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Artificial Intelligence and the Transformation of Maritime Transport: Opportunities, Risks and a Framework for Intelligent Shipping

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Abstract

Artificial intelligence (AI) is rapidly transforming maritime transport by enabling new capabilities in navigation, vessel operations, predictive maintenance, port management, logistics optimisation, environmental performance and autonomous shipping. Unlike earlier generations of maritime digitalisation, which primarily focused on automation and information exchange, contemporary AI systems can learn from large and heterogeneous datasets, identify complex patterns, generate predictions and increasingly support or execute operational decisions. Consequently, AI has the potential to reshape not only individual shipboard functions but also the architecture of global maritime transport systems.

This paper critically examines the effects of artificial intelligence on international maritime transport and proposes an integrated framework for understanding the transition towards intelligent shipping. The study synthesises developments across five interconnected domains: intelligent vessel operations, navigational safety and autonomy, port and terminal optimisation, maritime supply-chain resilience, and environmental sustainability. It argues that the principal impact of AI lies not in the replacement of human operators but in the redistribution of decision-making between humans, machines and shore-based organisations.

The paper identifies substantial potential benefits, including improved fuel efficiency, predictive maintenance, enhanced situational awareness, reduced navigational risk, optimised port operations and more resilient supply chains. However, these benefits are accompanied by significant challenges relating to algorithmic reliability, explainability, cybersecurity, data governance, regulatory compatibility, liability and the changing competence requirements of maritime professionals. Recent developments in the International Maritime Organization's regulatory approach to Maritime Autonomous Surface Ships (MASS) demonstrate that technological innovation is increasingly moving from experimental research towards formal international governance (International Maritime Organization [IMO], 2026).

The paper proposes the **Maritime AI Transformation Framework (MATF)**, which conceptualises AI adoption through four interacting dimensions: technological capability, operational integration, human oversight and regulatory governance. The framework suggests that the successful adoption of AI in maritime transport depends on balanced development across all four dimensions. The paper concludes that the future of maritime transport will be characterised not by fully autonomous ships replacing conventional shipping in the immediate future, but by progressively integrated human–AI systems operating across ships, ports and global supply networks.

Keywords: Artificial intelligence; Maritime transport; Intelligent shipping; Autonomous ships; Maritime logistics; Ports; Maritime safety; Digital transformation; Sustainable shipping.

1. Introduction

Maritime transport remains the foundation of international trade and global supply chains. The movement of cargo by sea connects producers, consumers, ports, shipping companies and industrial economies across the world. However, the maritime sector operates in an increasingly complex environment characterised by volatile freight markets, geopolitical disruptions, environmental regulation, crew shortages, port congestion, cyber risks and growing pressure to reduce greenhouse-gas emissions.

Artificial intelligence has emerged as one of the most significant technologies capable of addressing these challenges. AI is increasingly being applied to ship navigation, collision avoidance, route optimisation, weather forecasting, machinery diagnostics, cargo planning, port operations and supply-chain management. Recent research demonstrates particularly rapid growth in the use of machine learning and deep learning for vessel trajectory prediction, situation awareness, risk assessment and intelligent navigational decision-making (Shi et al., 2026).

The importance of AI in maritime transport extends beyond automation. Traditional automation generally performs predefined tasks according to programmed rules. AI systems, by contrast, can analyse large datasets, recognise patterns, make predictions and adapt decisions to changing conditions. This distinction is particularly important in maritime operations, where ships operate in dynamic environments characterised by uncertain weather, traffic interactions, equipment conditions and human decision-making.

The growing maturity of maritime AI has also created a regulatory imperative. In May 2026, the International Maritime Organization adopted the International Code of Safety for Maritime Autonomous Surface Ships (MASS Code), establishing a goal-based framework for the safe integration of remotely controlled and autonomous commercial ships. The Code took effect on 1 July 2026, marking an important transition from conceptual discussion towards structured international governance of autonomous maritime operations (IMO, 2026).

Despite significant technological progress, the effects of AI on maritime transport remain insufficiently understood as a system-wide transformation. Much existing research focuses on individual applications such as collision avoidance, autonomous navigation or machine learning-based optimisation. However, AI adoption affects a wider ecosystem involving vessels, crews, ports, logistics providers, regulators, classification societies and customers.

This paper therefore addresses the following research questions:

RQ1: How is artificial intelligence transforming operational, navigational and logistical activities in maritime transport?

RQ2: What are the principal benefits and risks associated with AI adoption in international shipping?

RQ3: How will AI change the relationship between seafarers, ships and shore-based organisations?

RQ4: What technological, human and regulatory conditions are required for responsible implementation of AI in maritime transport?

The principal contribution of this paper is the development of the **Maritime AI Transformation Framework (MATF)**, which provides an integrated perspective on the technological and organisational transformation of international maritime transport.

2. Artificial Intelligence in Maritime Transport

2.1 From Digitalisation to Intelligent Shipping

Maritime transport has experienced several phases of technological development.
The first phase involved the mechanisation of physical processes. The second phase introduced electronic navigation and computerised control systems. The third phase focused on digitalisation, connectivity and information exchange. The emerging phase can be described as **intelligent maritime transport**, in which AI systems increasingly interpret data and support operational decisions.
This transformation can be represented as:

Mechanisation → Automation → Digitalisation → Intelligence → Autonomous Operations
The transition towards intelligence is enabled by the integration of:

- Artificial intelligence and machine learning;
- Internet of Things sensors;
- Satellite and maritime communication systems;
- Automatic Identification System data;
- Electronic navigation systems;
- Digital twins;
- Cloud computing;
- Edge computing;
- Robotics;
- Advanced data analytics.

AI acts as an analytical layer connecting these technologies. It converts large volumes of operational data into predictions, recommendations and increasingly autonomous decisions.

2.2 Major AI Technologies Relevant to Shipping

Machine Learning

Machine-learning algorithms can analyse historical and real-time maritime data to identify relationships that may not be apparent through conventional statistical techniques.
Applications include:

- Fuel consumption prediction;
- Vessel performance analysis;
- Machinery failure prediction;
- ETA prediction;
- Traffic forecasting;
- Weather-based route optimisation.

Deep Learning

Deep-learning models are particularly useful for analysing complex and unstructured information.
Maritime applications include:

- Image-based vessel detection;
- Object recognition;
- Video-based surveillance;
- Trajectory prediction;

- Collision-risk assessment;
- Situational awareness.

Deep learning has become an important component of intelligent maritime transportation systems, particularly in safe navigation, trajectory analysis and autonomous decision-making (Shi et al., 2026).

Reinforcement Learning

Reinforcement learning enables systems to learn decision strategies through interaction with an environment.

Potential applications include:

- Autonomous collision avoidance;
- Dynamic route planning;
- Vessel manoeuvring;
- Energy optimisation;
- Port resource allocation.

Recent reviews indicate that reinforcement-learning approaches, particularly deep reinforcement learning, have become prominent in research on autonomous vessel collision avoidance (Yaseen et al., 2026).

Generative AI and Large Language Models

Generative AI introduces a further dimension to maritime operations. Potential applications include:

- Technical documentation support;
- Decision-support interfaces;
- Maritime knowledge management;
- Regulatory information retrieval;
- Training and simulation;
- Maintenance assistance.

However, generative AI creates significant concerns regarding hallucination, reliability and explainability when used in safety-critical maritime decision-making.

3. Effects of AI on Ship Operations

3.1 Intelligent Navigation

Navigation represents one of the most important areas for AI application.

Modern ships generate significant volumes of data through radar, AIS, GPS, ECDIS, engine monitoring systems and environmental sensors. AI can integrate these data streams to improve situational awareness.

AI-enabled navigation can support:

- Detection of vessels and objects;
- Prediction of vessel trajectories;
- Collision-risk identification;
- Route optimisation;
- Weather routing;
- Decision support for watchkeeping officers.

Research on intelligent maritime transportation systems has demonstrated the increasing importance of AI and deep learning in ship detection, trajectory prediction, collision avoidance and traffic modelling (Shi et al., 2026).
However, a critical limitation remains the relationship between AI decision-making and the International Regulations for Preventing Collisions at Sea (COLREGs). Maritime navigation requires interpretation of complex operational circumstances rather than merely mathematical optimisation.
Recent research has therefore focused on combining AI methods with COLREGs-based reasoning and hybrid navigation architectures (Namgung et al., 2026).

3.2 Predictive Maintenance

Traditional maintenance practices are often based on predetermined schedules or corrective action following equipment failure.
AI enables a transition towards **predictive maintenance**.
Machine-learning models can analyse:

- Vibration patterns;
- Temperature measurements;
- Lubricating-oil data;
- Pressure data;
- Engine performance;
- Electrical-system behaviour.

The system can identify abnormal patterns before a complete equipment failure occurs.
The benefits include:

1. Reduced machinery downtime;
2. Improved maintenance planning;
3. Lower operational costs;
4. Increased equipment reliability;
5. Improved ship availability.

The strategic importance of predictive maintenance is particularly high in shipping because equipment failure can create safety, commercial and environmental consequences.

3.3 Fuel Efficiency and Voyage Optimisation

Fuel represents one of the most significant operating costs in commercial shipping. AI can analyse multiple variables simultaneously, including:

- Vessel speed;
- Draft;
- Trim;
- Weather;
- Waves;
- Ocean currents;
- Engine performance;
- Hull condition.

AI-based optimisation can support decisions concerning the most efficient combination of speed and route.

This capability is particularly important as the shipping industry faces increasing decarbonisation pressure. Recent research increasingly connects AI adoption with green and intelligent shipping and with the low-carbon transition of the sector (Wang et al., 2026; Liu et al., 2026).

The relationship between AI and environmental performance, however, should not be assumed automatically. AI produces environmental benefits only when optimisation recommendations are translated into operational decisions and integrated with vessel design, propulsion systems, commercial schedules and regulatory requirements.

4. AI and Maritime Safety

4.1 Enhanced Situational Awareness

One of the most significant potential contributions of AI is the improvement of situational awareness.

Human navigators must continuously interpret:

- Radar information;
- Visual observations;
- AIS information;
- Weather conditions;
- Traffic patterns;
- Navigational hazards.

AI systems can process multiple data streams simultaneously.

Potential benefits include:

- Earlier detection of collision risks;
- Improved object recognition;
- Identification of abnormal vessel behaviour;
- Prediction of future traffic movements.

However, increased automation may also create new safety risks.

A major challenge is **automation bias**, in which operators place excessive confidence in automated recommendations.

Therefore, AI should initially be viewed primarily as a **decision-support capability**, rather than an unrestricted replacement for professional judgement.

4.2 Autonomous Shipping

The development of Maritime Autonomous Surface Ships represents one of the most visible applications of AI in maritime transport.

Autonomous operations may exist at different levels:

Level 1: Conventional Operation with AI Assistance

Human crew remain fully responsible, while AI supports specific decisions.

Level 2: Partially Automated Operation

Certain functions are automated, while humans retain supervisory control.

Level 3: Remotely Controlled Operation

The ship may be controlled from a shore-based control centre.

Level 4: Highly Autonomous Operation

The vessel performs most operational functions independently under defined conditions.

Level 5: Fully Autonomous Operation

The system performs operational decisions without continuous human intervention.

The IMO defines a Maritime Autonomous Surface Ship as a ship which, to a varying degree, can operate independently of direct human interaction. The IMO also distinguishes between conventional ships with enhanced automation and ships whose functions are genuinely supported or replaced by autonomous or remote technologies (IMO, 2026).

The adoption of the MASS Code represents a major regulatory development. The non-mandatory, goal-based Code was adopted in May 2026 and took effect on 1 July 2026, supporting the safe integration of remotely controlled and autonomous commercial ships into international shipping (IMO, 2026).

Nevertheless, fully autonomous international commercial shipping remains limited, and conventional and increasingly automated vessels are expected to coexist for a considerable period (IMO, 2026).

5. AI in Ports and Maritime Logistics

5.1 Intelligent Ports

Ports represent complex systems involving ships, terminals, trucks, railways, warehouses and customs authorities.

AI can support:

- Berth allocation;
- Crane scheduling;
- Container handling;
- Yard optimisation;
- Port congestion prediction;
- Vessel arrival management.

AI can improve the coordination of port resources by predicting demand and identifying operational bottlenecks.

The greatest benefits are likely to occur when ships and ports exchange information through integrated digital systems.

This creates the concept of the **smart maritime ecosystem**.

5.2 Just-in-Time Arrival

Traditional shipping schedules may result in vessels arriving early and waiting outside ports.

AI can improve ETA prediction and port coordination.

A more intelligent system can integrate:

Ship speed → Port readiness → Berth availability → Cargo operations → Departure planning

This can reduce unnecessary waiting and potentially reduce fuel consumption.

However, successful implementation requires information sharing between multiple commercial organisations, which introduces issues of data ownership and competitive confidentiality.

6. AI and Maritime Supply-Chain Resilience

Global maritime supply chains are vulnerable to:

- Pandemics;

- Geopolitical conflict;
- Extreme weather;
- Port congestion;
- Equipment failures;
- Cyberattacks.

AI can contribute to supply-chain resilience through:

- Disruption prediction;
- Dynamic route planning;
- Demand forecasting;
- Risk assessment;
- Port congestion prediction.

Recent systematic research has specifically identified AI as an increasingly important capability for improving resilience across maritime supply chains (Qiu et al., 2026).

However, resilience requires more than predictive algorithms. AI must be integrated with organisational decision-making, information sharing and contingency planning.

7. The Human Dimension: Will AI Replace Seafarers?

A common assumption is that autonomous ships will eliminate maritime employment.

This conclusion is premature.

AI is more likely to **transform maritime work** than completely eliminate it.

The role of maritime professionals may increasingly shift from:

Manual operation → System supervision → Data interpretation → Exception management → Remote decision-making

Future maritime professionals may require competencies in:

- Digital systems;
- AI-assisted decision-making;
- Cybersecurity;
- Data interpretation;
- Remote operations;
- Human–machine interaction.

This has significant implications for maritime education and training.

Traditional maritime education focuses heavily on technical competence, navigation and engineering knowledge. These competencies will remain essential, but they must increasingly be complemented by digital and analytical skills.

The future seafarer may therefore become a **hybrid maritime professional**, combining conventional seamanship with technological competence.

The IMO's MASS regulatory framework similarly emphasises that the development of autonomous and remotely operated shipping must retain appropriate human oversight and clearly address the roles and responsibilities of masters, remote operators and onboard personnel (IMO, 2026).

8. Risks and Challenges of AI Adoption

8.1 Algorithmic Reliability

AI systems are dependent on training data.
A system trained on historical conditions may perform poorly in unusual situations.
Maritime operations involve rare but high-consequence events, creating a significant challenge for machine learning.

8.2 Explainability

In safety-critical situations, operators must understand why a system recommends a particular action.
A highly accurate but unexplainable algorithm may create difficulties for:

- Masters;
- Shipowners;
- Investigators;
- Regulators;
- Courts.

Therefore, **explainable AI** should become an important research priority.

8.3 Cybersecurity

Greater digitalisation increases the potential cyberattack surface.
AI systems may themselves become targets of:

- Data manipulation;
- Sensor spoofing;
- Adversarial attacks;
- Communication disruption.

Cybersecurity must therefore be integrated into maritime AI architecture rather than treated as a separate technical issue.
The IMO's MASS Code specifically addresses cybersecurity as part of the safe design and operation of autonomous and remotely operated ships (IMO, 2026).

8.4 Legal Liability

A fundamental legal question arises:

Who is responsible when an AI system makes an incorrect decision?
Possible parties include:

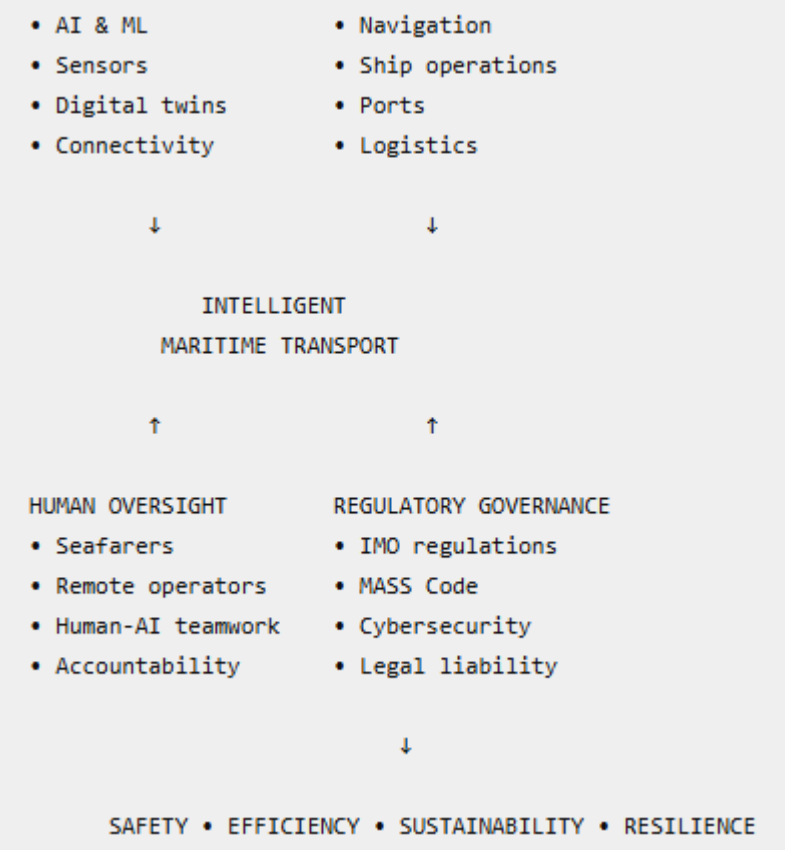
- Shipowner;
- Master;
- Software developer;
- System manufacturer;
- Remote operator.

Existing maritime legal frameworks were primarily developed for human-operated vessels.
The evolution of autonomous and AI-assisted systems will therefore require continuing regulatory interpretation and adaptation. The ongoing IMO work on MASS reflects the need to address

responsibilities relating to masters, crews, remote operators and the interaction of autonomous technologies with existing international legal instruments (IMO, 2026).

9. The Maritime AI Transformation Framework

This paper proposes the **Maritime AI Transformation Framework (MATF)**.
The framework consists of four interconnected dimensions.



Dimension 1: Technological Capability
This includes:

- AI algorithms;
- Sensors;
- Connectivity;
- Computing infrastructure;
- Digital twins.

Dimension 2: Operational Integration
AI must be integrated into:

- Navigation;
- Machinery operations;
- Port management;
- Logistics.

Dimension 3: Human Oversight

Human professionals must retain appropriate authority and competence.

This includes:

- Monitoring;
- Intervention;
- Verification;
- Decision accountability.

The importance of human oversight is also reflected in the IMO MASS Code, under which the master retains overall responsibility for the ship, including where operational functions are monitored or controlled remotely (IMO, 2026).

Dimension 4: Regulatory Governance

AI adoption must operate within:

- Safety regulation;
- Environmental regulation;
- Cybersecurity requirements;
- Legal accountability frameworks.

The framework can be expressed as:

Effective Maritime AI = Technology × Operations × Human Oversight × Governance

The multiplicative relationship is important.

Failure in any one dimension can significantly reduce the effectiveness of the entire system.

For example:

- Advanced AI without trained operators creates operational risk.
- Autonomous ships without regulation create legal uncertainty.
- Digital systems without cybersecurity create vulnerability.
- AI models without operational integration produce limited commercial value.

This perspective supports the argument that maritime AI adoption is a **socio-technical transformation**, rather than merely a software implementation project.

10. Discussion

The effects of AI on maritime transport will likely be evolutionary rather than immediately revolutionary. The most significant changes are expected to occur through progressive integration:

Phase 1: AI-Assisted Shipping

AI supports human decision-making.

Phase 2: Human–AI Collaborative Shipping

Humans and intelligent systems share operational responsibilities.

Phase 3: Integrated Ship–Shore Intelligence

Ships, ports and logistics networks exchange information and coordinate decisions.

Phase 4: Autonomous Maritime Ecosystems

Highly autonomous systems operate within regulated and digitally integrated maritime networks.

This progression is consistent with the broader understanding that autonomous shipping is not simply a vessel-level technology but a systemic innovation requiring coordination among multiple actors and

institutions. The IMO's regulatory approach similarly recognises that autonomous shipping must address vessel functions, remote operations, connectivity, human oversight and interaction with existing international instruments (IMO, 2026).

11. Future Research Agenda

Future research should focus on:

1. Explainable Maritime AI
Developing systems that can explain operational recommendations.
2. Human–AI Collaboration
Understanding how seafarers interact with intelligent systems.
3. AI and COLREG Compliance
Developing reliable systems capable of applying navigation rules in complex situations.
4. AI Cybersecurity
Protecting intelligent maritime systems from cyber threats and data manipulation.
5. AI Governance
Developing international standards for accountability and certification.
6. Maritime Workforce Transformation
Identifying future competence requirements for seafarers and shore-based professionals.
7. Integrated Maritime Digital Twins
Connecting ships, ports and supply chains through real-time digital representations.

12. Conclusion

Artificial intelligence is emerging as a transformative force in maritime transport. Its effects extend beyond autonomous ships and include navigation, maintenance, fuel optimisation, ports, logistics and supply-chain resilience.

The principal contribution of AI lies in its ability to transform maritime data into operational intelligence. However, the successful adoption of AI cannot be evaluated solely according to technological performance. Maritime transport is a safety-critical, internationally regulated and human-dependent industry.

This paper has argued that effective AI implementation requires the simultaneous development of technological capability, operational integration, human oversight and regulatory governance.

The proposed Maritime AI Transformation Framework provides a conceptual foundation for understanding this transition.

The future of shipping is therefore unlikely to be defined by a simple replacement of humans with machines. Instead, the emerging maritime system will be characterised by increasingly sophisticated forms of **human–AI collaboration**, connecting intelligent ships, smart ports and digitally integrated global supply chains.

The central challenge for the maritime industry is not whether artificial intelligence will be adopted, but whether it can be adopted in a manner that improves **safety, sustainability, efficiency and resilience without undermining human responsibility and international regulatory integrity**.

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