American Journal of Traffic and Transportation Engineering
2025, Vol. 10, No. 5, pp. 109-119
https://doi.org/10.11648/j.ajtte.20251005.12

Research Article

Analytical Study of Efficiency of Smart Ports

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Abstract

Ports serve as vital hubs for global trade, facilitating the import and export of a vast range of commodities. As the primary interface between nations, ports are integral to the worldwide economy, with over 75% of the world's trade by value passing through them. Today, ports are regarded as essential capital infrastructure, closely connected with a broad spectrum of economic activities. Smart ports are increasingly transitioning into automated facilities, leveraging advanced digital technologies to boost operational efficiency, transparency, sustainability, and overall competitiveness. These smart and automated ports integrate tools such as sensors, big data analytics, artificial intelligence (AI), machine learning (ML), deep learning (DL), augmented reality (AR), digital twins, and various automation systems to restructure cargo movement, minimize environmental impact, and offer improved services to stakeholdersincluding shipping companies, customs agencies, local communities, and other relevant parties. Furthermore, smart ports often incorporate eco-friendly features such as renewable energy sources, electric vehicle charging stations, onshore power supply, and smart logistics infrastructure. These innovations significantly boost the functionality and responsiveness of port operations, thereby playing a critical role in strengthening national competitiveness. The objective of this study is to develop a conceptual framework to evaluate the effectiveness of smart port in the context of technological advancement. Smart ports will be narrated in contest of how they are utilizing cutting-edge technologies such as AI, ML, DL, blockchain, and data science to enhance efficiency, optimize operations, and maximize profitability. It is an analytical study of smart port.

Keywords

Port, Automation, Smart, PCS, AI, ML, Blockchain

1. Introduction

Ports play a vital role in connecting nations and regions, ensuring the seamless movement of goods across international borders. Ports manage a diverse spectrum of commodities from raw materials to finished goods supporting global trade networks and a wide range of industries. Additionally, ports contribute significantly to employment generation in sectors such as cargo handling, logistics, transportation, and various support services. Modern ports function as integrated transport hubs, connecting multiple modes of transportation, including rail, road, sea, air, canals, and inland waterways [3]. This multimodal integration enhances supply chain connectivity and logistical efficiency. The presence of advanced infrastructure and automated systems at port terminals is essential for improving productivity and minimizing operational delays. Certain ports hold strategic importance in both regional and global trade landscapes, influencing economic development and geopolitical relations. For example, Chittagong Port is a key maritime gateway for Bangladesh [15].

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Received: 13 July 2025; **Accepted:** 31 July 2025; **Published:** 26 September 2025

The term port or seaport typically refers to facilities that accommodate ocean-going vessels, while river ports serve inland waterway traffic such as barges, coasters, and other shallow-draft ships [44], Historically, ports were simple harbors with limited functions. However, modern ports have evolved into complex, multimodal logistics centers [40], with extensive transport links via sea, river, rail, road, and even air [37]. Effective ports are usually located to ensure optimal access to an active hinterland [22], and are designed to offer safe navigation and shelter from natural hazards like cyclones, tsunamis, or rough seas. Many ports are naturally situated on estuaries, where shallow waters require regular dredging [27], to maintain navigability. In contrast, deep-water ports, though less common, are capable of accommodating larger vessels with deeper drafts. Contemporary ports are equipped with cutting-edge technologies and specialized cargo-handling machinery, such as gantry cranes, mobile heavy-lift cranes, straddle carriers, reach stackers, and forklift trucks [19]. Ports often specialize in particular functions: some are dedicated to passenger services and cruise operations, others focus on containerized cargo, bulk shipments, or general freight. Additionally, certain ports serve military or naval purposes. Ownership models vary globally. In many developed countries, ports are publicly owned, though it is also common to find ports jointly owned by national governments and municipal authorities.

A recent and significant trend in modern port development is the integration of automation and advanced technologies. This shift is placing increasing pressure on ports to upgrade their infrastructure and services to remain competitive and efficient [43]. Automated ports represent a new generation of digital and smart port systems, designed to be more efficient, sustainable, and technologically advanced compared to traditional ports [46]. These smart and modern ports leverage cutting-edge technologies such as Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), the Internet of Things (IoT), Data Science (DS), and blockchain to enhance operational performance and minimize environmental impacts [16-20]. Among these, AI stands out as a general-purpose technology with broad applications across industries similar to how steam engines, electricity, or computers once revolutionized the world [7]. AI enables machines, particularly computer systems, to simulate human intelligence. It is widely used in areas such as automation, robotics, language translation, image recognition, decision-making, online banking, healthcare, autonomous vehicles, e-commerce, agriculture, and, of course, automated port operations [17]. AI systems are designed to perceive, understand, learn from, and respond to their environment, making them a critical component in the digital transformation of ports [15]. ML, a subfield of AI, gained prominence in 1959 through the work of Arthur Samuel. ML involves algorithms that enable systems to learn from data and improve their performance over time without being explicitly programmed. These algorithms are instrumental in detecting spam, scams, and phishing attempts by analyzing and identifying malicious content [15]. DL introduced to the ML community by Rina Dechter in 1986 [16] and advanced further by Yann LeCun and colleagues in 1989 through the use of back-propagation algorithms, is a specialized subset of ML [8]. DL involves the use of multi-layered neural networks computational systems inspired by the structure of the human brain [12]. These networks, known as Artificial Neural Networks (ANNs), are powerful tools for recognizing patterns and making predictions by modeling relationships between variables [50]. DS is another key discipline in this ecosystem [17]. It is an interdisciplinary field that combines techniques from statistics, computer science, and domain-specific knowledge to extract meaningful insights and knowledge from large volumes of data [10]. In the context of port operations, DS plays a vital role in optimizing logistics, forecasting demand, and improving decision-making processes [19]. Overall, the convergence of AI, ML, DL, IoT, and DS is reshaping smart ports, turning them into intelligent and adaptive systems capable of responding efficiently to the demands of global trade and sustainability [26].

Effectiveness is thecapabilityofproducingorachievingadesiredresult or the ability to produce or serve to desired output. Port effectiveness embodies the degree to which ports achieve the goals or objective they have decided upon. Today, smart port are very effective as they identifying the assessments that offer the greatest benefits in relation to their cost will ultimately improve the cost-effectiveness of the port operation and entire system. A defining characteristic of smart ports is their high level of computerization and intelligent systems, which enable round-the clock operations with minimal or no human intervention effectively [19]. This not only enhances operational efficiency but also significantly reduces labor and operation costs [17]. The effective use of data is central to optimizing resource allocation and streamlining port operations [13]. These ports are increasingly integrated with surrounding logistics and industrial systems, utilizing advanced technologies to ensure a seamless flow of goods and information between ships, cargo terminals, and the broader supply chain [4]. Even minor disruptions in cargo movement at major maritime ports can lead to widespread consequences. For instance, due to the reliance on zero-inventory and just-in-time delivery models that underpin global trade, supermarket shelves and fuel stations could experience shortages within days of a supply chain disruption [5]. Technological advancements are also extending to maritime navigation and environmental monitoring. Smart ships now patrol the oceans, and technologies such as AI-powered satellite data analysis [23], passive acoustic systems, and remote sensing are being successfully employed for environmental surveillance. These applications leverage IoT, AI, ML, DL, DS, etc. to enhance accuracy and decision-making [20, 21]. Another notable trend is the increase in vessel size, a major technological shift that began in the 1990s with the introduction of postPanamaxcontainerships [49]. The continued growth in

ship dimensions across various types including container ships, bulk carriers, car carriers, and cruise vessels necessitates the development of specialized port terminals capable of accommodating them. The concept of sixth-generation ports envisions infrastructure that can support ultra-large vessels with capacities of up to 50,000 TEU. This conceptual framework will evaluate the effectiveness of smart port in the context of technological advancement. This study will focuses explain the efficiency of smart ports and evaluate the significant benefits they offer in terms of efficiency, sustainability, and global trade facilitation.

2. Smart Port Concept and Their Efficiency

In today's rapidly evolving landscape of technology and urbanization, the concept of smart cities is gaining increasing traction. At the heart of this transformation are smart ports critical nodes that not only facilitate global trade but also play a pivotal role in shaping the future of sustainable and interconnected urban environments. This next generation ports leverage advanced digital technologies to enhance resource efficiency, minimize environmental impact, and optimize operational workflows. Key technologies include blockchain, AI, ML, DL, DS, IoTsensors. To further improve functionality, smart ports adopt a wide range of digital innovations such as computerization, DS, and real-time data analytics. These tools support continuous monitoring and management of cargo handling, port infrastructure, and vessel movements. Additionally, smart port systems may incorporate predictive analytics, IoT-enabled sensors, robust communication networks, cybersecurity frameworks, and integrated supply chain platforms [16, 20, 21]. Other advanced features can include digital twin technology, augmented reality (AR), virtual reality (VR), and interoperable systems that ensure seamless connectivity and coordination across various stakeholders (SDP, 2024),

Smart port infrastructure development includes the construction of automated or smart berths equipped with advanced mooring systems, shore power facilities to reduce emissions, and energy-efficient intelligent lighting solutions. In addition to physical infrastructure development and maintenance, smart ports place a strong emphasis on ensuring high levels of security. A critical component of smart port transformation involves the comprehensive evaluation of port management software, which may encompass capabilities such as yard management, berth scheduling, and terminal operating systems (TOS). Effective port facility management focuses on the smooth operation and maintenance of various infrastructure elements and services to ensure efficient cargo flow, safety, security, and environmental sustainability. The integration of digital technologies in port operations is increasingly evident through initiatives like stakeholder collaboration platforms, digitalization strategies, and the implementation of port community systems (PCS). These innovations facilitate better coordination and transparency among port users. To enhance operational efficiency, smart ports are leveraging technologies such as automation, IoT sensors, data analytics, and real-time monitoring systems [17, 21]. These tools are used to track cargo handling, infrastructure conditions, and vessel movements in real time, thereby improving overall productivity and minimizing delays across the port environment.

To enhance overall efficiency and reduce operational delays, technologies are being developed to seamlessly integrate various port functions, including cargo handling, customs processing, and vessel scheduling. PCS facilitate smoother collaboration and information sharing among key stakeholders such as port authorities, shipping companies, terminal operators, customs agencies, and logistics providers. PCS enhances the flow of goods through the port, promotes transparency, and improves the coordination of port activities. Additionally, smart asset management systems utilize sensors, RFID technology, and GPS tracking to monitor the location, condition, and performance of critical port assets including cranes, containers, vehicles, and infrastructure. These intelligent systems support proactive maintenance, extend the service life of essential equipment, and ensure optimal asset utilization. Predictive maintenance, powered by advanced algorithms, analyzes sensor data, maintenance history, and equipment performance to identify potential failures in advance and schedule timely interventions. This approach boosts the reliability and safety of port operations while minimizing downtime and reducing maintenance costs. Furthermore, the use of data analytics combined with IoT sensors enables real-time monitoring of port equipment and infrastructure conditions, allowing for immediate responses to emerging issues and further optimizing operational efficiency [16, 20].

Energy efficient technologies are essential in modern port operations, as they help optimize electricity usage, manage peak demand, and incorporate renewable sources like solar and wind power. Implementing energy-saving solutions such as high-efficiency HVAC (Heating, Ventilation, and Air Conditioning) systems, advanced lighting, and micro-grid technologies within port facilities can significantly reduce carbon emissions, lower utility expenses, and promote environmental sustainability. To strengthen port security, advanced surveillance systems including high-definition video cameras, perimeter intrusion detection systems, and sophisticated access control technologies are deployed to monitor restricted zones, detect unauthorized activities, and alert security personnel in real time. Intelligent video analytics further enhance these systems by identifying suspicious behavior and potential security threats. Tracking cargo, vehicles, and goods across the port complex is made more effective with the use of RFID tags, GPS trackers, and blockchaintechnology [2]. These tools improve visibility and transparency across the supply chain, enabling better inven-

tory control, reducing theft and loss, and offering real-time insights into the location, condition, and status of shipments. Intelligent traffic management systems are also employed to optimize the flow of vehicles and cargo within the port area. These systems manage truck queues, parking assignments, and gate access while using live data on berth availability, traffic patterns, and vehicle movements to support dynamic scheduling and routingminimizing congestion and delays. A centralized, integrated port operations platform aggregates data from multiple stakeholders, including terminal operators, shipping lines, customs authorities, and logistics providers. This unified system enhances communication, facilitates collaboration, and supports efficient decision-making, ultimately boosting productivity and streamlining operations. Smart technologies also play a critical role in emergency preparedness and crisis response. Mobile communication platforms, GIS mapping, and automated alert systems enable quick coordination, help ensure the safety of personnel, and provide effective incident management during emergencies.

Figure 1. *A smart port [28] and their unmanned activities [45].*

3. Effective Use of Key Components of Smart Ports

Traditional supply chain management systems often struggle with fragmented data sources, making it difficult for management and operation system including managers to gain a inclusive view of logistics, procurement, and inventory status. Interactive dashboards consolidate data from various sources, including enterprise resource planning (ERP) systems, IoT sensors, AI, ML, and supplier databases, big data system, into a unified interface that enables managers to track supply chain movements in real-time. Traditional demand forecasting methods often rely on historical sales data and static models, which may fail to capture dynamic market conditions and seasonal variations [16]. The data management mechanism and system including the operational modalities and data management requirements of port operations are analyzed. The data model consists of four components like, data storage, data interaction, data visualization, and data security. The system achieves synchronous mapping of operational processes, integrated data management, and integration with other systems. For prospective clients interested in adopting automated port solutions, the initial step involves launching a structured program. This typically includes preparing a Request for Proposal (RFP), selecting a suitable technology vendor, and overseeing the development of a pilot project. Additionally, a Request for Information (RFI) can be issued to assess market capabilities and gather insights into the specifications, services, and end-to-end solutions that providers can deliver. Smart ports use technologies like IoT, AI, ML, DL, big data, and blockchain to streamline operations, monitor cargo movements, and improve decision-making in real-time. Smart ports operation encompasses the following components [15, 20, 21]:

1. *Automation and Control Systems:* Smart ports utilize advanced automation to enhance the performance of port machinery and operations. This includes remote-controlled cranes, automated guided vehicles (AGVs), smart mooring systems, and robotic container handling technologies.
2. *Labor Relations:* Managing labor relations remains complex, with challenges surrounding wage negotiations, working conditions, and concerns about job displacement due to automation. Port managers must carefully balance technological advancement with the interests of the workforce.
3. *Regulatory Compliance:* Ports are required to follow a wide range of regulations concerning safety, security, environmental standards, and customs. Staying compliant and up to date with regulatory changes can be

demanding for port operators.

4. *Supply Chain Integration:* As key nodes in the global supply chain, ports must synchronize operations with other logistics functions such as warehousing, distribution, and transportation. However, differences in technologies and processes among stakeholders can complicate seamless integration.
5. *Smart Terminal Operations:* Ports are increasingly adopting automation to enhance efficiency, reduce labor expenses, and improve safety. Technologies include robotic container handling, AGVs, and automated stacking cranes.
6. *Collaborative Ecosystem:* Promoting collaboration among port authorities, shipping companies, logistics firms, and other partners is vital for sharing information, optimizing workflows, and driving innovation within the maritime industry.
7. *Compliance and Standards:* Smart port initiatives must ensure adherence to applicable legal, environmental, and cybersecurity regulations, including those related to data privacy and operational safety.
8. *Enhanced Safety and Security:* Cutting-edge technologies like fencing systems, biometric access controls, surveillance networks, and cyber defenses are used to safeguard personnel, assets, and operations. Real-time monitoring and proactive risk management improve incident prevention and legal compliance.
9. *Asset Management Solutions:* These systems oversee the full lifecycle of critical port infrastructureincluding terminals, cranes, warehouses, and berths. Features include asset tracking, maintenance scheduling, and performance analytics to ensure optimal usage and upkeep.
10. *Remote Monitoring and Control Systems:* These tools allow centralized monitoring and management of port assets, providing real-time operational data, supporting remote diagnostics, and enabling safe and efficient remote equipment operation.

Smart ports increasingly utilize sensors to monitor various operational components such as security, traffic flow, environmental parameters, and cargo movement. These sensors generate real-time data that supports improved decisionmaking and enhances operational efficiency. To process and interpret the vast amount of information gathered from sources like shipping manifests, customs documentation, and sensor networks, automated ports rely on advanced data analytics. These insights help identify trends, uncover inefficiencies, and highlight opportunities for optimization. Smart technologiesincluding robotics, drones, and autonomous vehiclesare often employed to boost the accuracy and efficiency of tasks such as cargo handling, inspections, and monitoring. Additionally, by integrating digital tools like cloud computing, blockchain, digital twin systems, and the IoT, smart ports can foster greater collaboration and transparency among diverse stakeholders [18, 20]. Furthermore, in an effort to minimize the environmental footprint of port operations, automated ports promote the adoption of eco-friendly technologies, such as electric vehicles and renewable energy solutions. Smart ports can implement various energy-saving measures to reduce energy consumption and greenhouse gas emissions, such as using energy efficient equipment and LED lighting. They can also generate renewable energy by installing solar panels on rooftops, parking areas, and other suitable locations to capture sunlight. Additionally, wind turbines can be installed either onshore or offshore to harness wind energy. Geothermal systems, which tap into the Earth's internal heat, can be used to generate electricity and provide heating for port facilities. Ports located near rivers or coastal areas can utilize hydroelectric power by capturing energy from flowing water. Furthermore, automated ports can generate energy from biomass sources like agricultural waste or wood chips through processes like anaerobic digestion or combustion.

4. Effective Use and Benefits of Smart Technology in Smart Port

In recent days, AI is made a significant impact on smart port and terminal operations, with successful applications demonstrated through robotics. Regularly featured in the media, AI is driving innovation across various sectors, including industry, healthcare, finance, and pharmaceutical research. Its ML algorithms can generate text, images, and music, as well as assist in identifying genes linked to diseases [24]. As pressure mounts to reduce carbon emissions across shipping and broader supply chains, AI is poised to support ports in achieving more efficient and sustainable operations [17, 19]. By automating and optimizing key port activities like tug operations, pilotage, and container and cargo handlingAI is already enhancing sustainability and operational performance. ML models can analyze historical port data to predict how long specific tasks will take based on vessel types and the services required [25]. These insights allow AI systems to address complex scheduling challenges, factoring in variables like pilot licensing requirements for certain ship types and sizes, the number and type of tugboats needed, and the coordination of pilot transport to boarding points. Such predictive capabilities enable the smart allocation of port resources, including tugboats and pilot vessels [27]. The growing application of AI in port environments is evident, with several pilot projects and experimental programs expanding the concept of smart ports. Ongoing research is essential to understand current practices and anticipate future developments [39]. Overall, AI holds tremendous potential to revolutionize port management. Such as:

1. Real-time marine traffic management becomes possible by analyzing traffic patterns and predicting vessel arrivals at specific ports. This supports improved scheduling, traffic coordination, and optimal utilization of port space.
2. Monitoring real-time data to identify delays and work-

flow bottlenecks enables the optimization of loading and unloading processes. It also enhances scheduling accuracy and the coordination of different port operations.

3. Predictive maintenance can be achieved through continuous monitoring of equipment and analyzing sensor data, helping to prevent equipment failures and reduce operational downtime.
4. Supply chain operations can be streamlined by providing real-time predictive insights into cargo handling needs, helping to minimize delays in goods processing and storage.
5. Real-time supply chain efficiency can also benefit from enhanced port safety and security, achieved by analyzing data from sensors and surveillance cameras to detect potential risks and prevent accidents.

Figure 2. *AI will transform port [25] and AI will make port more intelligent [51].*

AI serves as the core technology driving automation in smart ports. In fact, without AI, the development of automated ports would not be feasible. AI is already influencing global logistics companies and will continue to play a vital role in the advancement of the shipping and maritime industries [16, 17]. Through AI-driven optimization and extensive use of ML, all operational elements align seamlessly to efficiently manage ship arrivals, significantly reducing vessel wait times. This, in turn, helps to alleviate congestion and cut down emissions associated with port activities [47]. ML also plays a key role in optimizing berth allocation by ensuring that each vessel is assigned to the most suitable berth at the right time. Managing this assignment process is highly complex due to numerous constraints, such as vessel size and type, crane availability, and requirements for shore power [35]. As the industry shifts toward cleaner technologies and alternative fuels, ships will have increasingly specific service needs at ports, making precise and efficient berth allocation even more critical in the future.

Smart ports are now integrating digital AI technologies to streamline system automation, enhance safety and security, improve vessel routing, reduce turnaround times, and optimize container dwell time (Port Technology, 2019). These technologies enable real-time performance monitoring, accurate predictions of vessel arrival times, and even the development of digital-twins virtual replicas of port operations for better oversight and control. As AI continues to advance, we may soon see algorithms capable of analyzing aerial imagery to monitor and forecast port congestion. This would allow ports to detect potential issues early and take proactive measures to manage traffic, improving operational efficiency while minimizing environmental impact [39]. AI and ML models can also significantly enhance the accuracy of vessel arrival time predictions, supporting initiatives like just-in-time arrivals. When combined with congestion forecasting, these models could notify ships when to slow down, reducing fuel consumption and lowering CO_2 emissions paving the way for smarter, greener maritime transport. Today's AI-powered software platforms rely on vast amounts of historical and real-time data from IoT sensors deployed across ports and the shipping industry [34]. While AI holds immense potential, much work remains to fully harness its capabilities for improving ports, terminals, and their surrounding infrastructure. Technologies like AI, ML, and DL offer significant opportunities to upgrade current systems and processes. Once the supply chain can consistently deliver high-quality data, ports will be able to leverage algorithms for better decision-making and performance assessment. AI is also playing an increasingly important role in automated machinery, with many ports already using it to control terminal operations and move freight and containers [15, 20]. These AI-driven systems enable vehicles to transport cargo more efficiently and safely under centralized management [38]. Looking ahead, AI and human operators will work side by side in most ports and terminals. While AI will be embedded in vehicles, ships, and other operational systems, human oversight will continue to be essential for managing centralized control systems.

5. Benefits of AI in Port Development

Today, AI is playing a vital role in enhancing port operations around the world. At the Port of Rotterdam, the AI system Pronto significantly improves the coordination and management of container loading and unloading by leveraging sensor data. It gathers crucial information, such as vessel docking times, from the Automatic Identification System (AIS) and the Port Authority's database. Data scientists use this information to develop self-learning computer models. According to the Rotterdam Port Authority, the implementation of AI has already led to a 20% decrease in vessel waiting times. This port uses machine learning algorithms to accurately predict ship arrival times and container handling durations, resulting in more efficient terminal operations [41, 42]. Meanwhile, the Port of Los Angeles is also utilizing AI through a system called Port Optimizer, which employs sensor data and predictive analytics to improve container scheduling and logistics coordination. This system uses machine learning to anticipate demand and optimize the planning and execution of port activities. In Singapore, the Maritime Single Window system is using artificial intelligence to streamline immigration and customs procedures. By combining natural language processing with predictive analytics, this system enhances operational transparency and speeds up processing. ML helps classify and interpret data from shipping and customs documents, improving overall port efficiency and management. Looking ahead; AI is poised to play an increasingly significant role in port administration and logistics. It offers numerous benefits, including:

1. *Data Availability Evaluation:* AI relies heavily on large datasets. Therefore, ports need to assess the availability of relevant data and consider integrating systems to collect additional information where needed [15].
2. *Operational Efficiency:* AI can pinpoint areas for improvement, particularly in productivity and efficiency. Future AI applications may include automating container handling, optimizing shipping routes, predicting cargo demand, and detecting fraudulent activities.
3. *Infrastructure Assessment:* AI can help determine whether existing infrastructuresuch as data storage and network capacitycan support AI implementation effectively.
4. *Team Formation:* AI can support the establishment of dedicated teams responsible for managing and integrating AI solutions within port operations.
5. *Investment Analysis:* AI systems can assist in evaluating the costs and benefits of AI adoption, helping stakeholders decide whether such investments are worthwhile.
6. *Strategic Partnerships:* AI can help facilitate partnerships with specialized AI firms to enhance implementation and develop in-house expertise.

While AI holds great promise for creating more intelligent, sustainable supply chains, it's important to recognize that not all AI solutions are equal. Careful planning, evaluation, and continuous development are essential to realizing AI's full potential in the maritime sector. AI transforms vast amounts of data through advanced algorithms that simulate human cognitive processes. In ports, where operations are often repetitive, massive volumes of historical and real-time data are generated deal for feeding into AI systems [18, 19]. Many aspects of port management have already been automated with AI, including vehicles, trucks, and administrative systems. For example, the Port of Los Angeles uses autonomous cranes and container trucks to move cargo within terminals, while the Port of Rotterdam employs AI to power its smart port operations. Smart port operations represent a branch of AI where digital simulations mirror real-world scenarios. These systems are designed to replicate and automate human decision-making. ML, a core AI technology, can integrate real-time data from blockchain and IoT sensors to monitor vessel trade routes [15, 21]. By doing so, ports can more accurately predict a ship's Estimated Time of Arrival (ETA), allowing for optimized berthing and reduced idle time [17]. Given that many ships currently arrive later than planned the global shipping industry stands to benefit greatly from AI-enhanced scheduling.

A report by Danish company Sea-Intelligence in November 2020 revealed that across 34 global trade routes, on-time reliability of carriers had dropped to 50.1%. Imagine the chaos if half of all aircraft arrived days late, this is the kind of unpredictability the shipping sector faces without AI. By accurately scheduling vessel arrivals and departures, AI can help reduce costs, limit environmental impact, alleviate port congestion, and ensure regulatory compliance. Furthermore, automated decision-making enables timely and efficient unloading of cargo at the correct berth. AI-powered smart ports can handle growing freight volumes, optimize workforce scheduling, minimize human errors, and significantly enhance supply chain efficiency. Overall, AI boosts productivity. The integration of AI into existing port infrastructure, a process known as retrofitting transforms traditional systems into safer, more organized environments. Through software-based platforms and AI-driven modules, maritime stakeholders can elevate their operational performance and gain comprehensive visibility into their logistics networks [15, 36]. With AI, ports can process complex datasets to make more informed decisions, accurately schedule vessel movements, identify optimal storage locations, and efficiently manage container handling. However, the maritime industry's long-established practices pose challenges to the integration of AI into routine operations. The success of AI largely depends on the quality of data it receives. While ports have no shortage of data, ensuring it is high-quality, reliable, and relevant is essential for effective AI deployment. Standardization also remains a key issue. Currently, the maritime sector lacks universal technical standards, and many AI solutions are customized to individual port requirements [16, 19]. To address this, ports working with AI experts can develop

scalable, adaptable solutions that benefit various stakeholders across the maritime ecosystem.

Today, many leading and technologically advanced shipping companies are effectively leveraging AI, ML, DL, etc. to optimize their operations. Maersk, for instance, has integrated AI across various segments of its global business. One notable innovation is its AI program Captain Peter, which helps ship captains improve fuel efficiency and reduce carbon emissions by analyzing sensor data through machine learning models [30]. Similarly, CMA CGM has developed an AI-driven platform known as Smart Containers. This system uses sensors and ML algorithms to monitor the condition of containers during transit. It allows customers to track vital information such as the location, temperature, humidity, and other environmental conditions of their cargo in real time [6]. Hapag-Lloyd has also adopted AI for optimizing maritime route planning. By analyzing data related to weather, shipping traffic, and fuel consumption, the system suggests the most efficient routes, thereby reducing operational costs and improving voyage efficiency [14]. Another major player, MSC, has launched an AI platform called Safeguard, designed to enhance ship safety. Utilizing sensor data and machine learning, the system helps prevent accidents and provides real-time emergency alerts to both onboard and shore-based personnel [31]. Evergreen Line has pioneered the use of AI in predictive maintenance. Its system continuously monitors machinery conditions and predicts when maintenance should be performed, helping to prevent equipment failures. In addition, Evergreen has introduced an AI-powered container tracking system that provides real-time updates on container locations [32]. Customers can enter their container number, booking reference, or Master Bill of Lading, and the system instantly displays the current position of their international shipments [11].

In today's port operations and shipping management, there is no scope of doing error. Unlike conversational AI systems, where experimentation is more acceptable, port safety and operational efficiency demand precision and reliability. For AI to deliver dependable results in this sector, proper training and implementation are critical. In port environments, AI and machine learning models can be trained using tailored datasets and clearly defined performance benchmarks. These systems learn to identify optimal responses based on this structured input. A key part of this training involves realistic validation comparing the AI's projected timelines and predictions with actual operational durations [9]. This feedback loop helps the algorithms adapt over time, refining their accuracy based on a port's specific constraints and operational patterns. Meanwhile, the global shipping industry has seen a steady rise in container ship cargo volumes. The demand for container shipping continues to grow rapidly worldwide. According to data from the Hong Kong Marine Department, Asian portsparticularly those in China which have become increasingly dominant in this field. In 2005, two European ports and one North American port were ranked among the top global maritime hubs. By 2021, only the Port of Rotterdam remained in the top 10, and it held the lowest position on the list [33, 48]. In recent years, China has achieved remarkable progress by integrating AI and digital technologies into its port operations and administrative systems, leading the way in modernizing the maritime sector.

Figure 3. *Smart port will be game changer in any hub of the world [1, 29].*

6. Conclusion

Smart ports play a vital role in national economic development, contributing significantly to government tax revenues that fund public programs and infrastructure projects. They also serve as key hubs for warehousing, container storage, and distribution, strengthening trade networks and ensuring the smooth flow of goods. The efficient operation of ports is essential not only for economic growth but also for social development, as it aligns logistical advancements with societal benefits. Ports are also critical to national security, necessitating strong protective measures to guard against threats and ensure safe, uninterrupted operations. Smart and technologically advanced ports enhance efficiency and elevate a country's position in global trade. These smart ports attract foreign investment, boost export capacity, and enhance a nation's competitiveness. Certain ports, due to their strategic geographic locations like the Port of Chittagong for Bangladesh play a pivotal role in both regional and international trade. They act as gateways for global connectivity, linking markets across continents and encouraging cross-border

collaboration. While ports bring substantial benefits to local economies and communities, they also face environmental regulations and responsibilities. Still, their value proposition remains strong, especially as container traffic continues to grow significantly. Ports are essential in maintaining robust supply chains and enabling trade, serving as key drivers of economic activity. The global expansion of container ports, along with their varying growth rates, highlights broader trends such as off-shoring and local economic transformation. Looking ahead, the development of sixth-generation ports could allow for the management of vessels more than twice the size of those currently in service, pushing the boundaries of maritime logistics and capacity.

Traditional maritime operations are undergoing a major transformation with the rise of smart ports. Leading ports around the world are now leveraging advanced technologies to enhance security, reduce environmental impact, and boost overall efficiency. AI, ML and DL play a critical role in optimizing berth management, a function that will become increasingly important as more vessels adopt alternative clean energy sources and require specialized port services. Looking ahead, ports could use AI powered algorithms capable of analyzing data such as aerial imagery to predict and assess congestion levels. This would enable port authorities to quickly identify critical situations and implement timely measures to alleviate traffic and maintain smooth operations. However, the increasing adoption of AI in the maritime industry must be accompanied by a strong understanding of the underlying technology and a commitment to responsible implementation. Proper training and strategic deployment are essential for port management teams to effectively harness AI's potential. Due to the repetitive nature of port activities, a vast amount of historical and real-time data is generated deal for feeding into AI systems. Automation has already been applied to port vehicles, trucks, and administrative functions in several facilities. Notably, ports like Shanghai and Singapore have gained recognition from the United Nations as the world's best-connected ports thanks to their effective use of AI. Meanwhile, the Port of New York and New Jersey has launched a five-year strategy to implement AI technologies, and the Port of Hamburg has integrated ML modules into its operations. AI is expected to continue driving advancements in port management. One of the most impactful applications is ETA prediction. Accurate and reliable ETA forecasting can significantly streamline port operations, enabling better scheduling, reducing idle time, and improving coordination across the logistics chain.

Smart ports leverage AI, ML and a range of smart technologies to ensure efficient and effective port operations and management. The integration of cutting-edge tools such as digital twins and blockchain has significantly enhanced customer service, increased transparency and traceability in freight movements, and strengthened stakeholder trust, ultimately driving profitability. The successful deployment of advanced technologies has the potential to positively influence nearly every area of port operations. This includes resource planning, infrastructure maintenance, workforce optimization (such as dockworkers and stevedores), equipment management (including cranes, straddle carriers, and forklifts), administrative processes, berth scheduling, port governance, and financial operations. Smart ports are also designed with sustainability in mind. They aim to reduce carbon emissions and protect marine ecosystems by incorporating renewable energy sources and environmentally responsible technologies. Moreover, they foster a culture of open innovation, continuously evolving by embracing new tools and strategies to improve operational performance. However, as smart ports become increasingly digital and interconnected, they also face sensitive cybersecurity risks. A cyberattack targeting critical systems such as energy supplies could have a severe ripple effect, disruptingsmart ports and potentially shaking the global economy.

Abbreviations

AI	Artificial Intelligence
ML	Machine Learning
DL	Deep Learning
ICT	Information and Communication Technology
IoT	Internet of Things
5G	Fifth Generation Mobile Network
LNG	Liquefied Natural Gas
UNCTAD	United Nations Conference on Trade and Development
IMO	International Maritime Organization
API	Application Programming Interface
KPI	Key Performance Indicator
GIS	Geographic Information System
ERP	Enterprise Resource Planning
CRM	Customer Relationship Management

Author Contributions

Hossain Khandakar Akhter is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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Biography

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