritime issue. Compared with conventional vehicle fires, lithium-ion battery thermal runaway involves high combustion intensity, rapid fire growth, toxic gas release, re-ignition tendency, and limited suppression effectiveness, making fires on enclosed Ro-Ro decks particularly hazardous. Bottom-Venting (BV) has been proposed to redirect thermal runaway products downward and reduce lateral fire spread. However, in Ro-Ro environments, deck openings such as lashing holes may interact with downward venting and create new vertical heat transfer pathways. This study compares the combustion behaviour of a ternary lithium-ion battery under free-burning and enclosed conditions. The results show that a stable downward jet flame is formed only when the battery is tightly enclosed and venting products are guided by the surrounding structure. In this case, the jet flame penetrates the lashing hole and significantly increases lower-deck thermal exposure. The findings indicate that the downward jet is not an inherent feature of thermal runaway, but a structurally induced fire behaviour. This highlights the importance of coordinated design between battery enclosure structures and Ro-Ro deck openings.

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Estimating CO_2 and $CO_{2\text{-equivalent}}$ Emissions from Cruise Ships at Berth: The Case of Galataport Istanbul

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Keywords

Cruise ships;
Galataport Istanbul;
CO_2 emissions;
$CO_{2\text{-equivalent}}$ emissions;
Berth emissions

Abstract

This study estimates carbon dioxide and CO2-equivalent emissions from cruise ships calling at Istanbul during 2024, with particular focus on emissions generated during berth operations. In particular the present analysis focuses on Galataport, a recently established cruise terminal (operational since 2021), that still lacks a consolidated body of port-based environmental assessment. By combining recent port-call records with an Information Handling Services (IHS)-derived ship database, this work provides empirical characterisations of the cruise traffic currently approaching this new terminal, including fleet statistics and a preliminary quantification of its greenhouse gas footprint. For each port call, berth duration was derived from recorded arrival and departure times, while auxiliary-engine total power was used as the main activity parameter for hoteling emissions. Where auxiliary-engine power data were unavailable, they were estimated as 16% of main-engine total power. Fuel consumption at berth was then calculated assuming an auxiliary-engine load factor of 0.40 and a specific fuel consumption of 210 g/kWh. CO2 emissions were estimated using the IMO carbon factor for diesel/gas oil, while CO2e emissions additionally incorporated CH4 and N2O. The assessment covers 162 cruise calls and yields total estimated emissions of 6,939.6 tCO2 and 7,007.7 tCO2e.

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Evacuation Time Prediction of Passenger Ships Based on Feature Selection

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Keywords

Maritime Safety;
Passenger ship evacuation;
Time prediction;
Machine Learning;
Feature selection

Abstract

Accurate prediction of passenger ship evacuation time is crucial for maritime safety. Existing methods struggle with complex factor interactions, noisy data, and emergency scenarios. This study proposes a framework combining multi-scenario evacuation simulation, feature fusion and selection, and machine learning models optimized by genetic algorithms. Key factors, including passenger number, response time, walking speed, stair availability, and guidance measures, were transformed into simulation variables using Pathfinder. Interaction features were constructed using association rules, and forward selection identified the most predictive subsets. Hyperparameters of RF, XGBoost, LightGBM, and ANN models were optimized to improve accuracy. Experiments show superior performance compared with traditional methods, with R^2 above 0.92. Interactions among environmental conditions, guidance measures, and ship state significantly affect evacuation time. The framework supports accurate evacuation prediction, multi-factor modelling, and applications in emergency planning, safety assessment, and ship design optimisation. Future work will include complex behaviours and multi-model fusion to enhance realism and reliability.

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Human-Autonomy Teaming in Maritime Unmanned Vehicles: A Socio-Technical Framework for Safe and Resilient Operations

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Keywords

Socio-technical; Human-autonomy teaming (HAT); Maritime Unmanned Vehicles (MUVs); Maritime operations

Abstract

The increasing capability of artificial intelligence (AI), machine learning, sensor fusion and remote or automatic communications systems is rapidly moving the industry away from traditional manned vessels in favour of a greater level of autonomous operations at sea. Although the advantages of automation-driven operations are well known, history teaches us that often, operating in highly automated domains can be potentially just as dangerous. Previous studies of maritime autonomy suggested that human factor issues, such as excessive dependence on automated systems, inappropriate use of navigational technology and automation complacency remain a significant risk. Therefore, this paper addresses this gap by proposing a socio-technical Human-Autonomy Teaming (HAT) framework for Maritime Unmanned Vehicles (MUVs) operations. The proposed framework conceptualizes autonomous maritime operations as collaborative systems where human operators and autonomous agents function as interdependent teammates to achieve safe, efficient, and resilient maritime operations. This study provides a theoretical foundation for future empirical validation and human-centered autonomous maritime system design. It is expected that his study will extend socio-technical systems into HAT context through validated measurement models empirically. In practice, the outcome of this study can guide the remote operation centre design for MUVs operations.

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Noise Emission from Vibrating Marine Vehicles in a Shallow Water Environment

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Keywords

External noise emission;
Boundary element method;
Waveguide Green's function;
Finite water depth.

Abstract

An application of the Boundary Element Method formulation to noise emission problem in a shallow acoustic environment is presented. Acoustic radiation behaviour of an elastic cylinder, representing a submarine pressure hull, floating on the free surface of a finite depth water is investigated and numerical predictions are presented together with experimental measurements. First, the Helmholtz integral equation (HIE) is employed to calculate sound emission from elastic structure vibrating on the free surface. Effects of the free surface and finite water depth are introduced by using waveguide Green's function where a chain image-source method is used for derivation. The boundary element (BE) framework is utilized to enable the evaluation of radiated pressure by discretizing only the fluid-structure interface for the acoustic field calculations. Acoustic radiation from a semi-submerged cylinder is investigated. The cylinder problem is first solved numerically. Also, an experiment is performed where a semi-submerged cylindrical shell is excited with a hammer hit and acoustic pressure is recorded by a hydrophone. The results obtained with the mathematical model are compared with the experimental data. It is observed that, although the predicted pressure values slightly differ from those of the experimental data, the acoustic pressure peaks occur at frequencies which are compatible with the wet natural frequencies of the cylinder, as expected. In general, the results obtained with the vibro-acoustic mathematical model are in good agreement with the finite element solutions and experimental measurements.

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Structuring Remote Human Intervention in Autonomous Ship Operation - An Event Sequence Diagram Approach

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Keywords

Remote Operation Centre;
Remote human intervention;
Event Sequence Diagram;
Human-machine collaboration;
Authority transition.

Abstract

Maritime Autonomous Surface Ships (MASS) operating requires effective collaboration between autonomous systems (ASs) and remote operators (ROs) in Remote Operation Centres (ROCs). However, limited attention has been given to how remote human intervention unfolds as a staged and branching process when autonomous operation becomes insufficient. This paper proposes a qualitative Event Sequence Diagram (ESD)-based scenario-structuring model to represent the remote intervention process in ROC-supported autonomous ship operation. The proposed ESD formalises the intervention pathway from initial situation recognition to the establishment and confirmation of a new human-machine collaboration (HMC) arrangement. The scenario analysis shows how different combinations of recognition, response, transition, confirmation, and fallback conditions could lead to different intervention outcomes. The results reveal that remote intervention in ROC-supported MASS operation should be understood as a dynamic HMC transition shaped by multiple dependent conditions, instead of a single takeover event. The model provides a structured basis for identifying intervention-critical points and deriving implications for ROC interface design, authority-transition procedures, and RO training requirements.

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From Shore Power to Port-Serving Nuclear: A Global Framework for the Policy and Technical Adoption of SMRs in Seaports

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Keywords

Decarbonization;
Seaport;
Nuclear;
Safety management;
Onshore power supply;

Abstract

Decarbonization and net-zero targets are reshaping maritime transport, with seaports emerging as critical sites for energy transition. Among low-carbon energy options, small modular reactors (SMRs) are distinctive because they can provide reliable firm power with near-zero operational emissions, making them a potentially attractive option for electrified container ports. However, their adoption in seaports is far more complex than a simple power substitution and depends on the resolution of multiple technical, regulatory, safety, environmental, social, and financial challenges. This study develops a structured framework to assess the applicability of port-serving SMRs in large container ports. Based on a broad documentary evidence base, 33 adoption factors were identified and grouped into five categories: port energy-service demand, nuclear technical integration, safety-security-regulatory conditions, institutional-commercial conditions, and supply-chain and lifecycle-support conditions. An LLM-assisted synthesis and ISM-MICMAC analysis were then used to reveal the structural relationships among these factors. The results indicate that siting compatibility, regulatory alignment, OPS dependence, and sustained firm-load magnitude act as foundational drivers, while financing and liability emerge as downstream but decisive conditions. The study provides a staged adoption pathway to help policymakers and port stakeholders identify when a container port becomes a credible candidate for SMR deployment.

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Green Shipping Corridors Development for Maritime Decarbonisation: A Systematic Literature Review

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Keywords

Green shipping corridors; Systematic literature review; Maritime decarbonisation; Gray literature

Abstract

Green shipping corridors (GSCs) have emerged as route-based mechanisms for coordinating the transition to zero- and near-zero-emission shipping. However, the knowledge base remains fragmented, and existing reviews have paid limited attention to systematically integrating peer-reviewed studies with policy and industry grey literature, which plays a crucial role in understanding the development GSCs due to its emerging and policy-driven features. To fill this gap, this study systematically selects relevant literature by applying the PRISMA framework, and combines bibliometric analysis and conceptual synthesis to explore the development trends, core concepts and analytical dimensions of GSCs. The results suggest that GSCs cannot be regarded merely as emission-reduction pilots on specific shipping routes. Instead, they should be conceptualised as a route-based implementation framework that integrates fuel supply, port infrastructure, vessel deployment, cargo flows and policy and commercial mechanisms within a manageable geographical scope. Based on the literature synthesis, this study identifies four core analytical domains of GSC development: ports and infrastructure, fuel and energy pathways, cargo, route and vessel operations, and economics, policy and society. Moreover, the review highlights major challenges in current GSC research and outlines general directions for future research. The results contribute to a clearer understanding of GSCs as route-based implementation frameworks and provide analytical support for future research, policy discussions and practical corridors.

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Initial-Action Envelope for Pilot Man-Overboard Response: Stern-Clearance Time and Heading Change

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Keywords

Man overboard;
Crew-witnessed MOB;
Stern-clearance time;
Ship manoeuvring;
Decision support

Abstract

In a pilot man-overboard (MOB) event, the casualty is immediately exposed to the stern–propeller hazard, requiring a sustained hard-over rudder action long enough to clear the propeller-hazard zone before any full recovery-turn pattern can be initiated. Existing guidance is qualitative and does not specify event-wise hold-time thresholds; furthermore, no historical dataset of bridge-team responses to pilot MOB exists, making pilot MOB a near-zero-record event class. This study formulates immediate protection as a stern-clearance problem and develops a prospective analytical envelope. A low-order yaw-response model coupled to bridge and rudder timing, stern geometry, loading effects, and environmental drift is applied to 5,302 scenarios constructed from AIS-observed pilot-transfer contexts under standardised emergency-action assumptions. Three outcome groups emerge: no hazard entry, clearance after entry, and no clearance within the simulation window. For cleared-after-entry cases, the baseline median hold-time is approximately 63 s, falling to approximately 32 s under a side-aware command convention reflecting bridge practice. A no-action counterfactual shows that the principal protective contribution of the hard-over command is converting stuck-in-zone events into cleared events, raising the entered-no-clear share twenty-five-fold when removed. The study provides the first reproducible analytical baseline for pilot MOB initial-response decision support.

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A Resilience-Based Multi-Objective Decision-Making Framework for Opportunistic Maintenance in Container Terminals

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Keywords

Container Supply Chain, Port Disruption, Resilience, Operation and Maintenance, Opportunistic Maintenance

Abstract

Among various disruptive factors, frequent and unexpected equipment failures severely affect port resilience. Maintenance activities for such equipment account for approximately 11% of total port operating costs. Due to the strong operational and economic interdependencies among port equipment, their maintenance follows a complex series-parallel structure, creating favorable conditions for implementing opportunistic maintenance (OM). Therefore, this study develops a novel OM strategy triggered by unexpected equipment failures, integrating reliability, cost, and resilience as multi-objective decision criteria. This framework consists of three components: 1) a machine learning model predicting port resilience under various equipment unavailability, 2) a maintenance model estimating maintenance performance, including failure probability, reliability, maintenance costs and losses under various maintenance options, and 3) a multi-objective decision making module identifying optimal decisions amid conflicting objectives. Using real operational data from ports, the proposed framework serves as a practical decision-support tool that guides maintenance strategies during the post-disruption recovery phase, assisting port managers in making informed decisions under highly uncertain operational environments.

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Integration of a System Identification-Based Ship Manoeuvring Model with Autonomous Path-Following Control

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Keywords

System Identification; Ship Manoeuvring; Autonomous Ships; Path Following; Bayesian Reasoning

Abstract

Autonomous ship navigation requires guidance and control architectures capable of generating dynamically consistent vessel motions under changing operational conditions. Conventional autonomous control applications commonly rely on mathematical manoeuvring models requiring predefined hydrodynamic formulations and extensive parameterisation procedures, which may reduce practicality in real-time implementations. This study presents an integrated autonomous path-following framework combining a System Identification (SI)-based ship manoeuvring model with Line-of-Sight (LOS) guidance and Proportional–Integral–Derivative (PID)-based heading control. The manoeuvring prediction framework is developed using a Dynamic Bayesian Network (DBN) formulation trained on free-running experimental data of the KRISO Container Ship (KCS). Rather than focusing solely on standalone manoeuvring prediction performance, the study demonstrates how SI-based motion prediction can be integrated directly into autonomous control architectures as a computationally efficient dynamic prediction component. Waypoint-based simulations demonstrate smooth trajectory tracking, realistic rudder behaviour, and dynamically consistent vessel responses during both straight-line and turning operations. The findings indicate that SI-based manoeuvring prediction can provide a practical framework for rapid trajectory generation in autonomous navigation systems and may also support future uncertainty-aware collision avoidance applications involving surrounding vessel trajectory prediction.

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Port Service Route Recovery in the Global Container Shipping Network

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Keywords

Maritime transport; Global container shipping network; Resilience; Port service route recovery

Abstract

This study aims to develop a port service route recovery (PSRR) solution to addressing a port-centred decision problem in the global container shipping network (GCSN). Two flow-based recovery perspectives are firstly analysed, where the overall throughput (OT)-oriented perspective helps evaluate the recovery of system-wide cargo flow circulation across the GCSN, while the port throughput (PT)-oriented perspective enables to evaluate the recovery of the disrupted port's own cargo handling function. Then, a deterministic mixed integer programming (MIP) model is developed to jointly schedule service route reconnection and evaluate time-dependent flow recovery under each perspective. Based on a data-driven GCSN structure, numerical experiments on the Port of Liverpool demonstrate that the MIP consistently outperforms four recovery heuristics. The results also confirm that recovery schedules under PT and OT perspectives generate strongly correlated but materially different recovery outcomes. The sensitivity analysis further indicates that increasing the number of recovery units accelerates functional recovery, but with diminishing marginal returns. By formulating the PSRR problem, this study contributes to shift the focus from disruption impact assessment to post-disruption recovery scheduling. Practically, the proposed framework provides an operationally interpretable decision-support tool for strategic port recovery planning and for improving post-disruption shipping resilience.

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Cybersecurity in smart port systems: A systematic review and future research agenda

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Keywords

Maritime Cybersecurity;
Smart Ports;
Digital Transformation;
Defence Strategy;
Port Digitalisation

Abstract

The rapid digitalisation of maritime logistics has transformed conventional ports into complex cyber-physical systems. Technologies such as the Internet of Things and blockchain improve operational efficiency and information transparency but also introduce new cybersecurity vulnerabilities. Recent incidents, including ransomware, phishing, and distributed denial-of-service attacks, highlight the increasing exposure of smart ports to cyber disruptions that may affect critical infrastructure and global supply chains. Despite growing attention, existing research remains fragmented and lacks a systematic understanding of the relationships between port digitalisation, emerging cyber threats, and defence strategies. This study presents a systematic review of cybersecurity risks in smart ports from technological, operational, and policy perspectives. A systematic review was conducted using the PRISMA framework and bibliometric analysis with CiteSpace to identify research trends and knowledge structures. Cyber incident data were further analysed to construct an attack network map, revealing key attack vectors and targeted systems. Based on these findings, a layered cybersecurity defence framework is proposed. In addition, the evolution of port digitalisation is synthesised into five developmental stages to identify stage-specific cybersecurity requirements. The results provide a structured understanding of cybersecurity risks in smart ports and offer guidance for developing more resilient cybersecurity strategies in digitally integrated port systems.

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A Two-Stage Ship Route Extraction Method for Structured Waterways

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Keywords

Shipping route modelling;
Trajectory clustering;
Busy water area;
AIS data;

Abstract

Shipping route information provides important spatial references for understanding ship behaviour and maritime traffic organisation. In structured waterways, such as Traffic Separation Schemes (TSSs) and navigational channels, ship trajectories share a common passage while following different approach and departure paths due to their different origins and destinations. Accurately distinguishing these route branches is essential for representing the complex traffic organisation and movement patterns in structured waterways. Conventional route extraction methods that represent a trajectory cluster using a single centreline may therefore fail to capture these distinct route features. To address this limitation, this study proposes a two-stage route extraction method based on ordered turning point sequences. Change Point Detection (CPD) is first applied to course variations to identify the turning points. Each turning point is characterised by its spatial location and the courses before and after the turn, and each trajectory is subsequently represented as an ordered sequence of these turning points. The route extraction is then performed in two stages. The first stage groups trajectories according to the spatial similarity of their turning point sequences, while the second stage further separates trajectories within each group according to differences in their entering and leaving courses. Hierarchical clustering is applied at both stages to identify trajectories that share similar route structures. The proposed method is evaluated using ship trajectories collected from Øresund waterway areas, a structured waterway between Denmark and Sweden involving ferry corridors, bridge areas, dredged routes, and TSSs. The results show that the proposed method distinguishes trajectories with spatially similar turning points but different approach and departure paths, thereby identifying route patterns that would otherwise be combined into the same cluster. The extracted routes provide a more detailed representation of the spatial organisation and branching structure of ship traffic in structured waterways, thereby offering more reliable route baselines for traffic pattern analysis and supporting fine-grained maritime traffic supervision.

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A Lightweight Construction Method for Maritime Route Grids Based on an Improved Adaptive SOM Model

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Keywords

Self-Organizing Map; Shipping Network; Lightweight Modelling

Abstract

To achieve sustainable transformation in the shipping industry and address increasingly complex green route demands, developing an accurate and lightweight navigation space grid is essential. Traditional uniform grids face challenges in balancing computational efficiency and spatial resolution, resulting in high computational demands in open sea regions and decreased accuracy near shores. This paper introduces an adaptive marine route grid method, leveraging an adaptive self-organising map (SOM) model to address and enhance the current challenges in marine routing. This method uses a spatial constraint mechanism that allows network nodes to understand the distribution pattern of the coastline. In nearshore waters, nodes are densely arranged near the coastline to aid navigation in complex environments, whereas in open waters, they should be distributed sparsely. Experimental results show that the framework effectively represents the spatial attributes of waterways, maintaining the near-shore model's accuracy and reducing redundant nodes in open sea areas. This study proposes an adaptive route grid modelling method, which combines lightweight computing with high precision, thereby overcoming the shortcomings of the traditional uniform grid. This lightweight modelling approach enhances computational efficiency for energy-saving path planning in new energy vessels, assessment of shipping carbon emissions, and optimisation of green shipping networks by reducing computational redundancy.

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Feasibility assessment of green shipping corridors: An evidential reasoning-based framework

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Keywords

Maritime decarbonisation; Green shipping corridors; Evidential Reasoning; Sustainable shipping

Abstract

Green shipping corridors (GSCs) are emerging as a key mechanism for maritime decarbonisation. This study develops a holistic feasibility assessment framework incorporating alternative fuel readiness, infrastructure support, market demand, and policy incentives. A fuzzy evidential reasoning (ER) approach is applied to integrate heterogeneous indicators under uncertainty. Four GSCs across different regions and development stages are evaluated. The results reveal that policy incentives are the primary driver enabling the transition of GSCs from strategic commitment to operational implementation, while demand aggregation plays a comparatively limited role. The findings contribute to the methodological advancement of GSC feasibility assessment and provide actionable insights for policymakers and industry stakeholders.

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A Data-Driven Estimation of Ship Engine Specific Fuel Consumption for Tanker Fleet EEXI Assessment

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Keywords

Specific fuel consumption; Tanker fleet; Random forest; Ship emissions; EEXI

Abstract

Engine-specific fuel consumption (SFC) is a key input to the attained Energy Efficiency Existing Ship Index (EEXI), yet vessel-level rated values are absent from many commercial ship databases. This study develops a data-driven framework to estimate main engine (ME) and auxiliary engine (AE) SFC for tanker fleets. Rated SFC records for 1,431 tankers were linked with ten ship design and engine variables. Missing values were imputed using multivariate imputation by chained equations, and 10 regression methods were evaluated using an 80:20 split, k-fold cross-validation, and mean absolute error. Random forest achieved the lowest test error for ME SFC (0.78 g/kWh) and AE SFC (1.12 g/kWh). An analysis of a database of 5,432 tankers showed that the mean ME SFC ranged from 166.86 to 170.55 g/kWh across vessel types, whereas AE SFC varied less widely. A fleet screen for vessels above 25,000 DWT indicated rounded non-compliance shares from 52.7% for very large crude carriers to 83.2% for Panamax tankers. Vessel-specific estimates therefore reveal technical heterogeneity obscured by fixed assumptions and provide a more defensible basis for preliminary EEXI screening when certified values are unavailable.

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Multi-Dimensional Port Risk Assessment in an Emerging Economy: Evidence from a National Survey of the Brazilian Port System

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Keywords

Port risk assessment; maritime logistics; resilience; emerging economies; Brazil

Abstract

This research analyses the risk landscape of the Brazilian port system based on a comprehensive national assessment conducted by ANTAQ and UFMA. Using a multi-dimensional framework encompassing economic, environmental, geopolitical, social, and technological risks, the study evaluates 76 variables across three temporal horizons (2025, 2026–2027, and 2035). The analysis is based on responses from 125 sector specialists and stakeholders, applying descriptive statistical techniques to assess perceived risk levels and temporal evolution. Results indicate that economic and geopolitical risks dominate in the short term, particularly political instability, regulatory burden, and global trade tensions, while environmental risks exhibit the highest long-term growth, driven by climate change and ecosystem degradation. Technological risks remain stable but reveal latent vulnerabilities related to digital infrastructure. The findings highlight strong interdependencies across risk dimensions, emphasising the need for integrated governance and resilience strategies. The research contributes to maritime risk literature by offering an empirically grounded, context-specific assessment of port risks in an emerging economy, providing policy and managerial implications for enhancing port resilience and sustainability.

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Digital Twin Applications in Port Energy Management: A Systematic Review and Bibliometric Analysis

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Keywords

Digital Twin;
Port Energy;
Management;
Systematic Literature Review;
PRISMA Framework;
Bibliometric Analysis

Abstract

This paper explores the application of Digital Twin (DT) technologies in port energy management through a combination of systematic literature review and bibliometric analysis. As port operations continue to expand, managing energy demand alongside environmental pressures has become increasingly challenging, and conventional approaches often struggle to capture system complexity. In this context, DTs have attracted growing attention for their ability to integrate real-time data with simulation and optimisation. A systematic review was conducted following the PRISMA 2020 framework, using publications from Scopus and Web of Science between 2016 and 2024. After screening, 54 studies were selected for detailed analysis. The results indicate that DT applications are mainly focused on operational optimisation, energy efficiency, and decision support. However, the literature appears somewhat fragmented, with limited integration across energy systems, port operations, and sustainability considerations. Many studies focus on specific components rather than system-level approaches. Overall, this paper outlines the current research landscape and highlights several gaps for future research.

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Assessing Railway Infrastructure Resilience to Extreme Weather Events Using a Fuzzy Rule-Based Bayesian Network

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Keywords

Climate risk;
Railway infrastructure;
Extreme weather events;
Fuzzy Rule-Based Bayesian Network;
Adaptation planning

Abstract

The increasing frequency and severity of extreme weather events (EWEs) are placing growing pressure on railway infrastructure systems, creating challenges for safety, reliability, maintenance planning, and climate adaptation. Existing studies provide valuable evidence on weather-related disruption and asset vulnerability, yet many remain constrained by deterministic assumptions, incomplete empirical data, or limited integration of expert judgement under uncertainty. This study develops a Fuzzy Rule-Based Bayesian Network (FRBBN) framework for assessing climate-driven railway risk under current and near-future conditions. The framework integrates objective prior evidence with structured expert elicitation from 53 domain experts recruited through RSSB, IMechE, and professional networks. Experts assessed five EWE categories across four infrastructure component groups and five risk/resilience dimensions. Linguistic judgements were converted into fuzzy belief degrees and embedded within Bayesian conditional probability tables for 2025 and 2035 scenarios. Results show that High Risk increases from 29.6% to 36.2% by 2035, driven mainly by a 22.4 percentage-point rise in High Likelihood. Scenario analysis shows that extreme risk emerges most strongly when flooding, structural exposure, and low resilience coincide. The FRBBN provides an interpretable uncertainty-aware tool for railway adaptation planning.

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Digitalization of maritime traffic rules for ship remote control

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Keywords

MASS;
AIS data;
Traffic regulation formalization;
Metric Temporal Logic;

Abstract

Compliance with navigational rules is fundamental for safe maritime traffic operations and is especially critical for Maritime Autonomous Surface Ships (MASS), which often relies on decisions without onboard human navigators. However, the human-oriented operations and often ambiguous nature of maritime traffic laws, particularly with respect to compliance thresholds, create a major obstacle for their direct implementation in autonomous systems to enable the timely detection of non-compliant behaviour. To address this issue, this study proposes an ship remote control framework for MASS. First, Metric Temporal Logic is employed to formalise maritime traffic laws into machine-interpretable monitoring rules, enabling the dynamic evaluation of vessel behaviour in real time. Second, a trigger-based hierarchical online monitoring architecture is developed to improve both the rationality and computational efficiency of the monitoring process by activating different monitoring modules only when relevant encounter conditions are satisfied. Third, counterfactual analysis is introduced to assess the safety implications of compliant and non-compliant ship behaviour, thereby providing an improved understanding of the operational consequences of compliance decisions. In addition, the ambiguous compliance thresholds are determined based on historical near-collision scenarios extracted from AIS data, and the sensitivity of threshold selection is systematically analysed. The proposed framework is validated using historical AIS data from the Baltic Sea. The results demonstrate that the method is effective in identifying compliance-related behaviour and has promising real-time capability for onboard self-assessment and regulatory monitoring in MASS operations.

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A Scenario-Driven Sensor Performance Modelling Framework for Reliable Autonomous Maritime Operations

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Keywords

Autonomous navigation; Sensor performance; Sensor fusion; Autonomous decision-making

Abstract

Sensor accuracy, reliability, and availability in Maritime Autonomous Surface Ships degrade substantially under fog, rain, heavy weather, and dense traffic — introducing compounding uncertainty into perception and autonomous decision-making that demands a rigorous, evidence-based sensor evaluation framework. This study develops a scenario-based evaluation framework for Radar, Gyrocompass, Camera, LiDAR, AIS, IMU, and GNSS based on seven performance criteria: detection reliability, measurement accuracy, latency, robustness, coverage, availability, and computational efficiency. The assessment is conducted under three representative conditions: night navigation, heavy weather with limited visibility and high traffic, and open-sea operations in moderate conditions. Entropy weighting is used to objectively determine the relative importance of each criterion for different navigational scenarios. The Dempster–Shafer theory-based evidential reasoning approach is applied to aggregate heterogeneous sensor information, enabling robust and uncertainty-aware decision-making. The framework generates scenario-specific sensor rankings, identifies suitable sensor sets, and examines performance degradation under single- and double-sensor loss. The proposed architecture provides a systematic and operationally grounded foundation for adaptive sensor evaluation and context-aware sensor fusion, supporting the development of resilient, reliable, and intelligently reconfigurable navigation systems for next-generation autonomous maritime operations.

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Trajectory Planning of Multiple Unmanned Surface Vehicles for Oil Spill Containment and Recovery

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Keywords

Marine Oil Spill;
Emergency Response;
USVs;
Trajectory Planning;
Synergistic Effect

Abstract

With the continuously increasing demand on energy, the scale of offshore oil exploration, development, storage, and transportation keeps expanding. The oil spill accidents appear to have a trend of growth in terms of number or scale, the impact on the marine environment is incalculable, and the improving efficiency of oil spill emergency response turns out to be pressing. Inspired by the theory of vessel-to-vessel collaboration, this article proposes a cooperative trajectory planning scheme for oil spill containment and recovery using multiple Unmanned Surface Vehicles (USVs). The oil spill emergency response using USV contains two stages, namely synchronisation and coordination, and the proposed scheme is based on an oil spill diffusion and drift prediction model, integrating an oil spill containment module and a recovery module. The synergy between these modules optimises the entire emergency response process. Experimental results show that the proposed multi-USV collaborative oil spill containment and recovery trajectory planning scheme significantly improve the efficiency of the oil spill emergency response, compared with the traditional scheme.

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Behaviour-Aware Distributionally Robust Quota Optimisation for Truck Appointment Systems under Uncertain Demand

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Keywords
Truck appointment system;
Uncertain demand;
Service level;
Distributionally robust chance-constrained program;
Data-driven

Abstract
The time-window appointment demand of a truck appointment system (TAS) is uncertain, affected by supply-chain front-end efficiency and truck-fleet scheduling. Considering this uncertainty and the differing service requirements of heterogeneous truck types, this paper establishes a data-driven distributionally robust chance-constrained program (DRCCP) that minimises total truck turnaround time over a decision cycle, using joint chance constraints to describe each truck type's service level and a Wasserstein ambiguity set built from historical gate and appointment records. The model is reformulated as a mixed-integer program (MIP) by duality, and Value-at-Risk (VaR) and Conditional Value-at-Risk (CVaR) approximations are derived. The paper further compares three truck-classification methods—business classification, K-means clustering, and an automatic Frank-Wolfe method whose number of types is obtained from the data—introduces a risk-pooling counterpart, characterises the trade-off between the service level and total truck turnaround time, and estimates from data how each type's no-show rate varies with the quota. Numerical experiments show that the VaR and CVaR models solve faster than the MIP model, that the MIP model attains a better objective value, and that the DRCCP model is more conservative than a stochastic chance-constrained (SCCP) model.

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A Safety Margin Method Based on FMECA-BN for Crane-Barge Salvage Operations

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Keywords

Salvage crane vessel;
Motion response;
Risk assessment;
Safety margin

Abstract

The risk assessment of crane-barge salvage is important for defining the safety boundary of emergency rescue operations in inland waterways. To address this problem, a risk assessment method for crane-barge salvage based on a dynamic criterion dataset is proposed. The motion response sequence of the crane barge is obtained through numerical simulation. The fluctuating environmental loads are converted into quantifiable dynamic risk indicators by FMECA-BN. Based on the safety margin method, the static failure value is converted into a dynamic risk boundary. The results provide a new technical approach for risk analysis of crane-barge salvage operations under complex environmental conditions.

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Modelling Correlated Failures and Maintenance Actions in Offshore Wind Farms: A Two-Stage Predictive Framework

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Keywords

Offshore wind turbines; Failure dependency; Reliability assessment; Predictive maintenance; Maintenance scheduling

Abstract

Offshore wind turbines are complex multi-component systems in which failure dependencies and maintenance interventions significantly influence long-term reliability and maintenance demand. This paper proposes a two-stage predictive framework for forecasting maintenance actions in offshore wind farms. First, a reliability-based failure model is developed to capture component failure correlations, hybrid maintenance effects, and variations in turbine service life. An inverse transform sampling algorithm is applied to simulate failure occurrence and propagation throughout the wind farm lifecycle. Second, a maintenance scheduling model incorporating vessel availability and maintenance-window constraints translates predicted failures into realistic maintenance actions. The framework is validated using data from an operational offshore wind farm. Sensitivity analyses demonstrate the importance of maintenance capability, vessel allocation, and scheduling strategies in reducing maintenance delays and turbine downtime. The proposed framework provides a reliability-informed decision-support tool for maintenance planning, resource allocation, and lifecycle management of offshore wind farms.

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Can E-Fuels Realistically Decarbonise the Shipping Sector? Lessons from System-Level Assessment and Vessel Case

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Keywords

E-fuels;
Decarbonisation;
Shipping

Abstract

Decarbonising the shipping sector is one of the major technological and environmental challenges facing global transport and maritime operations in general. Although improvements in energy efficiency and operational measures can contribute to emission reductions, achieving deep decarbonisation will require the deployment of low-carbon and carbon-neutral fuels. Among the proposed options, electricity-based fuels (e-fuels) are increasingly considered a promising pathway, particularly for vessel segments where direct electrification remains limited. However, the real environmental benefits of these fuels depend not only on their combustion characteristics but also on upstream production processes, electricity sources and vessel operational profiles. This lecture explores whether e-fuels can realistically contribute to the decarbonisation of the shipping sector from a system-level perspective. The discussion draws on insights from several competitive research projects, including the Horizon Europe projects E-TANDEM and IsoPROPEL, the Croatian Science Foundation project GREEN-FISH, and the Interreg projects GREENROUTES and Green-Pro. Case studies involving ferries, cruise ships and fishing vessels illustrate how lifecycle fuel pathways and vessel operational conditions jointly shape the environmental performance of emerging marine fuels.

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Ship Target Detection Based on Remote Sensing Images: Advancing Maritime Transportation Monitoring Through Multimodal Data Fusion

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Keywords

Remote sensing;
Ship detection;
Multimodal data fusion;
Maritime monitoring;
Deep learning

Abstract

Maritime traffic monitoring is severely constrained by single-modality remote sensing limitations and the susceptibility of Automatic Identification Systems (AIS) to signal loss or deliberate spoofing. This paper proposes a condition-aware multimodal deep-learning framework for robust ship detection using aligned optical and Synthetic Aperture Radar (SAR) remote sensing imagery. Sensor-specific preprocessing modules are designed to mitigate optical cloud occlusion and SAR speckle noise. A core novelty of this work is the Condition-Aware Cross-Modal Calibration (CACMC) block, which dynamically adjusts modality feature weights based on an inferred sea-state index rather than employing static fusion rules. Furthermore, contextual AIS trajectories are integrated as spatial priors to constrain candidate search regions and suppress coastal clutter. Validated against official benchmarks including SSDD and HRSID, the proposed methodology establishes a rigorous protocol for multi-sensor maritime surveillance, enhancing operational reliability in dense ports and harsh offshore environments.

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