Applications of Artificial Intelligence in Port Management and Operations: A Prisma-Based Review

Primjena umjetne inteligencije u upravljanju i poslovanju luka: pregled na temelju prisma modela

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Abstract

Artificial Intelligence (AI) has become an increasingly relevant technological component in the digital transformation of ports, supporting improvements in operational efficiency, safety and environmental performance. In recent years, several literature reviews have examined AI applications in maritime and port-related contexts; however, these studies typically focus on specific dimensions, such as safety and risk management, smart port development, or individual Machine Learning techniques. Consequently, a consolidated and application-oriented overview explicitly centered on port management and operations remains limited. This study addresses this gap by conducting a systematic literature review aimed at synthesizing current scientific evidence on the application of AI in port management and operational activities, while identifying emerging research gaps. The review follows the PRISMA protocol and analyses 30 peer-reviewed journal articles published between 2021 and early 2025. The results indicate that AI is predominantly applied in operational areas such as vessel arrival forecasting and scheduling, berth and quay crane allocation, container handling and predictive maintenance. Machine Learning and Deep Learning approaches are the most frequently adopted and exhibit higher levels of empirical validation. Reported outcomes include improvements in operational efficiency, enhanced decision-support accuracy and reductions in environmental impact. Despite these advances, the literature highlights persistent challenges related to data availability and quality, system interoperability, cybersecurity and the adaptation of AI solutions to heterogeneous port environments. The study concludes that, while AI adoption in ports is progressing beyond experimental stages, further empirical research and structured implementation strategies are required to support scalable and secure deployment across different port contexts.

KEY WORDS

Artificial Intelligence
Port Operations
Port Management
Systematic

Sažetak

Umjetna inteligencija (UI) postala je sve relevantnija tehnološka komponenta u digitalnoj transformaciji luka, podržavajući poboljšanja operativne učinkovitosti, sigurnosti i ekoloških performansi. Posljednjih godina nekoliko je pregleda literature ispitalo primjenu UI u pomorskom i lučkom kontekstu; međutim, te se studije obično usredotočuju na specifičnosti, kao što su sigurnost i upravljanje rizicima, razvoj pametnih luka ili pojedinačne tehnike strojnog učenja. Posljedično, konsolidirani i na primjenu orijentirani pregled, izričito usmjeren na upravljanje i poslovanje luka, ostaje ograničen. Ovaj rad ističe taj nedostatak provođenjem sustavnog pregleda literature usmjerenog na sintezu trenutnih znanstvenih dokaza o primjeni UI u upravljanju lukama i operativnim aktivnostima, uz istovremeno identificiranje novih istraživačkih nedostataka. Pregled slijedi PRISMA model i analizira 30 recenziranih članaka u časopisima objavljenih između 2021. i početka 2025. Rezultati pokazuju da se umjetna inteligencija pretežno primjenjuje u operativnim područjima kao što su predviđanje i raspored dolazaka brodova, dodjela privezišta i obalnih dizalica, rukovanje kontejnerima te prediktivno održavanje. Pristupi strojnom i dubokom učenju najčešće se primjenjuju i pokazuju višu razinu empirijske potvrde. Rezultati uključuju poboljšanja operativne učinkovitosti, veću točnost potpore odlučivanju te smanjenje utjecaja na okoliš. Unatoč tom napretku, literatura ističe trajne izazove vezane uz dostupnost i kvalitetu podataka, interoperabilnost sustava, kibernetičku sigurnost i prilagodbu UI rješenja heterogenim lučkim okruženjima. Rad zaključuje da, iako je primjena umjetne inteligencije u lukama sve više izvan eksperimentalne faze, potrebna su dodatna empirijska istraživanja i strukturirane strategije implementacije kako bi se omogućila njena skalabilna i sigurna primjena u različitim lučkim kontekstima.

KLJUČNE RIJEČI

umjetna inteligencija
lučko poslovanje
upravljanje lukama
sustavni pregled

1. INTRODUCTION / *Uvod*

The maritime industry constitutes an integral part of global commerce, being responsible for transporting more than 80% of the volume of international merchandise trade [1]. This sector fundamentally depends on accurate forecasts to maintain efficiency, safety and economic sustainability of its operations [2].

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Within this context, and driven by the broader digitalisation of the maritime sector, Artificial Intelligence (AI) has emerged as a transformative technological enabler of port operations, providing significant increases in efficiency, accuracy and safety [3]. With advanced data-processing capabilities and the ability to integrate multiple heterogeneous systems, AI enables the optimisation of a wide range of operational activities in vessels and port facilities, supporting decision-making in real-time. In response to these benefits, there is growing interest from the maritime industry in applying advanced AI and Machine Learning (ML) technologies to address contemporary challenges related to environmental sustainability, operational efficiency and compliance with increasingly demanding regulatory frameworks [4]. In this sense, AI is no longer viewed as an experimental technology, but rather as a strategic pillar of modern port digitalisation.

Existing studies on AI in the port sector present a fragmented panorama, predominantly focusing on specific applications. The utilisation of AI for vessel berthing has been addressed [5], whilst the dynamization of smart ports has been explored [6], [7]. Research focusing on optimising port operational efficiency has also been conducted [3]. This thematic fragmentation limits a holistic understanding of both the full potential and the inherent limitations of AI in the port sector, highlighting the lack of a systematic and comprehensive analysis capable of mapping the main technological applications and identifying knowledge gaps to guide future research.

Additionally, the promising results of specific models are frequently based on particular datasets and experimental conditions, limiting their generalisation. Studies [2] emphasise that, there is a need for more comprehensive investigations that reveal which AI modalities present comparative advantages in different maritime applications.

Recent literature presents reviews that, whilst valuable, maintain defined focuses. A comprehensive analysis on the application of AI in safety and risk management in maritime transport has been offered, contemplating areas such as predictive maintenance, navigation and hazardous materials management [4]. The concept of smart ports in the context of Industry 4.0 has been investigated, with emphasis on thematic structuring and identification of research gaps [7]. Some studies restrict their analysis to vessel berthing operations, examining how AI can replace tugboats and enhance the precision of port manoeuvres [5]. A bibliometric approach has been adopted by researchers, analysing trends and conceptual evolution of the literature on smart ports, highlighting the need for terminological standardisation [6]. And lastly, a systematic review focused on ML methods in port operations has been presented, categorising predictive, prescriptive and autonomous applications in various operational areas [8].

Although these contributions demonstrate the breadth and growing maturity of AI research in the port sector, they also reveal the absence of an integrative, up-to-date and application-oriented synthesis focused specifically on port management and operations as a unified system. Thus, this article addresses this gap by conducting a systematic literature review aimed at consolidating, structuring and critically analysing the current scientific evidence on the impact of Artificial Intelligence in the port sector. The review focuses on: (i) presenting the main AI applications already implemented in ports; and (ii) identifying knowledge gaps that may guide future research. By doing so, this study seeks to support both academic research and strategic decision-making by port authorities and stakeholders, reinforcing the relevance of AI for the future competitiveness and sustainability of ports.

2. PORT MANAGEMENT AND OPERATIONS / *Lučko upravljanje i poslovanje*

2.1. Port Management and Operations / *Lučko upravljanje i poslovanje*

Port management is a service-oriented activity that coordinates administrative, economic, and technical tools to achieve commercial objectives and meet sustainability requirements [9]. It involves governance of port activities through the interaction of public authorities and private actors, with management models shape by institutional arrangements [9]. Core functions include strategic planning, infrastructure development, and adaptive capacity to evolving global trade dynamics. Building on this foundation, port authorities are now redefining these traditional paradigms by embedding digital transformation into their governance frameworks. This shift toward smart ports represents a strategic evolution – from static, institutionally driven decision-making to dynamic, data-enabled systems that enhance managerial responsiveness, operational adaptability, and institutional transparency [7], [10].

Port operations comprise the integrated activities that facilitate efficient vessel handling and cargo throughput, ensuring seamless connectivity between maritime and land transport [3], [11]. The International Transport Forum categorises port operations into three principal phases – landside handling; berth assignment and turnaround; and risk and safety management [12]. Table 1 shows the key technologies and benefits of each phase, demonstrating AI as a core enabler. In addition, AI-enabled digital twins of equipment and operational workflows create live virtual replicas that integrate machine-learning analytics with real-time data streams, enabling non-intrusive "what-if" simulations for capacity planning, maintenance scheduling and emergency-response drills. Ports utilising these end-to-end digital-twin platforms report throughput gains up to 20%, operating-expenditure reductions of 15–20% and significant environmental benefits [13].

Table 1 Key Technologies & Benefits for each Port Operations phases
Tablica 1. Ključne tehnologije i prednosti za svaku fazu lučkog poslovanja

Phase	Key Technologies & Benefits
Landside Handling	Automated appointment systems driven by ML integrate real-time Optical Character Recognition (OCR) and Radio-Frequency IDentification (RFID) to process container and truck IDs. Terminals report up to 35% reduction in dwell times and 12% lower CO_2 emissions when streamed over private 5G into the Terminal Operating System (TOS) [14], [15].
Seaside Operations	Predictive algorithms that ingest Automatic Identification System (AIS) signals, tide and weather data optimise berth assignments and Estimated Time of Arrival (ETA) forecasts. Hong Kong's AI-based punctuality model achieved an 18% improvement; Singapore and Hamburg report 10–15% shorter waits and higher quay-crane utilisation [15], [16].
Risk & Safety Management	AI-driven collision-risk models and safe-berthing calculators combine historical incident logs, AIS feeds and meteorological inputs. Deployment at the Port of Singapore Authority reduced collisions by 14% since 2022; cost–benefit analyses show Return on Investment (ROI) within 18 months via avoided downtime and fines [13], [17].

2.2. Use of AI in the Port Sector / *Primjena umjetne inteligencije (UI) u lučkom sektoru*

AI has transitioned from pilot trials to a foundational element of contemporary port operations, underpinning improvements in planning, maintenance, scheduling, safety and sustainability. Core AI methods – ML, computer vision, optimisation algorithms and digital twins – now permeate all major port functions [3], [7], [8].

A flagship application is the AI-powered digital twin. High levels of accuracy in throughput forecasting have been reported, with hybrid network-analysis models achieving over 90% predictive accuracy [1], while digital twin-driven safety management systems have demonstrated reductions of approximately 25% in incident-response times during large-scale port trials [2]. Major providers (IBM, Siemens, Dassault Systèmes) have rolled out such platforms at Rotterdam, Antwerp and Shanghai terminals, with broad standardisation expected by 2026 [15].

Predictive maintenance represents another critical use case: neural-network models trained on vibration, temperature and load data can forecast crane and equipment failures up to 48 hours in advance. Research has demonstrated 85% recall for crane-fault predictions – cutting unplanned downtime by 20% – and similar outcomes have been confirmed in Chinese and Belgian ports [3], [13]. Machine-learning techniques such as Long Short-Term Memory (LSTM) networks and reinforcement-learning agents now optimise berth assignment and vessel-arrival forecasts. Researchers observed a 15% average reduction in vessel–berth mismatches [8], and report that ETA-forecast errors at leading terminals in Singapore and Hamburg have dropped from over 90 minutes to under 30 minutes [11] [17].

On the landside, deep-learning OCR systems paired with RFID readers automate gate processing and yard management. Researchers achieved 98% container-ID recognition under varied lighting, reducing gate-throughput times by 40% and improving yard retrieval times by 12%; when streamed over private 5G into TOS, these innovations yield a 35% cut in dwell times and a 12% CO_2-emissions reduction [3], [8], [13], [14]. AI also underlies advanced safety and security measures: Bayesian networks and support-vector machines forecast collision risks with 80% precision [4], and AI-driven intrusion-detection systems – compliant with National Institute of Standards and Technoloy Cybersecurity Framework (NIST CSF) and International Maritime Organization (IMO) Cyber Risk guidelines – monitor Operational Technology (OT) and Information Technology (IT) networks in real-time to flag anomalies. Sustainability is further enhanced by ML-based energy-management platforms that dynamically balance load and schedule shore-power connections, delivering up to an 18% reduction in peak energy demand and a 10% decrease in CO_2 emissions [6]. Successful, scalable AI adoption depends on modular, micro-services architectures, open APIs and robust data-governance policies. Studies highlight the need for standardised interfaces and algorithmic transparency to enable secure, multi-party data sharing in Industry 4.0 ports [7], and propose an Artificial Intelligence of Things-blockchain (AIoT–blockchain) framework to guarantee data integrity and traceability across complex port ecosystems [10].

3. METHODOLOGICAL APPROACH / *Metodološki pristup*

This study conducts a systematic literature review with two main objectives: (i) to present and describe the principal applications of AI technologies in the port sector; and (ii) to identify knowledge gaps that may guide future research. Although recent studies have explored the use of AI in port contexts, many adopt specific thematic focuses, which contributes to a fragmented understanding of the field. This review therefore aims to provide an integrative synthesis of the available evidence, offering a broader perspective on the impact of AI on port management and operations.

For the systematic review, the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was adopted. This methodology consists of a set of guidelines aimed at ensuring transparency and reproducibility of systematic reviews, focusing on transparent and comprehensive reporting [7]. The process followed four main phases: Identification, Selection, Eligibility and Inclusion (Figure 1).

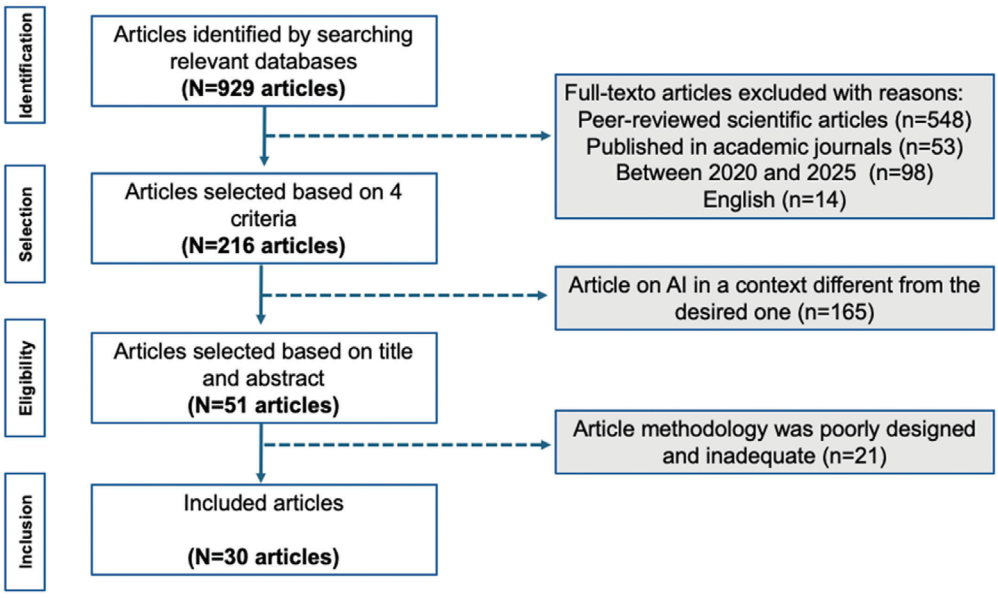


Figure 1 Selection and evaluation of reviewed articles
Slika 1. Odabir i vrednovanje pregledanih članaka

In the identification phase, we collected relevant studies from five major databases: Scopus, IEEE Xplore, Web of Science, ScienceDirect and DOAJ. These databases were chosen as they constitute extensive repositories of academic and scientific research, with broad coverage across various disciplines. They are considered essential resources for accessing high-quality, peer-reviewed articles, crucial for a comprehensive literature review [2].

The search terms used included combinations of "Machine Learning", "Deep Learning", "Neural Networks", "AI-driven systems", "Artificial Intelligence", "port operation", "port management", and "seaport". Given the relatively narrow scope of the research topic, there was a high degree of overlap across databases, as many of the journals in this field are indexed in multiple sources. Consequently, a substantial proportion of retrieved articles were duplicates. After the removal of these duplicates, 929 potentially relevant articles remained. The retrieval process began with the following search strings (Figure 2).

Search Scope: Titles, Keywords, Abstracts
Keyword 1: 'Machine' AND 'Learning', AND
Keyword 2: 'Deep' AND 'Learning', AND
Keyword 3: 'Neural' AND 'Networks', AND
Keyword 4: 'AI-driven' AND 'systems', AND
Keyword 5: 'port' AND 'operation', OR
Keyword 6: 'port' AND 'management', OR
Keyword 7: 'seaport'

Figure 2 Search strings and keywords
Slika 2. Pretraživanje nizova i ključnih riječi

The search strategy was structured around two main conceptual groups: AI-related technologies and port-related application domains. The Boolean operator "AND" was used to combine these two groups, ensuring that only studies addressing both Artificial Intelligence techniques and port management or operations were retrieved. Within each group, the operator "OR" was applied to include synonymous or closely related terms (e.g., Machine Learning, Deep Learning, Neural Networks, AI-driven systems), thereby broadening the search scope and maximising the retrieval of relevant literature while maintaining thematic relevance.

In the selection phase, we applied an initial screening based on the following criteria: (1) peer-reviewed articles, (2) published in academic journals, (3) between 2021 and 2025, and (4) in English, resulting in 216 articles. At this stage, records classified as conference papers, book chapters, technical reports, and non-peer-reviewed documents were explicitly excluded from the analysis. The definition of the time frame was guided by the intention to capture the most recent and relevant contributions in the field of AI applications within the port sector. Since 2021, there has been a noticeable intensification in the development and implementation of advanced technologies – such as digital twins, deep learning algorithms, and predictive systems – whose results have begun to be widely documented in scientific literature. Considering that previous reviews have mostly covered broader and less recent periods, such as [5], [6], [8] the decision was made to restrict the analysis to a more current timeframe.

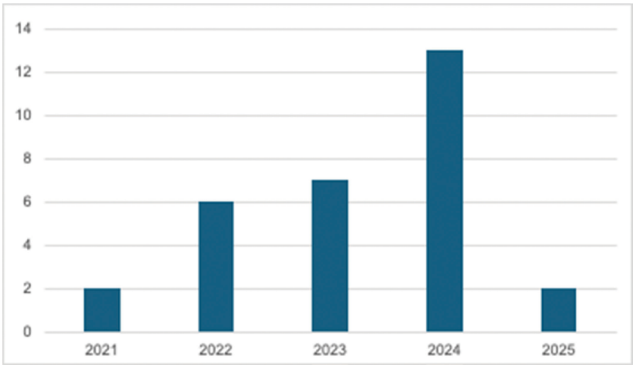
The eligibility phase consisted of an analysis based on the title and abstract, during which it was determined whether the study specifically focused on AI applications in ports or maritime terminals. This stage resulted in 51 articles. Finally, in the inclusion phase, a comprehensive reading of the articles was conducted to evaluate their alignment with the research theme, assess whether they presented practical implementation details or proposed solutions, and determine if they were grounded in empirical research, case studies, or systematic review methodologies. At this stage, the articles were also explicitly classified as either empirical or conceptual contributions, based on the presence (or absence) of data-driven validation, case studies, experiments, or real-world implementations.

The final selection of 30 articles was made collaboratively by the authors, who bring combined academic and professional expertise in artificial intelligence, port management, and port operations. This multidisciplinary evaluation ensured a rigorous and balanced selection process, reinforcing the relevance, methodological robustness, and practical value of the studies included. Both empirical and conceptual studies were retained in the final sample in order to capture not only applied solutions but also theoretical and methodological advances in the field. These 30 articles were then synthesised to support a critical analysis of the main AI approaches applied in the port sector. Table 4 (Appendix) presents the full list of selected articles.

4. FINDINGS OF SYSTEMATIC LITERATURE REVIEW / *Rezultati sustavnog pregleda literature*

4.1. Bibliometric Data / *Bibliometrijski podaci*

Of the 30 selected articles, published in international journals between 2021 and 2025, a growing trend in annual scientific production was observed. The year 2024 stood out due to a marked increase in the scientific community's interest in the application of AI in port operations and management (*Graph 1*). Although an increase in publications for 2025 was projected, it was necessary to emphasise that, considering that the current year was still underway, the continuation of this trend could not be confirmed.



Graph 1 Number of articles by year of publication
Grafikon 1. Broj članaka prema godini publikacije

Regarding the journals, the 30 analysed articles were distributed across 23 different journals (Table 2), revealing an interdisciplinary landscape of research. Among these journals, 9 were directly related to the maritime sector, addressing topics such as naval engineering, maritime transport, port policy and management, as well as environmental impacts on the sector, with prominent publications such as the *Journal of Marine Science and Engineering*, *Frontiers in Marine Science*, and *Maritime Policy & Management*. The remaining 15 journals belonged to various fields of knowledge, including logistics and transport (*Transportation Research Part E*), applied sciences

(*Applied Sciences*), electrical engineering and intelligent transport systems (*IEEE Potentials* and *IET Intelligent Transport Systems*), as well as sustainability (*Sustainability*), operations research (*International Transactions in Operational Research*), and sensor technology (*Sensors and Materials*). This diversity highlighted the multidisciplinary nature of AI research applied to the port sector, demonstrating how the maritime field intersects with other areas of knowledge to develop innovative and sustainable solutions.

Table 2 Journals with relevant publication
Tablica 2. Časopisi s relevantnim publikacijama

Journals	N
Applied Sciences	4
Journal of Marine Science and Engineering	3
Transportation Research Part E: Logistics and Transportation Review	2
Frontiers in Marine Science	1
IEEE Potentials	1
IET Intelligent Transport Systems	1
IFAC PapersOnLine	1
Indian Journal of Geo-Marine Sciences	1
International Journal of Production Research	1
International Journal on Informatics Visualization	1
O International Transactions in Operational Research	1
Journal of Advanced Transportation	1
Journal of King Saud University - Computer and Information Sciences	1
Journal of Mega Infrastructure & Sustainable Development	1
Journal of Shipping and Trade	1
Logistics	1
Maritime Policy & Management	1
Maritime Research and Technology	1
Polish Maritime Research	1
Sensors and Materials	1
Sustainability	1
Systems	1
Transactions on Maritime Science	1
WMU Journal of Maritime Affairs	1

Regarding the methodological approach, empirical studies predominated, representing 63% of the sample, with 19 articles adopting this methodology, suggesting a strong trend towards the practical validation of AI applications in the port context (Appendix).

In the analysis of the keywords, a total of 122 occurrences were observed, of which 84 were distinct. The most frequent keywords were: AI (13 occurrences), ML (8 occurrences), Port Operations (5 occurrences), and Port Management (4 occurrences). The remaining keywords showed a more scattered distribution, with one or two occurrences each, reflecting the diversity of topics covered within the context of artificial intelligence applied to port management and operations. This pattern suggested that, although the main themes were centred around AI and its applications in the port sector, a wide range of subfields were being explored within the research.

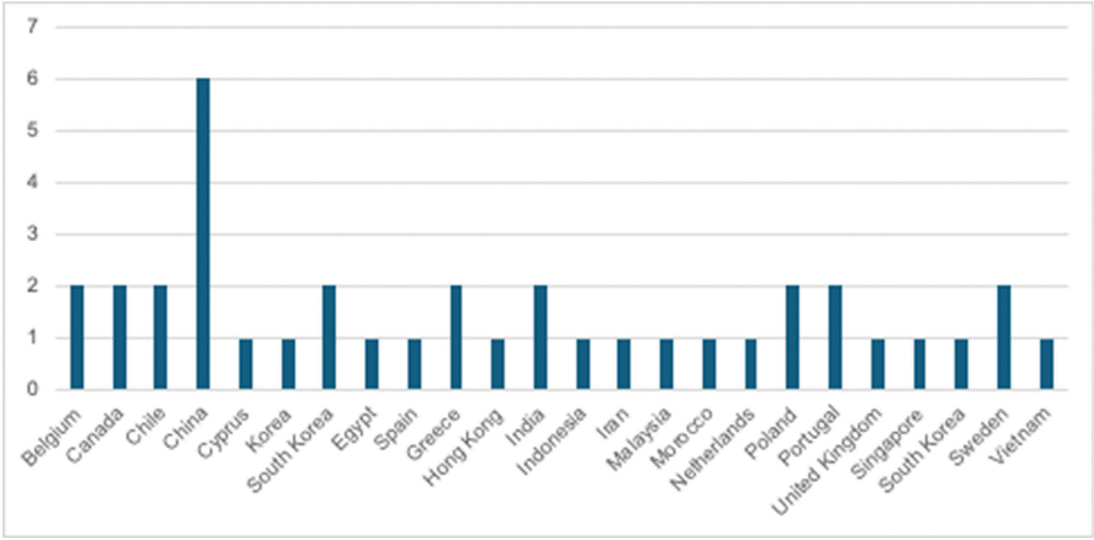
The analysis of the authors' geographical origin revealed contributions from 23 different countries. As illustrated in *Graph 2*, China stood out with 6 publications, followed by Belgium, Canada, Chile, India, Greece, Poland, and Portugal, each contributing 2 publications. This geographical overview highlighted a significant concentration of research in Asia and Europe, particularly in China, South Korea, and India. The presence of countries from America and Africa, such as Canada, Chile, Egypt, and Morocco, demonstrated the global reach and international relevance of AI research in the port sector.

4.2. Classification and Prevalence of Artificial Intelligence Methods / *Klasifikacija i zastupljenost metoda umjetne inteligencije*

An analysis of the 30 selected studies revealed that ML is the most widely adopted AI technique in port-related applications, appearing in 57% of the reviewed articles. Within this category, supervised learning methods such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), and decision trees are the most commonly applied.

ANN, Deep Learning (DL) methods, particularly Convolutional Neural Networks (CNN) and Long Short-Term Memory networks (LSTM), appear in 40% of the literature, primarily supporting visual recognition and time series forecasting.

Reinforcement Learning (RL) is used in 13% of the studies, especially in contexts requiring sequential decision-making,



Graph 2 Authors' geographical origin
Grafikon 2. Zemljopisno podrijetlo autora

such as quay crane scheduling and vessel traffic coordination in constrained environments. Computer Vision (CV) techniques are reported in 17% of the publications, frequently in combination with DL models for real-time object detection and automated monitoring.

Less frequent, but still relevant, approaches include Metaheuristics (6%), such as Genetic Algorithms (GAs) and particle Swarm Optimisation (SO), typically applied in scheduling and optimisation problems. Predictive AI Systems and Decision Support Systems (AI based) (20%), focused on forecasting ETA, failures, and energy consumption. Digital Twin technologies (6%), employed for simulation and visualisation of port operations. Blockchain integrated with AI (6%), used for ensuring transparency and traceability in logistics. Natural Language Processing (NLP) (3%), mentioned in system integration and data interpretation contexts. Table 3 presents the classification and prevalence of AI methods in the reviewed studies.

When we relate the types of AI to port areas, the analysis of the articles reveals a broad but relatively concentrated application of AI technologies in port operations, with a particular focus on several key management areas. The most frequently addressed domains include berth allocation and scheduling, container handling and yard operations, maritime and landside traffic management, predictive maintenance, and environmental and energy monitoring.

In berth allocation and quay crane scheduling, the predominant techniques are supervised ML models [8], [18], [11], [22], [2], [30], [17], [7], especially ANN, regression models, decision trees, and ensemble methods such as Random Forest and eXtreme Gradient Boosting (XGBoost). These are employed for tasks such as predicting vessel ETAs, estimating waiting times, and optimizing resource allocation, contributing to improved operational flow and reduced congestion.

Container handling at the quay and in the yard is another area that significantly benefits from deep learning solutions, particularly CNN and LSTM [2], [17], [1], [4]. These techniques are applied to image recognition, anomaly detection, and forecasting of logistic flows. The integration of AI with CV, AIoT, and autonomous systems such as automated Guided Vehicles (AGVs) and drones has enabled greater automation of internal logistics processes, enhancing both safety and productivity [7], [20], [22].

In maritime and landside traffic management, including channel navigation, vessel entry and exit, and lorry movement within terminals, there is a growing application of reinforcement learning algorithms [5], [23], [28]. Models such as Q-Learning and Deep Q-Networks are used to generate optimal, real-time decisions under operational constraints and dynamic environmental conditions.

Predictive maintenance and energy management are supported by forecasting models based on ML and digital twins [11], [8], [28]. These technologies facilitate failure prediction, more efficient resource usage, and better planning of interventions. Simultaneously, LSTM and regression-based models are applied in forecasting energy consumption and greenhouse gas emissions, contributing to the environmental sustainability of port activities [10], [27], [31], [32].

Finally, environmental monitoring [25] and operational safety [2], [7], [10] have benefited from the combined use of CV, IoT sensors, and DL, allowing for real-time control of air and water quality, as well as risk indicators. In some cases, these applications are complemented by NLP techniques [22] for automated data extraction and the integration of administrative systems.

In summary, the type of AI adopted is closely related to the operational context and the nature of the decision being supported. While supervised ML techniques and neural networks are widely applied in predictive and classification tasks, reinforcement learning methods are more commonly found in sequential decision-making and dynamic control problems. The current applications are mostly concentrated in operational areas such as berth scheduling, container handling, and equipment maintenance. However, there remains significant potential for expansion into strategic planning, integrated supply chain management, and large-scale environmental performance analysis.

4.3. Operational Impact and Benefits / *Operativni utjecaj i prednosti*

The analysis of AI-related benefits and contributions underscored the growing breadth and diversity of AI applications within port operations and management. The contributions observed vary according to the type of AI employed, demonstrating that these technologies address a range of logistical, operational and strategic

Table 3 Classification and Prevalence of Artificial Intelligence Methods in Reviewed Studies
Tablica 3. Klasifikacija i zastupljenost metoda umjetne inteligencije u analiziranim studijama

Type of AI	Specific Examples	References
Machine Learning (ML)	Supervised (ANN, SVM, Decision Trees, Random Forest), Unsupervised (K-means, DBSCAN)	[5][8][18][19][20] [21] [11] [22] [4] [16] [23] [3] [7] [1] [24] [31] [17]
Artificial Neural Networks & Deep Learning (ANN & DL)	Feedforward, RBF, PID-ANN, CNN, CRNN, LSTM	[5] [25] [10] [4] [21][20] [23] [26][27] [2], [17] [1]
Reinforcement Learning (RL)	Q-Learning, Deep Q-Networks (DQN), MADDPG	[8][11][23] [28]
Computer Vision	Container recognition, object detection with YOLOv7	[30] [17] [7], [20], [22]
Metaheuristics	Genetic Algorithms (GAs), PSO, A*	[18][29]
Predictive AI Systems and Decision Support Systems (AI based)	ETA forecasting, failure prediction, energy consumption prediction	[32] [6] [23] [33] [17] [34]
Digital Twins	3D simulations, digital replicas of operations	[11] [2]
Blockchain (combined with AI)	For traceability and transparency	[10] [24]
Natural Language Processing (NLP)	Occasional mentions in system integration	[22]

challenges. Overall, the application of AI has shown benefits in terms of efficiency, predictability, sustainability and safety.

Among the most frequently used technologies, ML stands out as the most widely adopted. This prevalence is largely due to its versatility and adaptability to different operational problems, such as ETA [8], [16], [18], [25], vessel turnaround times [3], [17], resource allocation and real-time decision support [10], [22]. ML has enabled more efficient management of maritime traffic and container flows, leading to shorter waiting times, improved operational flow and optimised use of port infrastructure.

Within the ML domain, ANNs have proven particularly effective in modelling complex, non-linear relationships. They have been successfully applied to accident prediction [4], [5], [33], crane allocation and equipment control [18], [29], supporting more robust and adaptive operational decisions. In parallel, DL techniques – especially CNNs and LSTMs – appears particularly in applications involving computer vision [20], [23] and time series forecasting [8]. These models have enabled automatic recognition of containers, licence plate reading, visual anomaly detection and pattern prediction, thereby facilitating process automation and reducing human error.

Reinforcement Learning (RL) plays a significant role in sequential decision-making scenarios, such as quay crane scheduling, one-way channel traffic management and dynamic resource allocation under uncertainty [5], [23]. RL-based models have demonstrated the ability to adapt in dynamic environments, offering more resilient and efficient solutions compared to traditional deterministic or heuristic methods.

CV technologies are often used in conjunction with DL models. They support automated surveillance, obstacle detection and visual inspection of containers, significantly improving operational safety and asset tracking [20], [21]. Metaheuristics remain an effective approach for solving combinatorial optimisation problems, such as berth allocation, vehicle fleet scheduling and task sequencing in terminals [18], [29].

Other relevant technologies include Systems and Decision Support Systems (AI based), which support fault prediction in critical equipment and improve maintenance planning [32], [34]. Digital twins are emerging as key tools for real-time simulation and monitoring, enabling proactive management through dynamic data and virtual representations of port operations [11].

Though less frequent, the integration of blockchain with AI contributes to enhancing traceability and transparency in port logistics chains, particularly in contexts that require interoperability among multiple stakeholders [10], [24]. Lastly, NLP has been applied to automatic data extraction and system integration tasks, assisting the digitalisation of administrative processes and communication across heterogeneous systems [22].

In summary, the review highlights that those different types of AI provide distinct and complementary benefits. Their application is contributing to the transformation of traditional ports into intelligent, resilient and sustainable infrastructures, effectively meeting current demands for operational efficiency, safety, emissions reduction and digital integration. This technological shift points towards a port future increasingly driven by data and automated decision-making, with AI playing a central role in supporting competitiveness and sustainability across the maritime-port sector.

From a comparative perspective, the reviewed studies indicate that Machine Learning (ML) techniques currently demonstrate the highest level of technological readiness and empirical validation for practical implementation in port environments, particularly in applications such as ETA prediction, vessel scheduling, predictive maintenance and energy management. These methods are supported by a substantial number of real-world case studies and operational datasets, reflecting their maturity and reliability. Reinforcement Learning (RL), while showing strong potential in dynamic optimisation problems such as quay crane scheduling and vessel traffic management, remains largely confined to simulation-based or pilot-scale implementations, indicating a lower level of immediate operational readiness. Digital Twin technologies, although still emerging, exhibit growing empirical validation in safety management and decision-support contexts, particularly in hazardous cargo handling and emergency response; however, their large-scale deployment is still constrained by high infrastructure and integration costs. Overall, ML-based systems appear to be the most mature and deployment-ready category, whereas RL and Digital Twins represent high-potential technologies that require further large-scale empirical validation for widespread operational adoption.

4.4. Key Barriers to the Adoption of Artificial Intelligence in Port Management and Operations / *Ključne prepreke za usvajanje umjetne inteligencije u lučkom upravljanju i poslovanju*

Regarding the challenges associated with the implementation of AI in port operations and management, it is possible to identify a number of recurring and critical issues that range from technical limitations to organisational and legal barriers. These challenges have been systematised and classified according to the frequency with which they appear in the reviewed literature and their relevance to the effective application of AI in this context.

The most frequently cited challenge concerns the quality, availability, and integration of data. Several studies [8], [18], [19], [25], [29] pointed out that the absence of reliable, up-to-date, and structured data significantly limits the ability of AI algorithms – particularly those based on ML and deep learning – to generate useful outcomes. Issues such as noisy data, lack of standardisation across terminals, fragmented databases, and the absence of real-time sensors hinder not only the training of models but also their validation and deployment in real-world environments.

Another widely reported obstacle relates to insufficient technological infrastructure [4], [10], [20], [22], [24]. Many ports, particularly smaller ones or those located in less developed regions, lack the connectivity, storage capacity, sensors, or computing platforms required to support AI-based solutions. This limitation is often compounded by the high investment costs associated with upgrading equipment, adopting solutions such as digital twins or computer vision, and maintaining up-to-date and secure AI systems.

The computational complexity of the models themselves also presents a significant barrier [1], [5], [8], [26], [34]. Numerous articles highlight that hybrid algorithms, real-time simulations, and advanced optimisation methods not only require substantial processing power but also demand highly qualified human resources to operate, fine-tune, and interpret the systems. The shortage of professionals with expertise in data science, AI, and systems engineering is, therefore, a transversal challenge across most ports [22], [23], [30].

Integration with existing port systems, many of which are legacy or outdated, constitutes another frequently noted impediment [4], [23], [24]. AI solutions are rarely immediately compatible with the operational platforms already in use, necessitating either the adaptation or replacement of such systems – a time-consuming, costly process that also involves operational risks.

From an organisational perspective, there is a notable resistance to change and a lack of digital culture among many port stakeholders [22], [23]. The adoption of AI requires not only technological innovation but also the reconfiguration of processes, team training, and strategic alignment between operators, authorities, and service providers. This issue is further aggravated by the limited technical knowledge among port managers, which hinders informed decision-making regarding technological investments and adoption.

Other challenges identified include: difficulties in the economic and operational validation of solutions [4], [11], legal uncertainty and a lack of clear regulation (particularly concerning data sharing, system interoperability, and cybersecurity), as well as ethical and social concerns related to privacy and workforce automation [10], [20], [22], [32], [35]. Additionally, the high variability of port environments makes it difficult to generalise models and scale solutions across different terminals [5], [25].

Another important challenge is related to data governance and interoperability are increasingly being addressed at an international policy level. Initiatives promoted by the IMO, notably the Maritime Single Window framework established under the Facilitation (FAL) Convention, aim to standardise and harmonise data exchange among maritime and port stakeholders, thereby supporting interoperability and the integration of AI-enabled systems [36]. Similarly, European Union policy initiatives on port and transport digitalisation – including the European Maritime Single Window environment and the Digital Transport and Logistics Forum – emphasise standardized data architectures, secure data sharing and interoperability as prerequisites for advanced digital and AI-based solutions in ports [37], [38]. These frameworks indicate that the future adoption of AI in port environments will depend not only on technological maturity but also on regulatory alignment and robust data-governance structures.

In summary, the implementation of AI in ports faces a combination of structural, technical, economic, and human challenges. Overcoming these barriers requires a coordinated and multidisciplinary approach, involving technology, training, regulation, and a clear organisational strategy, so that ports may effectively and sustainably harness the transformative potential of artificial intelligence.

5. CONCLUSION / *Zaključak*

This systematic review has explored the current landscape of AI applications in port management and operations, drawing insights from 30 peer-reviewed studies published between 2021 and early 2025. The findings reveal a growing interest in leveraging AI to optimise operational efficiency, enhance safety, improve environmental sustainability, and support data-driven decision-making across port ecosystems.

ML techniques, especially supervised approaches such as ANN, are the most frequently employed and exhibit the highest level of empirical validation and implementation readiness, applied in areas such as ETA prediction, vessel scheduling, and predictive maintenance. DL and RL also feature prominently, enabling automation in visual recognition tasks, adaptive crane scheduling, and intelligent traffic control. Other emerging technologies, including digital twins and blockchain integrated with AI, demonstrate the sector's movement towards more intelligent, connected, and autonomous port environments.

Despite these advancements, the review identifies persistent barriers to adoption. These include fragmented data infrastructures, limited access to high-quality training data, high implementation costs, skills shortages, and organisational resistance. These challenges underline the importance of multidisciplinary collaboration, investment in digital infrastructure, and the development of regulatory frameworks that support ethical and secure AI adoption in port environments.

Beyond these general challenges, the review reveals several specific research gaps that merit further investigation:

Limited empirical evidence from small and medium-sized ports and bulk cargo terminals, which are often underrepresented in AI research despite their operational and economic relevance.

Insufficient quantitative assessment of environmental impacts, as many studies cite sustainability benefits without rigorously measuring reductions in emissions, energy consumption or environmental externalities.

Scarcity of hybrid approaches combining AI with operations research methods or human-in-the-loop decision frameworks, particularly in complex or safety-critical port operations.

Limited exploration of socio-organisational dimensions, including workforce transformation, user acceptance, governance models and policy alignment in AI-enabled port systems.

It is also important to acknowledge that the review's time frame, limited to studies published between 2021 and early 2025, may have excluded relevant earlier works or foundational studies that could provide additional context.

In conclusion, AI is playing an increasingly central role in transforming ports into more intelligent, efficient, and sustainable systems. However, bridging the identified gaps through targeted empirical research, inclusive innovation strategies, and policy development is essential to ensure that the full potential of AI is realised across the global port sector.

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APPENDIX / *Prilog*

Table 4 Summary of all the selected manuscripts

Tablica 4. Sažetak svih odabranih rukopisa

Title	Author	Year	Keywords	Research Objectives	Research Type
Applications of Artificial Intelligence in Ship Berthing: A Review	[5]	2021	AI, Ship Berthing, Maritime Operations, Port Scheduling	To analyse and evaluate literature on the application of AI in ports.	Conceptual
Machine Learning-Based Models for Accident Prediction at a Korean Container Port	[33]	2021	Machine Learning, Accident Prediction, Container Port, Safety	To predict accidents in container ports using MLalgorithms.	Empirical
Applications of MLMethods in Port Operations – A Systematic Literature Review	[8]	2022	Seaport, Port, Machine learning, Data analytics, Systematic review	It provides a comprehensive systematic review of the literature on machine learning, analysing previous research from different perspectives, such as area of application, type of application, MLmethod, data, and study location.	Conceptual
MLModels for Efficient Port Terminal Operations: Case of Vessels' Arrival Times Prediction	[25]	2022	Machine Learning, Port Terminals, ETA, Intelligent transportation systems	To use MLmodels to predict vessel arrival times and optimise port terminal operations. Using AIS data, we address one of the key planning and scheduling issues in port terminal operations, related to the Estimated Time of Arrival (ETA) of vessels.	Empirical
Port Container Terminal Quay Crane Allocation Based on Simulation and MLMethod	[18]	2022	Container Terminal, Quay Crane, Simulation, Machine Learning	The article aims to propose a quay crane (QC) allocation model for container terminals, based on: computer simulations; MLtechniques; and metaheuristics. The focus is on increasing the efficiency of container handling in a port terminal, particularly in contexts with limited resources (e.g., a restricted number of cranes).	Empirical
Reducing Port City Congestion Through Data Analysis, Simulation, and Artificial Intelligence	[19]	2022	Congestion, AI, Port City, GHG Emissions, Traffic Flows	To reduce congestion in port cities and decrease GHG emissions using data analysis and artificial intelligence.	Empirical
Smart ports: Sustainable smart business port operation schemes based on the Artificial Intelligence of Things and blockchain technologies	[10]	2022	Smart ports, AIoT, Blockchain, Port logistics, Sustainability, Digitalization	The aim of the article is to propose a sustainable and intelligent port operations model based on the integration of two emerging technologies: Artificial Intelligence of Things and Blockchain. The proposed model seeks to improve efficiency, sustainability, safety, and the integration of supply chains within ports.	Conceptual
Towards AI-Driven Environmental Sustainability: An Application of Automated Logistics in Container Port Terminals	[31]	2022	AI, Environmental Sustainability, Automated Logistics, Container Ports	The study focused specifically on the automated and intelligent movement of containers using AGVs in port terminals, with an emphasis on environmental benefits.	Empirical
A Survey on Computational Intelligence Approaches for Intelligent Marine Terminal Operations	[29]	2023	Computational Intelligence, Marine container terminals, Optimization, Berth allocation	To present an in-depth review of computational intelligence (CI) approaches developed to enhance the performance of maritime container terminals, with respect to the berth allocation problem and the quay crane allocation problem.	Conceptual
A Systematic Review of Computer Vision and AI in Parking Space Allocation in a Seaport	[21]	2023	Port management, Computer vision, Deep learning, AI, Parking space allocation	The aim of the article is to systematically evaluate and summarise existing studies on the use of AI and computer vision in the management and allocation of truck parking spaces in seaports. The intention is to understand how these technologies can improve traffic flow, reduce congestion, and optimise space utilisation within ports.	Conceptual
AI-Powered Intelligent Seaport Mobility: Enhancing Container Drayage Efficiency through Computer Vision and Deep Learning	[20]	2023	Computer vision, Deep learning, AI, Seaport, Parking space allocation	The main objective is to propose a model based on AI and computer vision to improve the efficiency of container drayage in ports, specifically through the real-time detection of lanes and parking spaces for trucks using CCTV footage.	Empirical
Application of IoT Technologies in Seaport Management	[32]	2023	IoT, RFID, Seaport management, Smart ports	The article aims to analyse how IoT technologies can be applied to the management of seaports, focusing on the transformation of traditional ports into smart and sustainable ports. The authors highlight the role of IoT in enhancing operational efficiency, improving safety, and reducing environmental impact in ports.	Empirical
Contemporary Challenges and AI Solutions in Port Operations: Applying Gale–Shapley Algorithm	[11]	2023	AI, Gale-Shapley Algorithm, Port Challenges, Machine Learning	The article aims to create a structured method for matching challenges faced by ports (such as ETA prediction, route optimisation, and emission reduction) with AI-based solutions. To achieve this, the authors develop a modified version of the Gale–Shapley algorithm, enabling stable matches between specific port operational problems and appropriate AI solutions.	Conceptual
MLfor Promoting Environmental Sustainability in Ports	[27]	2023	Machine Learning, Environmental Sustainability, Ports	The aim of the article is to analyse how MLtechniques can be applied to promote environmental sustainability in seaports. To this end, the authors conduct a Systematic Literature Review.	Conceptual

Smart Port: A Bibliometric Review and Future Research Directions	[6]	2023	Smart port, Bibliometric review, Performance indicator, Concept evolution	To review the state of research on smart ports and suggest future research directions.	Conceptual
Artificial Intelligence in Indonesian Ports: Opportunities and Challenges	[22]	2024	Artificial intelligence, Automated container handling, Indonesian ports	The study aims to identify the benefits and challenges of implementing AI in Indonesian ports, with a focus on improving operational efficiency, maritime traffic management, and the automation of container handling.	Empirical
Artificial Intelligence in Maritime Transportation: A Comprehensive Review of Safety and Risk Management Applications	[4]	2024	AI, Maritime Safety, Risk Management, Crew Resource Management	The article aims to provide a comprehensive review of AI applications in safety and risk management within maritime transport. It seeks to demonstrate how AI can reduce accidents, improve operational efficiency, and protect the environment, using real-world examples and case studies.	Conceptual
Dependable MLfor Seaports Using Blockchain Technology	[24]	2024	Blockchain, Machine learning, Logistic management, Smart port	The article proposes a new method called DMLBC, with the aim of integrating AI and Blockchain technologies into port management, enhancing operational efficiency, traceability, and security, improving management control based on key performance indicators, and preparing ports for requirements such as the United Nations Maritime Single Window (IMO).	Empirical
Digital Twin-Driven Safety Management and Decision Support Approach for Port Operations and Logistics	[2]	2024	Digital Twin, Safety Management, Port Logistics	The article proposes an intelligent system based on Digital Twin technology for monitoring, safety management, and decision support in ports, with a particular focus on the storage and handling of containers carrying hazardous cargo. The objective is to predict risks, prevent accidents, and improve emergency response.	Empirical
Evaluation and Prediction of Punctuality of Vessel Arrival at Port: A Case Study of Hong Kong	[16]	2024	Vessel Arrival Punctuality, Hong Kong, ETA, ATA, Port Management	To evaluate the punctuality of vessel arrivals at the Port of Hong Kong, predict the actual time of arrival (ATA) based on historical estimated time of arrival (ETA) data, and reduce the impact of schedule uncertainty on port operations.	Empirical
Handling Uncertainty in the Quay Crane Scheduling Problem: A Unified Distributionally Robust Decision Model	[30]	2024	Quay Crane Scheduling, Robust Optimization, Uncertainty	The article aims to address the quay crane scheduling problem in ports, taking into account uncertainties in processing times. To this end, it proposes an innovative model based on Distributionally Robust Optimisation, which enables the generation of solutions that are more resilient to uncertainty, balancing risk and performance.	Empirical
Harnessing AI for Sustainable Shipping and Green Ports: Challenges and Opportunities	[23]	2024	AI, Sustainable Shipping, Green Ports, Maritime Industry	The article aims to analyse how AI can be used to promote environmental sustainability in the maritime sector, with a focus on port operations and maritime transport. The intention is to demonstrate how AI can reduce emissions, improve energy and operational efficiency, and support the development of green ports.	Conceptual
How AI Can Influence Efficiency of Port Operation: Developing a Cost–Benefit Framework	[17]	2024	AI, Cost-Benefit, Ship Arrival, Port Operations	The article aims to develop a cost–benefit analysis framework for the implementation of AI technologies in ports; to apply this framework to the ship arrival process; and to assess how AI can improve operational efficiency and positively influence various port stakeholders.	Empirical
Leveraging Artificial Intelligence to Enhance Port Operation Efficiency	[3]	2024	AI, Port Operations, Machine Learning, Logistics Efficiency	The main objective is to use AI models to accurately predict vessel waiting times and turnaround times in the port, in order to improve the efficiency of port operations and optimise resource utilisation. The study focuses on a specific port in Vietnam – the Port of Haiphong.	Empirical
Smart Ports in Industry 4.0: A Systematic Literature Review	[7]	2024	Smart Ports, Industry 4.0, ICT, Performance Evaluation	The aim of the article is to conduct a Systematic Literature Review on the concept of smart ports within the context of Industry 4.0, with the purpose of identifying current research trends; understanding the main themes and technologies involved; classifying the performance indicators used; and suggesting directions for future research.	Conceptual
Systemic Modelling and Prediction of Port Container Throughput Using Hybrid Link Analysis in Complex Networks	[1]	2024	Port Throughput, Hybrid Modelling, AI, Link Prediction, Complex Networks	The article proposes a hybrid forecasting model for container throughput in ports, combining complex network theory, link prediction, and AI algorithms. The objective is to improve the accuracy of container volume forecasting, which is essential for the strategic management of port resources and operations.	Empirical
TG-PGAT: An AIS Data-Driven Dynamic Spatiotemporal Prediction Model for Ship Traffic Flow in the Port	[26]	2024	Ship Traffic Flow, AIS, Spatiotemporal Prediction, Port Navigation	The objective is to develop an advanced predictive model, called TG-PGAT, which uses AIS data to forecast maritime traffic flow in port areas, taking into account the complex and dynamic nature of these operations. The focus is on the Port of Qingdao (China).	Empirical

The Transformative Potential of Artificial Intelligence in the Maritime Transport and its Impact on Port Industry	[35]	2024	Artificial Intelligence, Maritime industry, Port operations	The aim of the article is to analyse the transformative impact of AI on port operations and the maritime sector. It seeks to provide a clear overview of how AI is enhancing efficiency, safety, and accuracy in ports; what the challenges and ethical implications of its implementation are; and how managers and policymakers can strategically integrate AI into port environments.	Empirical
Optimization of Inbound and Outbound Vessel Scheduling in One-Way Channel Based on Reinforcement Learning	[28]	2025	Vessel Scheduling, Reinforcement Learning, One-Way Channel, Port Operations	The article proposes an intelligent scheduling model for vessels in one-way channels, with the aim of minimising waiting times and delays during vessel entry and exit, improving port operational efficiency, and avoiding safety conflicts by respecting real-world constraints such as minimum distances between vessels and berth occupancy.	Empirical
Process Optimization in Sea Ports: Integrating Sustainability and Efficiency Through a Novel Mathematical Model	[34]	2025	Process Optimization, Sustainability, Port Efficiency	The article proposes a mathematical optimisation model to improve the efficiency and sustainability of port operations, with a focus on the Port of Leixões (Portugal). The objective is to reduce vessel waiting and operating times, optimise berth and crane allocation, and minimise environmental impact, particularly greenhouse gas (GHG) emissions.	Empirical