



ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ

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Student: Ergina Angouri

Supervisor: Dr Ioannis N. Lagoudis

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1. Introduction

1.1. Definition of Smart Ports

Smart ports are an innovative advancement of the maritime industry through its integration of highly digitized technologies in order to improve operations and optimize efficiency, as well as in terms of sustainability. Smart ports differ in that they employ automation, real time data analytics and interconnected systems as they have processes that are automated and data analytics are real time. With IoT, artificial intelligence (AI), big data, blockchain, port infrastructure will become smart — that is, these advanced port infrastructure and technologies further benefit from the Internet of Things (IoT), artificial intelligence (AI), big data, blockchain, and 5G connectivity, facilitating direct communication and smart making decisions (Fusco Girard, 2013).

Smart port is a smart ecosystem where different technological components cooperate to improve the process of logistical and operational processes. IoT devices and sensors that are connected to port cargo movement and environmental monitoring can help the port authorities monitor data in real time and predict possible bottlenecks. Predictive maintenance based on this technology increases both reliability of port equipment and reducing downtime. In addition, blockchain technology guarantees less paperwork and reduces the possibility of forgery in the process of transactions (Heilig et al., 2017a).

Adapting to the changes in the world of international trade is one of the key smart port traits. Juggling higher volumes of cargo with greater accuracy and speed is becoming more important as maritime logistics become more complex, therefore, ports are required to process more cargo with more accuracy and speed. Smart ports automate and digitalize to smoothen out any sort of congestion that would otherwise slow the resources and thus lower operational costs. In addition, autonomous container handling, drone surveillance, and digital twin simulations for the ports are further combined into more efficient means, making ports dynamic and cross correlated trade and commerce hubs (Kovač, 2021).

The smart ports concept is also strongly correlated with the category of smart cities and sustainable development. Nowadays many modern ports have been utilizing green technologies and eco-friendly solutions to lessen their environmental impressions. Global efforts to reduce carbon emission and improve maritime sustainability are reflected in the incorporation of energy efficient system, shore-to-ship power supply

and alternative fuel source. In the hands of digitalization, the time has come for smart ports to establish a model of smartness in global trade by to be an industry of efficiency, security, and environmental responsibility (Meyer, 2021).

1.2. Importance of Smart Ports in Modern Maritime Logistics

Smart ports were brought into existence as a result for growing complexity of global supply chains along with the ever arising need of speedy and efficient trade. International commerce depends on ports which in turn facilitate the large and diverse volume of goods which support worldwide economic activity. Information on the temporal evolution of the structural patterns of vessel structure and vessel operations is curtailed not only by frequent vessel schedule changes, but also due to inefficiencies, long processing times, and logistical bottlenecks in traditional port operations, as well. Smart port technologies introduce these challenges and overcome them by turning cargo into hold, shipboard, and operations management into a revolutionized smart technology process (Heilig et al., 2017b).

Smart ports are a well known to deliver different benefits especially high operational efficiency. Smart ports leverage the power of automation and use of digital connectivity to reduce the human error and its associated time, reducing human dependence. The fast loading and unloading processes with automated cranes, self-operating cargo trucks and AI powered logistics platforms, greatly decrease the port congestion. The efficiency is required especially in global trade in which delays in port operations could disrupt the supply chains and result in economic losses (Molavi et al., 2020).

Besides operational efficiency, smart port helps improve the security and transparency of the maritime logistics. The safeguarding of data exchange along such networks is done by such cyber measures as blockchain based documentation and secure encrypted communication networks between port authorities, shipping companies, and regulatory authorities. It helps minimize risks of smuggling, fraud, and unlawful access to sensitive information attached to the phone. Furthermore, these AI driven surveillance and monitoring systems make safety even more feasible, for it is able to track down potential threats and even make sure of its compliance in international regulations (Othman et al., 2022).

Another factor for adoption of smart port technologies is in the area of sustainability. Ports are put under more and more pressure to reduce its carbon footprint all the time

as more and more people start to worry about climate change and environmental degradation. The smart ports have energy efficient solutions, such as electrification of the cargo handling equipment, using renewable energy sources and waste management system to reduce pollution. Also, digital technologies are used to optimize fuel consumption, that is, through tracking vessel emissions in real time and suggesting energy efficient navigation routes. The smart ports play a part towards this direction through promoting extending eco friendly practices in maritime transport (Sarabia-Jácome et al., 2019).

The smart port is more than the economic significance of smart ports within the operation of an individual port. Smarter ports are served by known investment, employ people, stimulate regional economic progress. It increases trade volumes by enhancing port's efficiency resulting in improved service for local industries and businesses based on the smooth flow of logistics services. On top of that, the digitalization of port operations enables port operations bursting with more collaboration among different stakeholders such as shipping companies, customs authorities and logistics providers (Yang et al., 2018).

However, smart ports are very important in modern maritime logistics. “We are integrating the latest technologies that make a difference in cargo handling and transportation as well as improve global trade networks, and at the same time, improve the security and sustainability of freight transportation,” they say. As the world of international commerce evolves, smart ports will have an important role to evolve the future of maritime logistics and maintain the flow of supply chains as they evolve in the face of these bigger and changing demands (Zhao et al., 2020).

1.3. Research Aims and Objectives

This study aims at primary innovation of the concept of smart ports and their position in the modern maritime logistics. Due to ongoing market evolution, global trade, digital technologies have been fully integrated into port operations. This study aims at reviewing the facets in technology that will make up smart ports, assess their implication in efficiency and sustainability and inquire into challenges of implementation. The research seeks to understand in the comprehensible level how smart ports help to optimize Sail sector of global supply chains by boosting security and environmental responsibility as well.

This study also aims to identify the corresponding specific technologies that lead to port transformation from traditional to smart ports. Turning to such new innovations as artificial intelligence, big data analytics, automation, blockchain technology for example, this case will analyze how they are making ports more efficient, reducing congestion, making better decisions. Additionally, this study endeavors to determine the importance of smart connectivity using 5G networks and Internet of Things on enabling real time exchange of data among the port authorities, shipping companies and logistics operators.

The other important objective is to evaluate the benefits and the challenges of the use of smart port technologies. Certainly, digitalization has the potential to completely transform port operations, but it does come with its task of handling the cybersecurity, implementation cost and regulatory compliance. The purpose of this study is to understand the possible risks and limitations to which ports may be subject when under smart infrastructure. In addition, this research would also examine the real world case studies of smart ports' leading, in order to give the insights of best practices and successful strategies implemented in maritime logistics for the digital transformation process.

1.4. Scope and Limitations of the Study

Smart ports are something of technological advancements that are defining these days, and in this case the port logistics. The research includes the analysis of the digital tools and automation processes for an improvement of port operations. Specifically certain technologies including artificial intelligence, Internet of Things, big data analytics, blockchain technology and 5G connectivity are explored around utilization of these factors to enhance port efficiency and green for further study. Additionally, case studies are investigated of the smart ports in the world, including such cases that are real life examples of successful digital transformation in the port operations.

The study seeks to offer an overview of all smart ports while there are limitations of it. First, this is not an empirical data collection research, but a bibliographic review. Therefore, these findings are derived from the available literature, reports and case studies rather than made through direct observation or primary data sources. Technological advancements will continue to be innovations, and this may reduce the possibility to analyze real time development in smart port infrastructure.

A second limit to the study is that it is limited to technological and operational aspects of a smart port development rather than the economic and political implications. However, the research does not study the economic feasibility of smart port implementation in different regions, even as they require significant financial investments for it. The study is similarly short on the study of the policy and regulatory frameworks that govern smart port initiatives without conceding their importance in their adoption.

Moreover, the study focuses on large scale commercial ports that have digitized. Little is said of such challenges faced by smaller regional ports or in developing economies in implementing smart technologies. However, the limitations of the study are due to the focus on the technological advancement, operational improvements and sustainable consideration.

1.5. Structure of the Paper

This study is structured with regard to the smart ports research, their foundations in information and communication technologies, and the input role of smart ports in modern maritime logistics. It provides an introduction to smart ports and their importance, the research aims, scope and limitations of the thesis. A detailed explanation on the approach of the bibliographic research methodology is given; it speaks about how the literature sources have been selected and analysed. In the literature review, it is addressed deeply the key technologies like artificial intelligence, big data, blockchain and automation as well as addressing the sustainability and security challenges. The last section discusses the conclusion, which is the summary of the key findings and the future trends of the development of the smart port and digitalization. Structure of the paper is such that the objective of the paper is to evolve a clear and comprehensive perspective of smart ports, their operational benefits and the overall significance of smart ports for global trade..

2. Literature Review

2.1. IoT and Smart Ports

Integration of the Internet of Things (IoT) in the smart port operations is a transformative technological paradigm that has significantly improved efficiency, security and sustainability of port operations. Port 4.0, the next generation of the digitalized port ecosystem, is based on IoT, which is the interconnection of physical devices with the Internet to communicate and exchange data. Using the IoT smart ports can reduce the costs, optimize the operations and improve the decision making processes, this will enhance logistics and supply chain management (Yang et al., 2018).

Traditional, manually operated ports are gradually transforming into smart ports with fully automated ecosystem, in which IoT enabled sensors, actuators and communication network are working together in optimizing the workflow. The main objective of using IoT in port operation is to improve efficiency, safety and environmental sustainability, and cut down on operational cost (Heikkilä et al., 2022). The real time monitoring of port activity is one of the key advantages of the use of the IoT in smart ports. Cargo movement, equipment usage and environmental data from the port facility are collected through sensors installed across port facilities for the port operators to make data driven decisions. This real time data collection upgrades the asset usage and decreases all downtime, that is necessary specifically for the major ports to process mass load (Kapkaeva et al., 2021)..

2.1.1. IoT Applications in Port Operations

IoT is transforming how cargo is managed, assets are maintained, environment is monitored and security is handled in ports. Through the use of IoT, cargo handling operations on supply chains have been made much easier and automated to include real time tracking and tracing of goods. All these can be established by smart containers that use RFID tags, GPS trackers and temperature sensors, and the port authorities can monitor the conditions of the cargo from the initial point up to the final point of transport. Moreover, this is advantageous in the case of perishable goods, which need temperature sensitive environments, including, pharmaceuticals and fresh food products (Liao et al., 2023). Additionally, IoT powered Automated Guided Vehicles (AGVs) and smart cranes use effective cargo loading and unloading to reduce the human error and increase the operational efficiency (Yang et al., 2018). In addition to

all of the above, AI predictive analytics' deployments are used for predicting the upcoming bottlenecks and optimizing resource allocation (D'Amico et al., 2021).

Furthermore, for predictive maintenance, IoT enabled sensors can also play a key role as they are capable of detecting failure of equipment before it occurs. Quay cranes, automated vehicles and conveyor belts are fitted with sensors to monitor the performance of this equipment continuously and any anomaly such as excess vibrations or overheating. Through examining this data, maintenance teams can arrange timely repairs cutting off unexpected breakdowns as well as minimizing maintenance costs (Jović et al., 2019). Not only will predictive maintenance enable operational continuity, but worker safety is guaranteed also, since the malfunctioning of equipment will be rectified prior to creation of hazardous conditions (Makkawan & Muangpan, 2021).

As they are made to comply with stringent environmental regulation, smart ports can't afford to do without the IoT based environmental monitoring system. Real time detection of pollution levels by means of air and water quality sensors that prevent ships and port operations exceeding permitted criteria (Othman et al., 2022). Further to this, IoT technology allows for a great contribution towards energy efficiency initiatives. Simply put, smart grids and IoT systems based on energy management facilitate ports to save on their energy consumption by incorporating renewable energy sources (solar and wind sources) into their infrastructure (Ben Farah et al., 2020). It also facilitates shoreline to ship power supply automation to enable docked ships to switch off their engines with regard to make use of port supplied electricity to reduce greenhouse gas emissions.

Port security is a huge concern for the modern ports and with the use of the IoT technology, the port security has been improved vastly. As a mean to increase security, smart surveillance cameras, automated access control systems and facial recognition technology permit real time port facility monitoring. It can be detected immediately and addressed unauthorized access to reduce risk of theft or sabotage (González Cancelas et al., 2020). While port systems come more connected, however, so do they become more exposed to the cybersecurity risks. IoT networks should be protected against such cyber threats as hacking and ransomware attacks through the robust cybersecurity measures implemented at the ports. A prevention is done using secure blockchain based

communication protocols and AI based threat detection systems (Ben Farah et al., 2020).

2.1.2. Case Studies of IoT Implementation in Smart Ports

However, smart port development has been successfully integrated in some ports globally and used as benchmarks.

- In Netherlands – Port of Rotterdam: This is one of the most technologically advanced port. This is where the digital twin technology has been utilised wherein IoT sensors create a virtual replica of the port in real time. This makes scheduling of vessels and cargo handling easier by the operators (Heikkilä et al., 2022).
- The Port of Hamburg, Germany uses the IoT to manage traffic. It has improved the efficiency of the cargo transport and significantly reducing the congestion. Also, it has integrated AI driven logistics solutions, autonomous trucks to optimize the supply chain operations (Kapkaeva et al., 2021).
- Port of Singapore: The second busiest port in the world, Singapore has utilized IoT enabled smart berths that automatically assign the docking space to vessels that are coming in using real-time data. It has greatly reduced waiting time and increased port efficiency (Yang et al., 2018)..

2.1.3. Challenges and Future Prospects

Nevertheless, this smart ports has several challenges. High initial investment cost necessary to deploy IoT infrastructure is one of the main obstacles. The integration of legacy port systems with new IoT technologies is also a complex and time consuming task (González – Cancelas et al., 2020). An important problem is also data security and privacy. As data is exchanged across the IoT, a considerable amount of sensitive data is exchanged and cybersecurity measures need to be implemented that are robust enough so that no unauthorized access is made and no cyberattacks take place (Ben Farah et al., 2020). Future aspects of IoT regarding smart ports will involve more usage of AI, faster data transmission with the help of 5G connectivity and blockchain solutions for secure data management. This development of these technologies will usher in a further step in the efficiency, security and sustainability of port operations and the globally digital transformation of maritime logistics.

The Smart port revolution is inherently IoT powered. When IoT enabled sensors are integrated with real time monitoring systems and AI powered analytics, Port can become more efficient and reduce the cost at the same time and also do the provision of complying with environmental regulations. But smart ports are only possible once all this technology, cybersecurity, and integration of infrastructure has been done. With global trade in continuous growth, IoT will continue to be a basic of modern port digitalization and automation, and ports will need to be competitive and adapt to the increasingly interdependent world.

2.2. AI and Smart Ports

Artificial Intelligence (AI) integration into the smart port operations in the maritime industry is changing it all for their better as it improves the decision making and optimises process and increases overall efficiency. With an expanding global trade and port traffic heightening, the need for intelligent automation, as well as data driven solutions peaked in recent times. Machine learning, predictive analytics, and autonomous systems are now some of AI's biggest driven technologies that ports are applying to make them fully digitalized and automated ecosystems (Min, 2022).

Automation of port logistics, optimization of vessel traffic, improvement of the port security and environmental sustainability of ports are among the areas that largely depend on AI. An example of smart ports instrumentally involves the use of AI driven analytics, as the data from millions of containers and other shipments can be analyzed in real time, thereby enabling ports to handle cargo more efficiently along with reducing their operational delays, and efficiently planning the allocation of their resources (Behdani, 2023). A main benefit of AI is its potential to predict and reduce congestion problems by looking at data from the past and using data from the real time ships movements. Port authorities can dynamically change the vessel schedule, berth allocation, as well as the container handling operation based on the demand forecast by means of the advanced AI driven traffic management systems (Heilig et al., 2017). Similarly, AI also improves supply chain visibility with the inclusion of shipping company, freight forwarders and customs authorities' data. Ports are able to predict potential disruptions including weather delays, equipment failures as well as geopolitical factors via leveraging AI powered predictive analytics and predetermine decision making (Rodrigo González et al., 2020).

2.2.1. AI Applications in Smart Port Operations

Automated cargo handling, prediction of ship arrival, predictive maintenance, cybersecurity and environmental management are all benefiting from the use of AI in a port. With each passing hour, AI is reshaping how cargo is handled and products are shipped (or ‘shipped’), bringing in automated guided vehicles (AGVs), robotic cranes and intelligent storage systems etc. Features of AI-powered solutions for container loading and unloading includes reducing the error of human operations, accelerating turnaround times (Cunha et al., 2023). Through AI based dynamic routing algorithms, those goods are routed through the port in the least unreasonable manner, eliminating pulls and congestion on the roads. There is also an analysis of machine learning models that help to predict the shipping patterns and as such help to improve the cargo forecasting, to ensure proper inventory management and resource utilization (Sankla & Muangpen, 2022). Played a crucial role in continuous port equipment operation. If we analyze the sensor data from cranes, conveyor belts, and automatic transportation vehicle, an AI can pick up signs of mechanical failure before it actually happens and thereby prevent costly breakdowns and minimize downtime (Alop, 2019). By preventing some potential hazards before becoming acute problems, this approach reduces maintenance cost as well as makes worker safer. It is possible to make smarter decision about equipment usage, replacement, and repair schedule of the equipment via AI based real time monitoring on port infrastructure (Chen et al., 2019). Modern ports become increasingly concerned for security, the AI based solutions significantly enhanced the threat detection, access control, as well as the cybersecurity protocol. Facial recognition technology and biometric scanning systems use AI data to make port security better in preventing unauthorized access and to detect security threats in real time (Othman et al., 2022). This system is also based on AI, and, hence, it can detect the instance of an anomalous network activity or a cyberattack on the port infrastructure. With the rising digitalization involved in port operations, there is a need for strong AI driven threat detection mechanisms that can protect sensitive data and key systems against cyber threats (Yau et al., 2020). Sustainable port operations are supported by AI in terms of improved energy efficiency, emissions control as well as waste management. AI driven air and water quality, noise pollution and carbon emission tracking are done in real time at smart ports (Behdani, 2023). AI based energy management systems utilize renewable energies like solar and wind power for

optimizing the use of the consumed power integrated into port operations. Energy distribution in these systems is adjusted dynamically, dependent upon demand fluctuations, which help to reduce the overall carbon footprint in them (Rodrigo González, et al., 2020). In addition, AI enables the optimized vessel speed management and, thus, fuel consumption and cutting of the greenhouse gas emissions. To eco-friendly navigation planning for incoming and outgoing vehicles (Min, 2022), AI performs the weather condition analysis, tide level, and availability of the berth.

2.2.2. Case Studies of AI Implementation in Smart Ports

Several AI driven solutions have been adopted in so many leading ports across the world to improve operational efficiency and sustainability.

- The Port of Rotterdam, Netherlands, deploys AI enabled predictive analytics to optimize the vessel traffic, lessen the congestion by improving the supply chain coordination (Heilig et al., 2017).
- Port of Singapore: AI driven automated cranes and AGVs have raised consumers handling efficiency of containers by reducing turnaround time and labour cost (Cunha et al., 2023).
- AI based real time emissions tracking in Port of Los Angeles, USA: The system helps in enforcing environmental regulations by ensuring to comply with air quality standards (Sankla & Muangpan, 2022).

2.2.3. Challenges and Future Prospects

However, the smart ports AI offers plenty of advantages that have to be overcome with challenges. The main obstacle, however, is a very high initial investment to deploy the AI infrastructure. However, a majority of the ports, especially the smaller and developing ports face financial constraints towards AI-based automation (Rodrigo González et al., 2020). There is another challenge related to data integration and interoperability of the data. Because port ecosystems are complicated with multiple stakeholders such as shipping lines, logistics providers, and regulatory bodies, sharing data in a smooth manner amongst the various platforms is a complex process as well along with having a set of standardized protocols (Behdani, 2023).

Undoubtedly, cybersecurity remains a big challenge because while ports are relying more on AI powered digital systems, cyber threats are rising. Advanced AI based security frameworks need to be implemented to protect sensitive operational data and avoid any disruption to the critical port function (Yau, Potpiroglou, Kotsampasi, Zekios, & Tsourdos, 2020). Turning to the future, the integration of AI and smart ports with 5G networks will introduce this technology further for building smart ports and will facilitate faster data transmission and will promote real-time analytics. In addition, there will be improvements in autonomous ship navigation and at AI based supply chain optimization that will boost the efficiency of ports and global trade competitiveness (Min., 2022).

Smart ports are being revolutionized by AI, through better operational efficiency, logistics are being optimized, security is being improved and sustainability is being promoted. Machine learning, predictive analytics, and automation implementation makes ports cheaper, the cargo flow to flow smoothly, and an environment to be compliable to. But for full power of AI enabled smart port ecosystems, to take off, integration challenges, cybersecurity risks and investment barriers must be overcome. In the oncoming evolution of the international maritime logistics, AI will be an important enabler of digital transformation in and toward competitiveness and sustainability of the modern port operations.

2.3. 5G and Smart Ports

5G technology is bringing on the revolution of changes for the ports operations and logistics to make them more efficient, secure and sustainable within the maritime sector. With ports evolving into smarter ports, they need reliable, high bandwidth, and low latency connectivity to integrate autonomous systems, real time data analytics, and cloud based services. This is exactly what 5G technology based networks can provide by creating a technological backbone for seamless data communication for large volume of data between various port activity and optimize for automation, safety and environmental performance (Agarwala & Guduru, 2021).

The use of 5G technology is revolutionizing smart ports as the high speed of wireless connectivity and real-time communication between ships, smart infrastructure, port authorities and logistics operators make them. However, traditional communication systems like 4G LTE and Wi-Fi networks tend to be challenged by the vastly intricate

and heavy data content of modern port operations. 5G with its increased bandwidth, ultra low latency, and massive device connectivity provides the ports with an efficient mechanism for managing automated cargo handling, predictive maintenance and environmental monitoring and security surveillance (Liao et al., 2023).

One of the advantages of 5G is that it makes large scale IoT implementation (IoT deployment) in smart ports possible. It includes the sensor based tracking systems, the smart grids and the automated guided vehicles (AGV) that improve the operational efficiency as well as reducing human intervention in high risk environments whereas 5G networks empower access to real time analytics to better port decisions and resource allocation (Behdani, 2023).

2.3.1. 5G-Enabled Applications in Smart Port Operations

Autonomous cranes, vehicles, and robotic systems at port terminals demand an uninterrupted network infrastructure for their operation, and 5G technology generates remote cargo handling operations enabling operators to control loading and unloading processes from a centralized control room. 5G's low latency capabilities serve to reduce accidents, operation delays, and labour costs (D'Amico et al., 2021). Furthermore, 5G opens up the possibility of remote piloting of tugboats and other port vessels for the real time control of ships in congestion port areas. The improvement of navigation safety, decrease the probability of a collision, and help to streamline traffic in port logics (Agarwala & Guduru, 2021).

5G powered predictive maintenance systems are used to monitor crane, conveyor belts, fuel storage tanks and other critical infrastructure in smart ports. By using real time sensor data and AI powered predictive models, one can predict equipment failures and perform corrective maintenance before it is possible to perform cost constraint repairs (Ben Farah et al., 2020). Additionally, real-time tracking of asset using 5G connected sensors provides real time of inventory whilst minimising misplacement and allowing for fuller use of port assets. Smart maintenance solutions increase the lifespan of assets, improves security and reduces operational downtime (Liao et al. 2023).

Remember that smart ports are increasingly relying on digital platforms. As 5G is used more, both in providing networked options as well as just being connected to other networks in a broader context, network security is improved through enhanced encryption and real time threat detection technologies to protect against cyber attacks

and data breach security and unauthorized access. The 5G networks have been integrated with AI powered security frameworks that help identify and prevent cyber threats within real time, and therefore, safe the sensitive port infrastructure and logistics operations (Ben Farah et al., 2020). 5G also enables secure, device to device authentication of IoT devices in port environments which mitigates vulnerabilities of unauthorized data interception and network breaches as effectuated numbers of IoT devices in port continue to proliferate. Also, blockchain based security solutions can be linked through 5G technology to make the records of transactions in supply chain management open and unbreakable (Agarwala, Guduru, 2021).

5G enables ports to bring real time analytics platforms to life which process massive amount of data from the sensors, cameras and tracking systems. Thus, port authorities can optimize the flow of cargo, improve vessel scheduling and generally improve logistics efficiency. Furthermore, digital twin enabled by 5G empowers port managers to understand and simulate port operations through the real time virtual replicas to enable enhanced decision making, optimization and detection of inefficiencies. This data driven approach alters the risk assessment, planning operation, and overall performance outcome (D'Amico et al., 2021).

With the move toward smart ports, reducing environmental impact through such sustainable practices also becomes an important part of smart port functioning, and 5G is also playing a key role in this regard by enabling real time environmental monitoring. Air and water quality sensors kept note of pollution level, greenhouse gas emission and noise pollution and did it continuously via IoT supported sensors to ensure compliance with regulations. 5G enabled smart energy grid further boost energy efficiency in integrating renewable energy sources, minimizing power utility, and low carbon footprint. Behdani (2023) supports global sustainability initiatives through these innovations, which help to sustain the eco friendly port operations.

2.3.3. Case Studies of 5G Implementation in Smart Ports

Autonomous cranes, vehicles, and robotic systems at port terminals demand an uninterrupted network infrastructure for their operation, and 5G technology generates remote cargo handling operations enabling operators to control loading and unloading processes from a centralized control room. 5G's low latency capabilities serve to reduce accidents, operation delays, and labour costs (D'Amico et al., 2021). Furthermore, 5G

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2.3.4. Challenges and Future Prospects

Remember that smart ports are increasingly relying on digital platforms. As 5G is used more, both in providing networked options as well as just being connected to other networks in a broader context, network security is improved through enhanced encryption and real time threat detection technologies to protect against cyber attacks and data breach security and unauthorized access. The 5G networks have been integrated with AI powered security frameworks that help identify and prevent cyber threats within real time, and therefore, safe the sensitive port infrastructure and logistics operations (Ben Farah et al., 2020). 5G also enables secure, device to device authentication of IoT devices in port environments which mitigates vulnerabilities of unauthorized data interception and network breaches as effectuated numbers of IoT devices in port continue to proliferate. Also, blockchain based security solutions can be linked through 5G technology to make the records of transactions in supply chain management open and unbreakable (Agarwala, Guduru, 2021).

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data driven approach that contributes to improve risk assessment, operational planning, and overall performance (D'Amico et al., 2021).

With the move toward smart ports, reducing environmental impact through such sustainable practices also becomes an important part of smart port functioning, and 5G is also playing a key role in this regard by enabling real time environmental monitoring. Air and water quality sensors connected to IoT monitoring the pollution levels, greenhouse gas emissions levels, noise levels which are continuously tracked to comply with environmental regulations, 5G powered smart energy grids further incorporate energy efficiency by integrating renewable energy sources, minimizing power consumption and cutting down carbon footprints. Behdani (2023) supports global sustainability initiatives through these innovations, which help to sustain the eco friendly port operations..

2.4. Blockchain and Smart Ports

Implementation of blockchain technology in smart ports is a key development in maritime logistics which leads to increased security, transparency and efficiency in the whole operations of smart ports. Being part of the global trade system that takes many stakeholders, the blockchain is an immutable and decentralized ledger system which helps to streamline data sharing, document verification and supply chain operations. Blockchain technology helps to cut down the bureaucratic inefficiencies, avoid fraud and improve tracking of cargo, allowing for real time, tamper proof transactions, helping the entire ecosystem of the port to be more interconnected and automated (Tsiulin et al., 2020).

Current port operations are paper heavy based on paper documentation and centralized data are managed which causes delays, vulnerabilities in terms of security and inefficiencies. Because blockchain made information adoption by port authority, shipping companies, customs agencies, and logistics providers possible in a decentralised and secure manner. By this data is not kept in silos but automatically updated and verified in real time without the need for third party intermediaries (Weernink et al. 2017).

It supports smart contracts, which is one of the key advantages of integration of blockchain in smart ports — smart contracts allow performing automatised of financial transactions, customs declarations, etc. and their performance occurs under

predefined conditions. Automation lowers manual errors, processing times and administrative expenses, hence bettering operational practicability in world-wide logistic stations (Alahmadi et al., 2022).

2.4.1. Blockchain-Based Applications in Port Management

With blockchain technology we are able to revamp the management of documents in port logistics through creation of tamper proof digital records. Typically, traditional port operations include many stakeholders that need access to shipping records, customs declarations and cargo information. Paper based systems, however, tend to be prone to frauds, loss and delays which tend to cause more costs and inefficiencies. Blockchain allows such digitalized records to be made immutable and traceable, such that all supply chain's participants have access to a single source of truth. Transactions or updates of documents are securely recorded on the blockchain, each of which can be securely used by authorized parties via real time visibility. It greatly lowers the possibility of fraudulent activities and arbitrary changing, making the port's logistics significantly more trustworthy (Tsiulin et al., 2020).

Smart contracts are one of the foremost transformative features of blockchain in smart ports. They are self executing agreements which will execute based on predefined conditions and ensure contract obligations are discharged automatically. An example is where after a cargo shipment has arrived at a port and meets all required customs clearance requirements, a smart contract is able to immediately authorize the release of the cargo without going through any sort of manual verification or intermediaries. In trade finance sphere, letters of credit, payment settlements and insurance claims are processed instantly through this automation: this is particularly valuable. Smart Contracts aids in lowering operational cost of global trade by cutting through bureaucratic dint and increasing speed and efficiency of global trade, making trust between trading partners better (Weernink et. al, 2017).

Real time tracking is one of the best things that blockchain brings to the table, specifically when it comes to cargo shipments. You can now track the movement of containers, storage conditions and delivery timelines real time. Ports can then be able to monitor cargo status at every node in the supply chain by integrating Internet of Things (IoT) with blockchain based ledgers. For example, pharmaceuticals and perishable goods are temperature sensitive and must have strict environmental controls

for example. Real time temperature monitoring can be ensured along with the compliance with regulatory requirements, with the help of Blockchain. Temperature, humidity and other deviation conditions in the handling can be recorded on the blockchain to serve as evidence for insurance claims or disputing (Alahmadi et al., 2022). Moreover, the blockchain minimizes the risks of cargo theft and counterfeiting because it allows only authorized entities to obtain certain parcels. However, this enhanced security framework is utilized to prevent unauthorized tampering and for logistics providers to be able to check the goods authenticity prior to transporting them (Kapkaeva et al., 2021).

Manual verification processes and separating communication among various regulatory bodies usually lead to delays in the port operations because of the customs procedures. Customs clearance can be greatly streamlined through the automation of the trade document validation through secure blockchain shared ledgers. The clearance process can be accelerated and the amount of port congestion decreased by the fact that regulatory authorities are able to instantly verify the cargo details, tax payments and the records of compliance. As a consequence, ships' and cargo turnaround times accelerate and port efficiency is enhanced, as well as demurrage and detention charges reduced (Cunha et al., 2023).

Blockchain's decentralized nature improves cybersecurity in smart ports because it alleviates the risk of a centralized data breach and cyber attack. In traditional port management systems, the sensitive trade data is stored in centralized servers and thus, susceptible to hacking, tampering or unauthorized access. As narrow, cryptographically secure, and stored across multiple nodes, each blockchain transaction is sure, in terms of data integrity and resilience to cyber threats. In addition, permissioned blockchain networks restrict access to only authorised stakeholders, and therefore unauthorized modifications are not permitted and data breaches do not occur (Kapkaeva et al., 2021).

2.4.2. Challenges and Future Prospects

Although smart ports have many advantages, widespread blockchain adoption in smart ports suffers from several problems: high cost of implementation, lack of regulatory certainty, and compatibility problems. Most of such ports are running on legacy platforms and will have to undergo a technological overhaul to operate a blockchain based framework. Moreover, it is also necessary to have global standardization in

ensuring that the blockchain integration becomes seamless in different ports and regulatory bodies. A dispersed, human maintained finance based on a ledger protocol cannot hope to gain widespread adoptions due to the lack of universal protocols that remain compatible with each other. Moreover, there are data privacy, scalability and governance models that need to be attended to for the industry at large to adopt blockchain (Weernink et al., 2017). Based on this, it is safe to say that blockchain technology will play a central role in shaping the smart port ecosystems and this is especially true as more ports continue to invest in digital transformation. Combination of the blockchain technology with AI, IoT, and 5G technologies will create a completely new round of automation, predictive analytics and real time decision-making improving efficiency and security of global maritime trade (Tsiulin et al., 2020).

The smart ports are being transformed using the blockchain technology to increase the transparency and operational efficiency and to secure it. Blockchain makes use of secure document management, automated customs clearance and tracking of real time cargo and execution of smart contracts that minimize the age old inefficiencies and builds trust between the supply chain stakeholders.

However, challenges associated with the adoption cost, regulatory compliance, and integration of the system are expected to hinder the use of blockchain in the smart ports. Accordingly, blockchain will be at the core of transforming the port business, and it will continue to be so as ports modernize and adopt digital transformation strategies.

3. Methodology

The research method used in this study was labeled PRISMA Analysis (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). Lastly, the PRISMA framework was selected because it presents a structured and rigorous approach to approach to systematically identify, screen and select studies according to predefined inclusion and exclusion criteria. This methodology is highly accepted in systematic literature reviews because this methodology ensures the traceability and reproducibility. As maritime research on smart ports and the digital maritime logistics became more complex and voluminous, PRISMA stood as a structured method for eliminating bias through research filtering. Through this study, empirical studies that discuss about the integration of 5G, AI, IoT and Blockchain technologies for smart port are systematically analyzed such that such studies are included only if they are high quality, peer reviewed and methodologically sound empirical studies.

Three of the well established academic databases were employed for the literature search, these databases include Google Scholar, Scopus and CORE. The reason why I choose these database is mainly because I know that they all have wide coverage of scientific literature, which include journal articles, conference proceeding, and technical reports for subjects like engineering, computer science, and maritime logistics. Particularly helpful was the use of Google Scholar in retrieving a rather wide range of research articles, much wider than would have been possible by searching the commercial databases. In turn, Scopus, which is well known for its comprehensiveness in covering peer reviewed literature avoided inclusion of low impact publications. But according to CORE, the leading aggregator of open access research, the recent transformation of the digital port chimes in with recent developments in the sector.

3.1. Keywords

Specific keywords and Boolean operators were used in trying to refine the search process in order to identify relevant studies. The search process was primarily based on the use of the keywords Smart Ports, Digital Ports, Automated Ports, Port Logistics, Maritime Digitalization and Port 4.0. To keep track of the broad scope of technological innovations in port operations, keywords were chosen. Moreover, technology specific keywords like Artificial Intelligence (AI) in Seaports, Internet of Things (IoT) in Port Operations, Blockchain in Maritime Logistics, and 5G for Smart Airport Connectivity

were incorporated to expand the scope of keywords and include last year's technology which may not apply in many other years but can be found useful in few others. These terms made sure that the search returned only studies that were specifically about incorporating emerging technologies into the overall port infrastructure.

However, to obtain more accurate and useful search results, Boolean search strategies were used. The application of these strategies permitted to combine multiple search terms, so that selected studies included both general smart port concepts and specific technological implementations. Below are Boolean search queries that were used.

- ("Smart Ports" OR "Digital Ports" OR "Automated Ports") AND ("AI" OR "Artificial Intelligence" OR "Machine Learning"). These terms were used in combination to find studies on the application of AI driven automation in predictive analytics, autonomous operations, and in port logistics.
- ("5G" OR "IoT" OR "Blockchain") AND ("Maritime Logistics" OR "Seaport Management"). This query has concentrated on the research work that this thesis explores in terms of integration of 5G, IoT, and Blockchain in modern port infrastructures, including real time data analytics, automation of cargo handling, and digital transactions.
- ("Port Digitalization" OR "Maritime Industry 4.0") AND ("Case Study" OR "Experimental Study" OR "Simulation"). This query was intended to exclude certain studies that reported technological deployment in ports without empirical studies but concentrating on studies that include implemented projects, pilot studies, and performance evaluations.

3.2. Inclusion and Exclusion Criteria

Studies for this research were selected in a structured and rigorous fashion to make sure that only relevant, high quality and sound methodologically studies were included in the PRISMA. Clear inclusion and exclusion criteria were first established in order to filter out irrelevant or low quality studies and second to narrow down to papers that are target to answer the question; what are roles of 5G, AI, IoT, and Blockchain in developing smart port? To achieve the above mentioned, the criteria of relevance, methodological rigor, and real world applicability were set to choose studies that will further the understanding of digitalization of port operations, in terms of actionable insights.

In order to guarantee that the studies include modern technological advancements in port logistics, there were inclusion criteria. Because the movement of digitalization, automation, and connectivity in the maritime industries is rapidly increasing, research that predates 2015 has been excluded so as to concentrate on studies which correspond to current smart port frameworks. Moreover, only studies included which are related to practical applications at operational ports, rather than theoretical speculation, their feasibility is therefore of practical relevance. This research was aimed at prioritizing research on the efficiency improvement, security enhancement, cost reduction and sustainability measures with the use of digital technologies, since these areas are in line with the main goals of smart port transformation.

However, the exclusion criteria deliberately filtered out certain studies that did not considerably provide to the research objectives. Excluded were arguments based on literature reviews, scoping reviews and theoretical discussions, unless they put forward a structured conceptual model with practical implications. Moreover, we removed research solely conducted by general logistics or supply chain management without specific 'port operation' connection. It was done to make sure that the results were appropriate for maritime logistics and port automation only. Also excluded were studies that did not include to supply empirical data, detailed methodology or peer reviewed credibility.

The study applies these criteria to make sure that the PRISMA analysis is robust methodologically, transparent, and reproducible. The last set of chosen studies give an evidence based view of the integration of emerging technologies to modern port environments.

Inclusion Criteria

The following conditions were required for a study to be included in the PRISMA analysis:

- Timeframe Criterion
 - Studies published after 2015 to ensure relevance to modern smart port technologies and recent digitalization efforts.
- Technological Focus

- Research explicitly addressing 5G, IoT, AI, or Blockchain in the context of:
 - Smart port development
 - Digital logistics
 - Automation in port operations
- Geographical Coverage
 - Studies had to focus on real-world applications in operational ports, ensuring that findings were:
 - Applicable across diverse maritime environments
 - Relevant to both large and medium-sized ports
- Research Methodology
 - Only empirical studies were included, specifically:
 - Case studies, pilot projects, experimental research, or field implementations
 - Conceptual models were also considered if they provided a structured framework for digital transformation in port logistics.
- Impact-Oriented Studies
 - Research had to highlight tangible benefits of technology integration in ports, such as:
 - Efficiency improvements
 - Sustainability measures
 - Security enhancements
 - Cost reduction strategies

Exclusion Criteria

The following conditions led to the exclusion of a study from the PRISMA analysis:

- Literature Reviews & Theoretical Papers

- Studies classified as:
 - Systematic reviews, scoping reviews, or purely theoretical discussions
- Exception: Theoretical research was considered only if it introduced an innovative conceptual model with practical applications.
- Non-Port-Specific Studies
 - Research focused on general logistics or supply chain applications that:
 - Did not explicitly address port infrastructure, maritime logistics, or port operations
 - Lacked a direct link to smart port digitalization
- Outdated or Redundant Studies
 - Studies published before 2015 were excluded to:
 - Ensure alignment with Industry 4.0 advancements
 - Avoid outdated technological perspectives
 - Research that duplicated findings from more recent studies without new empirical contributions was also removed.
- Non-Empirical or Editorial Content
 - The following types of publications were excluded:
 - Opinion pieces, editorials, and non-scientific reports
 - Conference abstracts without detailed methodology or results
 - Studies had to provide detailed data collection, methodology, and findings to be considered.
- Unverifiable or Non-Peer-Reviewed Sources
 - Research from non-peer-reviewed sources, including:
 - White papers, industry reports, and non-academic blogs
 - Research not published in credible academic databases

- This ensured that all included studies had undergone rigorous peer review processes.

3.3. Selection Process

The methodology employed during the selection of the studies that are included in this analysis was structured and systematic, in order to ensure that the studies are relevant, methodologically sound and empirically well founded. Firstly, a total search was conducted in three academic databases; Google Scholar, Scopus, and CORE using the pre-defined keywords and Boolean search strategies. In order to refine the search results and focus on recent advancements on smart port technologies, a chronological filter was applied such that the search returns only studies published after 2015. This ensured that only research based on modern digitalization trends, as well as developments taking place in the context of Industry 4.0 in port operations and related activities, was included.

After obtaining studies from several databases, the deduplication step was conducted to remove any duplicate studies that were present among two or more database entries. Because many high impact studies are indexed in more than one source, the step was necessary to prevent duplicate studies from being reviewed. The second stage was a title-based screening wherein the studies were evaluated according to their titles to see their relevance to the research focus after eliminating the duplicate ones. This stage involved excluding studies which clearly did not relate to the study of 5G, AI, IoT, or Blockchain in port operations.

After the title based filtering was finished the rest of the studies were further screened at the level of the abstract. The abstracts of each study were reviewed to see if the research was empirical findings, case studies, experimental analysis, or conceptual frameworks of smart port technologies. From there, studies on broader supply chain logistics that did not have a direct connection to port digitalization as well as studies that showed methodological clarity were removed from further consideration.

Then, the full-text review was performed on the remaining studies according to the abstract screening. This segment entailed an elaborate assessment of the content to determine if the research abided by the designed inclusion and exclusion criteria. Based on the analytical framework developed, it selectively queried some studies that were lacking empirical data, based only on theoretical discussion and have no practical

applications, and also did not contribute to knowledge of smart port digitalization. Also removed were studies that did not follow core objective of analysis, i.e. studies that dealt with various sectors different from core, or were generic discussions on digital transformation.

Final selection of studies was done after completion of the whole filtering process based on the aforementioned inclusion and exclusion criteria. The studies included in this research are those that provided empirical insights, case studies, experimental research, as well as those that developed structured conceptual models that have applied emerging technologies on port logistics and digitalization. To achieve this, a multi-step selection process was conducted so that the PRISMA analysis was done with methodological precision, transparency, and rigor, which in turn resulted in a comprehensive dataset of high quality research on smart port transformations.

Using the systematic selection process described above, 958 studies were initially retrieved from the three selected databases namely, Google Scholar, Scopus, and CORE. To satisfy the scope of smart port digitalization and the integration of 5G, AI, IoT, and Blockchain in maritime logistics, and using the structured keyword search strategy with Boolean search operations, these studies were finally identified.

After the deduplication process was performed, 113 duplicate studies indexed in more than one database were identified and removed. This step was done to ensure that each study is counted only once by avoiding any bias related to double counting the same study. Subsequently, a heavy filtering process was applied based on the pre-defined exclusion criteria, which led to the removal of 824 studies. The main problems observed in these exclusions were the irrelevance to smart port operations, too theoretical and not empirically proved (except maybe for the theoretical ones without a peer review), focus only on general supply chain management approach rather than a port specific logistic etc.

This was a systematic multi-stage selection process, meaning that at the end of it only 18 studies fulfilled the above inclusion criteria and could be included in this systematic review. The selected studies supplied high quality empirical insights, case study tests, experiments, and framed conceptual frameworks that contributed to a better understanding of how emerging digital technologies are impacting the port modernization process. Figure 1 shows the new visual representation of the selection

and screening process (the systematic filtering stages as well as the final selection studies which are included in this PRISMA analysis).

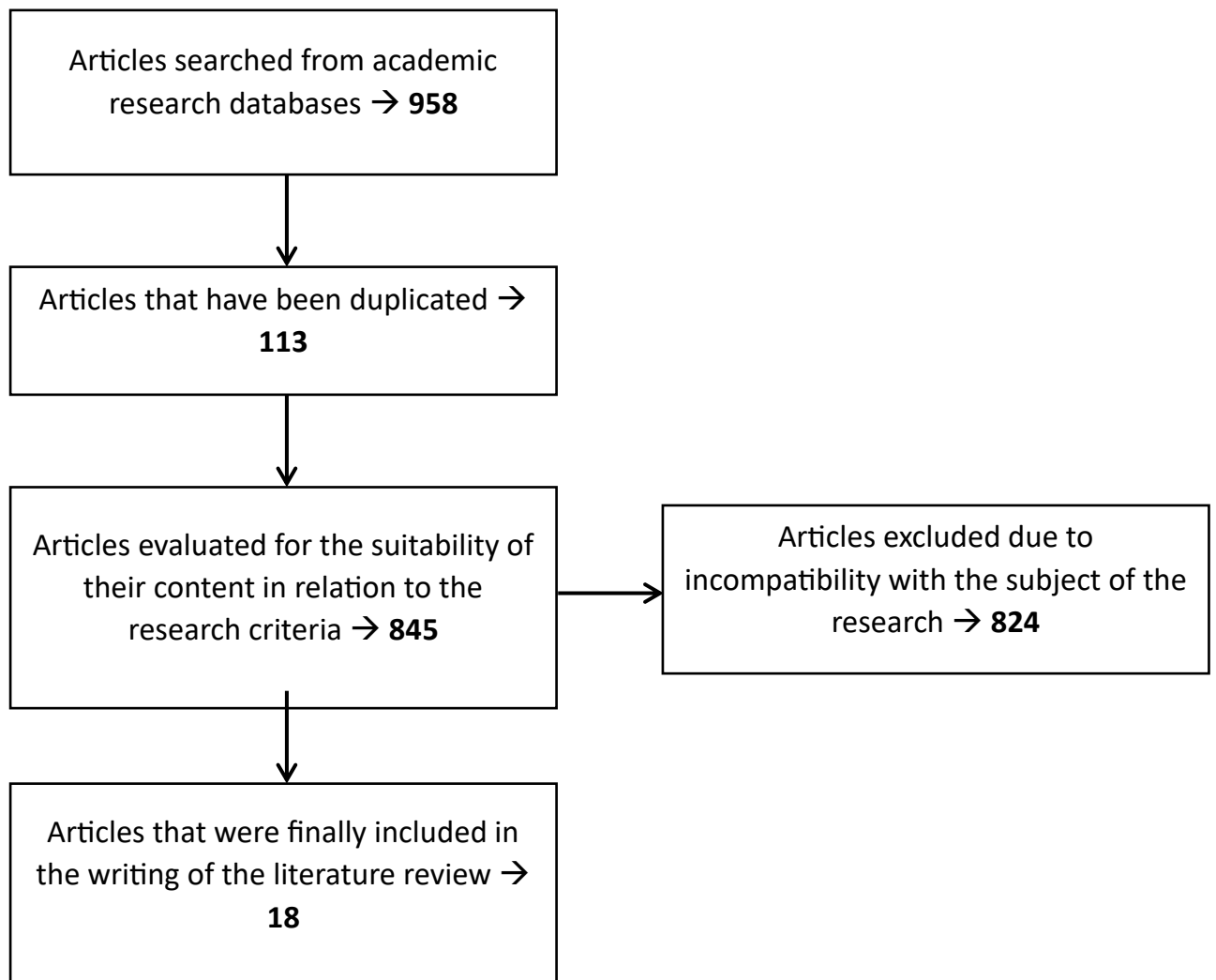


Figure 1. PRISMA Review article flow chart.

4. Results

The 18 studies that were selected following the PRISMA Analysis process are presented below. Table 1 presents a brief description of each study, followed by a detailed description of each study.

Table 1. Summary table of the 18 studies included in the PRISMA Analysis.

Authors & Date	Country	Study Purpose	Category (5G, IoT, Blockchain, AI)	Methodology	Key Findings
Yigit et al., (2023)	Turkey, Vietnam, UK	Development of a 5G drone-assisted data collection system using Digital Twin technology for smart seaports to improve ship maneuvering	5G, AI, IoT	Experimental study: Developed and tested the TwinPort system combining 5G, IoT, and drones for real-time navigation support in congested seaports	The system improved ship trajectory precision, reducing fuel consumption and environmental impact. Demonstrated cost savings and increased port efficiency
Barasti et al., (2021)	Italy (Livorno)	Development of an ICT framework integrating 5G, Blockchain, and IoT to optimize port logistics and security	5G, IoT, Blockchain	Case study: Implemented an ICT framework at the Port of Livorno, analyzing three industrial applications (Navigation Safety, e-Freight, Logistics)	The integration of 5G, IoT, and Blockchain enhanced efficiency and security, improved data sharing, and automated decision-making
Cavalli et al., (2021)	Italy (Livorno)	Evaluating the impact of 5G technology on port operations in terms of sustainability and efficiency	5G	Pilot project: Implemented a 5G-based model at the Port of Livorno and assessed economic, social, and environmental impacts	5G improved operational efficiency, reduced energy consumption, and supported real-time logistics and sustainability goals
Tsolakis et al., (2022)	Greece (Piraeus Port)	Examines AI-driven automation in container port logistics, focusing on Automated Guided Vehicles (AGVs) for	AI, IoT	Simulation study using real-world container terminal data to quantify environmental benefits of AGVs.	AI-powered AGVs can optimize logistics, reducing emissions and improving operational efficiency.

		environmental sustainability.			
Durán et al., (2019)	Chile (Medium-sized ports)	Develops a conceptual model for smart medium-sized ports using cyber-social-technological-cognitive (CSTC) domains to enhance decision-making and logistics.	IoT	Conceptual model development based on expert analysis of Chilean medium ports' digitalization gaps.	Identified technological gaps preventing Chilean ports from reaching Industry 4.0, proposing improvements.
Philipp et al., (2021)	Germany (Wismar Seaport)	Explores renewable energy and automation technologies for bulk cargo loading operations in ports, aligning smart and green port concepts.	5G, IoT	Case study approach analyzing digital and green technology integration at Wismar Seaport, including 5G campus networks.	5G networks and automation improve energy efficiency in bulk cargo operations, reducing carbon footprint.
Durán et al., (2021)	Chile	Examines the application of Blockchain and Crowdsourcing to enhance decision-making in smart ports and reduce governance gaps.	Blockchain	Conceptual framework development for Blockchain-based Crowdsourcing (CrowdBC) applied to port governance and logistics.	Blockchain combined with Crowdsourcing enhances participatory governance in ports, reducing decision-making inefficiencies.
Ahmad et al., (2021)	United Arab Emirates	Explores Blockchain's role in automating port logistics and supply chain operations, improving transparency, traceability, and security.	Blockchain, IoT	Design of Blockchain architectures (Hyperledger Fabric, Besu) for port operations and logistics, including use-case analysis.	Blockchain improves logistics automation, enhances security, and minimizes documentation errors in maritime transport.
Boison & Antwi-Boampong, (2019)	Ghana & Denmark	Proposes a Blockchain-ready port supply chain for the West African maritime industry, focusing on transparency, efficiency, and fraud reduction.	Blockchain	Case study on the adoption of Blockchain for port operations in West Africa, identifying challenges and technological gaps.	Blockchain adoption in ports can significantly enhance transparency, reduce delays, and prevent fraud in supply chain operations.

Sangeerth & Lakshmy, (2021)	India	Explores the role of Blockchain-based smart contracts in automating port shipping documentation and reducing inefficiencies.	Blockchain	Development and deployment of smart contracts using the Ethereum blockchain for automation in port logistics.	Smart contracts reduce paperwork manipulation, enhance trust, and improve efficiency in port operations.
Liu et al., (2022)	China & Singapore	Verifies smart contracts in port supply chains using probabilistic model checking to improve reliability and security.	Blockchain	Probabilistic model checking of Blockchain-based smart contracts using Discrete-Time Markov Chains (DTMC) and BPMN modeling.	Blockchain verification improves contract security, reduces transaction risks, and enhances transparency in port supply chains.
Philipp et al., (2019)	Estonia & Germany	Examines how Blockchain and smart contracts facilitate collaboration among SMEs in maritime supply chains.	Blockchain	Case study approach using expert interviews and analysis of small and medium-sized port collaborations in the EU.	Smart contracts lower entry barriers for SMEs, increase efficiency, and reduce reliance on intermediaries in maritime logistics.
Yoon et al., (2020)	South Korea	Examines the priorities and factors influencing blockchain adoption in Korean maritime logistics, focusing on Busan and Incheon ports.	Blockchain	Analytic Hierarchy Process (AHP) analysis based on surveys and expert interviews from the Korean maritime logistics industry.	Blockchain adoption in ports is hindered by a lack of understanding among logisticians and concerns about technological maturity among consultants. Economic factors heavily influence adoption.
Cil et al., (2022)	Turkey	Develops an IoT-enabled system for real-time cold chain monitoring in container ports, ensuring temperature-sensitive goods are properly stored and transported.	IoT	Development of an IoT system with sensors (RFID, IEEE 802.15.4), real-time monitoring software, and performance evaluation using the OPNET simulator.	IoT-enabled cold chain logistics improve real-time monitoring, reduce spoilage risks, and enhance operational efficiency in container ports.
Bracke et al., (2021)	Belgium	Designs and evaluates a	IoT	Development of a multi-tenant	A reactive micro-services-

		scalable IoT backend for smart ports, integrating logistics optimization and environmental monitoring.		cloud-based IoT platform (Obelisk), evaluated using an air quality monitoring use case in Antwerp.	based IoT platform ensures scalability, security, and interoperability for smart port applications, facilitating logistics optimization and environmental data processing.
Zhao et al., (2020)	China	Examining sustainable and smart development strategies for coal ports with IoT integration.	IoT	Case study of Huanghua Port with performance evaluation on sustainability measures.	IoT-driven smart port technologies improve economic, environmental, and social sustainability through intelligent control and automation.
Muñuzuri et al., (2020)	Spain	Investigating IoT applications to optimize intermodal port logistics and supply chains.	IoT	Development and implementation of an IoT-based intermodal transport system at the Port of Seville.	Real-time tracking, data-sharing, and IoT-driven optimization enhance logistics efficiency and decision-making in intermodal transport.
Ozturk et al., (2018)	UK	Developing an energy-efficient smart connectivity framework for IoT networks in smart ports.	IoT, AI	Reinforcement learning optimization for IoT energy efficiency in port environments.	Smart IoT connectivity frameworks significantly reduce energy consumption while meeting operational efficiency and security requirements.

The study by Yigit et al. (2023) develops a 5G drone assisted data collection system for improving smart seaport navigation. It used Turkey, Vietnam, and the UK as the benchmark for 5G network and Digital Twin technologies applied in the modification of the ship maneuvering phase within ports. To begin with, TwinPort system has been introduced as an automated port management system including 5G, IoT and drone assisted data collection to present accurate real time ship positioning. For the research, drones were designed with the capacity to collect real time navigational data to assist

ships in better docking. Whereas, the state of the art communication system over 5G powered system ensures low data latency data transfer between ships and the control centre for very less navigation errors and also minimises congestion. Findings of the study showed ship trajectory accuracy improved by a large margin and docked ships make unnecessary detours in addition to decreasing travel distance per docking by 500 meter. Due to this, an estimated 3,200 liters per ship per day of fuel was saved resulting in an annual fuel cost saving of \$2.3 million. Also, the system reduced carbon emissions, thus, it contributed to environmental sustainability. In general, this study highlights the importance of 5G, AI, and IoT in automating and enhancing the seaport logistics, resulting in tangible improved efficiency, cost and also environmental impact.

Barasti et al. (2021) designed an ICT framework for transforming existing ports into fully digitalized smart ports in their study. The research was carried out at the Port of Livorno, Italy, where methods for multi-layered technological infrastructure were developed to improve the port's operations, security and logistics. Next, the study aimed at integrating 5G with IoT and Blockchain for port management systems, to attain high quality, accurate, timely, and real-time data collection, automation and decision making. The industrial applications of the framework included three industrial applications.

- Navigation Safety – Real-time monitoring of vessel movement.
- IoT enabled eFreight for digitalization of freight logistics.
- Automate port operations to become efficient.

The methodology used in the research was case study to analyzes how the application of this ICT infrastructure affected port efficiency. The findings revealed that automated cargo tracking data collection also automated predictive analytics, improving cargo tracking accuracy and reducing delays, while increasing safety. Also, the use of the blockchain enhanced data security and transparent it, preventing fraud during a cargo deal. It was concluded that the ICT framework has a significant impact on the improvement of efficiency, security, and data sharing capabilities in the smart port. The port uses 5G, IoT, and Blockchain synergistically to make ports more resilient and sustainable.

The work by Cavalli et al. (2021), focused specifically on the effects of 5G technology in the operations of the Port of Livorno, Italy, and in the ports in general. It was carried out with respect to sustainability, efficiency and competitiveness, as well as the United

Nations' Sustainable Development Goals (also known as the SDGs). Thus, the researchers took a pilot project approach to implement a 5G powered port management model that enabled real time tracking of cargo, automated logistics and energy efficient operations. The authors measured the impact of 5G deployment to the port operations in terms of economic, social and environmental benefits. The results showed that 5G technology brought significant reduction in the energy consumption by improving data transmission and the supply chain management. The cargo handling efficiency was also improved by the system resulting into reduction of loading time and unloading time besides decreasing the operational costs. Additionally, the study pointed out that 5G connectivity allows real time decision making that allows ports to respond better to dynamic logistical challenges. The lower carbon emissions and a more sustainable port ecosystem of reduced energy use and improved operational efficiency, both directly contribute to. To sum up, this study emphasizes the significance of 5G as a transformative technology which does not only lead to operational efficiency but also contributes to meeting the sustainability targets, thus making 5G a requisite of the "Port of the Future".

This study, according to Tsolakis et al. (2022), studies how dumpers machines can have an AI powers to improve container port logistics while adopting AGVs in order to enhance environmental sustainability. The research was carried out at the Port of Piraeus in Greece, one of the fastest developing container hubs in Europe. Firstly, the study can be classified under the categories of Artificial Intelligence (AI) and IoT because it involves the integration of decision support systems and optimization models to efficiently manage AGVs in port operations. The methodologies used were simulation based case study for AGVs routing scenarios and the environmental impact of the implementation. According to the findings, AI enabled AGVs can lower emissions and enhance operations by overhauling the movement of the vehicle and dropping dead times. The study shows how incorporating sensor driven robotic operations brings AI to ports through sustainability and helps the intelligent switchover in port logistics processes. The research further gives design principles for the integration of automation into existing non automated port terminals, without compromising operational performance and environmental benefit.

Considering the work realized by Durán et al. (2019), a systemic conceptual model was developed to facilitate the transition of medium-sized Chilean ports to Industry 4.0. The

objectives of the research were to identify the important factors that differentiate between traditional port operations and smart port decision and logistics. The study based on the topic falls in the category of IoT as it focuses at the integration of cyber-social- technological-cognitive (CSTC) domains in port management. Thus, the methodology of research consisted of an analysis carried out by experts on three medium port cases in Chile, diagnosing their digitalization level and identifying the technological gaps. The results demonstrated that Chilean ports do not provide investment in disruptive technologies and advance digital transformation schemes, which create inefficiencies in port operations. Therefore, it suggested that smart port technologies, including automated logistics, digital networking, and process optimization, could be integrated in order to comply with standards in Industry 4.0. In the end, the conducted research has helped to develop the model for strategic planning of digitalization of medium ports, and thus to ensure their viability and competitiveness against the background of increasing digitalization of the maritime industry.

The results of Philipp et al. (2021) show how renewable and automation technologies can be integrated into bulk cargo loading operations in ports. The study was carried out in the Seaport of Wismar, Germany, with aim of synchronizing green port approaches and smart port technologies. This research complies with 5G and IoT categories as it mainly deals with the role that 5G campus networks and digitalization have to play on improving port efficiency. Research was conducted by following case study approach of expert interviews, field research and feasibility study of implementing a self sufficient automated dry bulk cargo plant. It revealed that 5G networks facilitate real-time processing of data and thus help minimize downtime and optimize energy use for handling bulk cargo. Logistics processes were automated and accompanied by renewable energy sources (solar & wind) hence there was a massive reduction in the carbon emissions and operational costs. This research shows how green and digital transformation can be combined to be a success pathway for smart and sustainable port development.

As stated by Durán et al. (2021), this study explores the use of Blockchain technology with Crowdsourcing for enhancing the decision-making in the smart ports. The study is concentrated on the Chilean ports, paying special emphasis on how these technologies can be used to eradicate the governance inefficiencies and fill the space between port authorities, private stakeholders and public. The focus is on how

decentralized ledgers can be used for management of ports governance and logistics; therefore, it is a Blockchain research. CrowdBC is a conceptual framework, used as a methodology, to integrate domains CSTC Cyber-technological, social, and cognitive. They present a model for interconnecting data collection, public participation, and information within secure Blockchain based decision making. Block Chain improves trust becomes more transparent and therefore more efficient in port governance by tracking of cargo and digital contracts in real time. Furthermore, Crowdsourcing facilitates public participation, in a sense that policy developed at the ports is done so in collaboration with the people of the port or the port workers. Also, the study points out that the Chilean ports are behind in adopting Blockchain and the implementation of decentralized decision making models, which undoubtedly enhances the port governance, sustainability and efficiency.

The study done by Ahmad (2021) delves into the combining of Blockchain and IoT technologies to improve automation, security, and traceability during logistics through port operations. Research is conducted on United Arab Emirates (UAE) ports as a location that is highly developed in terms of technology in the maritime logistics and trade facilitation. The study is under the Blockchain and IoT categories as it seeks to identify how Hyperledger Fabric and Hyperledger Besu Blockchain architectures can be applied in port logistics automation. The methodology revolves around Blockchain framework designing and mapping on Blockchain to improve data exchange, ensure better security and decrease logistics ineffectiveness in port operations. By using Blockchain, logistics planning is constrained better, the documentation process is greatly automated and port operation transparency is increased. The study showcases how using smart contracts can eliminate a lot of risk of fraud, errors or inefficiencies in shipping documentation, cargo tracking, and customs clearance through real time data processing. We also discover regulatory hurdles and technological adoption barriers along with challenges such as the need for the global standards for Blockchain enabled maritime logistics.

Boison & Antwi-Boampong (2019) carries out a study on adoption of the Blockchain technology in West African ports concentrating on selected ports in Ghana and Denmark. Based on this, the research endeavors to increase supply chain transparency and drive reduction of fraudulent activities in maritime trade. This study is placed under Blockchain as it introduces a Blockchain ready port supply chain that protects

flexibility, efficiency, and reliability of port logistics. This methodology entails a case study of the West African seaports with technological adoption barriers and solutions when integrating Blockchain. The results indicate that switching to blockchain can cut delays, curb fraud and improve transparency of trade in West African ports. Challenges of the study include bureaucratic inefficiencies, technological gaps and resistance of traditional stakeholders from adoption of distributed ledger technologies (DLT). But Blockchain also points out that Blockchain can establish a safer and more efficient trade ecosystem for the importers, exporters, and the regulatory authorities.

Sangeerth & Lakshmy (2021) state that this study investigates how the Blockchain based smart contracts can automate shipping port documentation and logistics process. It is about ports in India where many traditional paper based processes result in slowdown of operations, increase inefficiencies and are susceptible to manipulation. This work is categorized as Blockchain, where it uses Ethereum based smart contracts instead of manual paperwork to automate, immutable and decentralized the digital contracts. The methodology was the development, deployment and testing of smart contracts on Ganache private blockchain environment. To this end, the authors designed a blockchain model that follows the standard port documentation steps that ensures that data transactions are secure, transparent and efficient. In the end, it was found that Blockchain technology has the ability to reduce the mistakes of humans, improve efficiencies, and remove fraudulent practices in port logistics. Thus, by creating the smart contracts for cargo agreement verification, customs clearance and freight monitoring, the researchers presented how they can transform ports to 100% automated, paperless one. Finally, the study indicates that adoption of Blockchain in Indian ports as a technology has its potential to save costs, enhance security and improve operations. Nonetheless, it should be mentioned that a number of challenges are faced like the demand for regulatory adaptation, initial investment costs, and the hesitation from the traditional stakeholders.

According to Liu et al. (2022), the study focuses on the verification of Blockchain based smart contracts on port supply chains. This research focuses on the operations of the Chinese and Singaporean ports, which are hindered by the absence of trust amongst stakeholders and inefficiency in contract execution. This is part of the Blockchain study on how probabilistic model checking techniques can assist in improving the smart contract reliability and security. A methodology of analyzing probabilistic behavior of

smart contracts related to port operations is developed, which involves Discrete-Time Markov Chains (DTMC) and Business Process Model and Notation (BPMN) to verify the probabilistic operation of smart contracts. An example of using Hyperledger Fabric as a simulated customs clearance process of Shanghai Yangshan Port is specified. The study discovers probabilistic verification improves drastically the security and reliability of the smart contracts, decreasing transaction risks and increasing trust of smart contracts among port stakeholders. To show the effectiveness of automated contract verification, the authors prove that there can exist more efficient and robust to fraud or human errors port supply chains. Challenges such as computational complexity, integration with existing port systems as well as with regulatory compliance are also covered in the study. Even so, it is a convincing argument for using Blockchain securitization smart contracts in global port logistics.

Philipp et al. (2019) analyze the feasibility of using Blockchain and smart contracts to enable collaboration of SMEs (Small and Medium Enterprises) in a maritime supply chain. This research area concentrates where large corporations have dominance in maritime logistics, which makes it difficult for the smaller players to compete – in the ports of Estonia and Germany. This is a study within the Blockchain and smart contracts are investigated as to how they can facilitate reduction of barriers to entry for SMEs and increase operational efficiency in transnational maritime supply chains. The methodology includes field research, interviews of experts, and the analysis of EU funded projects of Connect2SmallPorts and CSHIPP. Two case studies are also included on the study: a scenario for contracting of a charter party, and on port logistics in Wismar, Germany. Blockchain enabled smart contract helps to reduce the dependence on intermediaries, reduces transaction costs and increases the efficiency in the maritime logistics. It is shown in the study that transparent, automated contractual agreements can be opportunity for SMEs to compete more effectively the international shipping markets. But it also indicates hurdles like regulatory uncertainties, lack of digitally opened businesses and their difficulty in complying with digital standards. In general, the study provides a roadmap for utilizing Blockchain technology for fostering fair competition and efficiency in maritime logistics.

This work, as per a study by Yoon et al (2020), focuses on the priorities and factors on which the adoption of blockchain technology will be focused in the maritime logistics sector of South Korea. This study aims at finding out how blockchain can be embedded

into port logistics operations in Busan and Incheon ports in order to improve transparency and efficiency. Accordingly, the study is under the category of Blockchain under the smart ports framework. The researchers explored this using the Analytic Hierarchy Process (AHP), a structured process which ranks items on a list of factors that affect decision making by surveying professionals in maritime logistics. Because of insufficient secondary data, they obtained primary data by means of surveys and interviews with experts. The results show that different stakeholders across the industry perceive how blockchain will be adopted differently. On one hand, logisticians are trying to understand the value of the blockchain, on the other hand, consultants and academics lament on technological immaturity of the system. Economic factors (financial feasibility and time efficiency) showed to be the most influential in petroleum operations blockchain adoption. Although blockchain's potential is there, it has been slowed by general hesitancy of the industry as well as a slow changing regulatory environment. It elaborates on the importance of government and industry partnership to facilitate blockchain at South Korean ports. These insights provide more general insights into the adoption of emerging technologies, such as blockchain, into port logistics taking care of existing hurdles related to the technology.

Cil et al. (2022) carried out research about investigating IoT technologies to monitor the real time cold chain at container ports. Due to the high risks connected with the transportation of perishable products including food, pharmaceutical, and chemical, the study aims at developing an IoT enabled system able to guarantee that these products stay within the required temperature and humidity levels. This study, which is carried out in Turkey, sets out an IoT integrated WSN and RFID based monitoring system to continuously monitor the goods condition in a container ship. In order to remotely monitor, alert for temperature fluctuation, and send automated notification when something goes wrong via email or SMS, the researchers have designed a software and hardware interface. The port logistics environments were modeled in realistic conditions and the performance of the system was evaluated through simulations through OPNET simulator. It is observed that real-time monitoring leads to reduction of spoilage risks resulting in substantial improvement of logistical efficiency and ensuring logistics compliances to transportation regulations. By using automated monitoring solutions, study implies that IoT driven logistics management can help increase the level of transparency, minimize waste and adjust port operations. Our

results show that smart ports can use IoT to ensure the safety of maritime supply chain based on transportation of LNG.

Bracke et al. (2021) develops a scalable IoT backend to improve smart ports efficiency and evaluates it. This research was carried out in Belgium within the scope of the EU H2020 PortForward project aiming to optimize the port logistics by means of digital transformation. The research belongs to IoT category and its goal is to connect the optimization of logistics with environmental monitoring. And hence the researchers designed Obelisk, a cloud based IoT integration platform specifically tailored for multi tenant smart port applications. It also allows access to uniform centralized data, which is an aggregating service for data from heterogeneous devices using different IoT protocols, and is available similarly across all port operations. Another challenge this study attempts to tackle is that of scalability since a large amount of data is generated by sensors, tracking systems, environmental monitoring tools, etc. An air quality monitoring use case at the Port of Antwerp was used to evaluate the platform with regards to large datasets processing efficiency. The findings show that reactive micro-services architecture increases port smartness scalability, improves security and interoperability of the port operations. The system improves decision making in port logistics, it reduces environmental impact by continuous monitoring, and allows for real-time data processing. The research provides evidence that port operations would achieve great efficiencies if they were integrated with IoT technologies and hence will propel the progress toward fully digitized smart ports.

The study presented by Zhao et al. (2020) focuses on sustainable and smart development of coal ports, of which Huanghua Port in China is a case. The smart port technology, based upon IoT, is considered to improve the sustainability in terms of three dimensions, such as economic, environmental, and social. The method is a case study approach that measures the key performance indicators associated with the sustainability measures such as intelligent control systems, pollution management and efficiency of operations. Smart port technologies improve port sustainability by enabling safeguarding of ecosystems and environmental sustainability, optimizing the decision making processes and above all reduce environmental pollutants. It shows how the use of IoT to automate handling operations, environmental protection systems and streamline supply chain integration improves the overall sustainability for coal ports.

The study undertaken by Muñuzuri et al. (2020) aims at using IoT applications to improve the intermodal transport logistics at the port of Seville, Spain. In the study, an IoT based system is introduced that can be employed to effectively manage the port based intermodal supply chains. In particular, the methodology consists of the development and implementation of an IoT system for the real time monitoring and optimization of the container transport in the combined respect of rail scheduling and inland navigation. Real time tracking and sharing of data is seen to yield most improvement of logistics efficiency, transparency as well as decision making processes. It is shown that the adoption of IoT in intermodal transport improves operational efficiency, contributes to capacity reduction and enables supply chain coordination.

An energy efficient smart connectivity framework for IoT networks in smart ports is studied by Ozturk et al. (2018). This work is based on research conducted in the UK using artificial intelligence and IoT based optimization, focusing on optimizing energy consumption, while keeping a secure and responsive IoT connectivity. In doing so, the methodology employs reinforcement learning techniques to dynamically change network connectivity for and computational resources used at ports depending on port operational needs. Results show that smart IoT connectivity frameworks help in reducing the energy consumption by minimizing the energy wastage while maintaining the high levels of the operational efficiency, security, and response time. This study emphasizes that only with the help of AI driven optimization, sustainable and efficient smart port operations can be achieved. The conclusions made through these analysis enables us to carry out insights regarding how IoT and AI driven technologies enable the development of smart port in different regions as it affects on sustainability, logistics efficiency, and energy optimization.

5. Conclusions

Transformation of the traditional port infrastructure into smart ports has become the fundamental shift in the global maritime industry. Internet of Things (IoT), Artificial Intelligence (AI), Blockchain, and 5G connectivity have become percolating concepts enabling port operators integrate it into their port developments and manage efficient operations. In modern maritime logistics, smart ports have been playing an important role in increasing the efficiency of trade flows and supporting the development of the economy. This paper has given an extensive study of the main technologies in smart port technology and its applications, benefits and challenges. The findings are that digitization of port ecosystems, in addition to optimizing logistics and cutting operational costs, adopts a path towards environmental sustainability and towards global resilience of supply chains.

Secondly, this research article contributes a key insight: that IoT becomes a primary vehicle to monitor cargo, equipment, and environmental conditions in the real time, a facet which determines the success and the efficiency of smart ports. Ports can track shipments, detect maintenance need and optimize resources allocation by using sensor network and automated data collection systems. It eliminates a very high amount of downtime, avoids equipment failures, and creates better operational efficiency overall. Furthermore, with IoT working hand in hand with AI analytics, predictive maintenance can be carried out along with real time decision making which diminishes the possibilities of managing the risk caused by unexpected interruptions. But to enable broad deployment of IoT in port environments, there remain big interoperability and cybersecurity risk challenges.

Artificial intelligence has become a game changer on the way toward smart ports in optimal issuing of vessel traffic, cargoes and predictive analytics. With AI powered autonomous vehicles, robotic cranes and machine learning algorithms cooling container cargo is quicker, and much of the congestion and time taken to turn a ship around is bettered. Additionally, AI driven analytics brings more visibility to supply chains not only allowing to proactively mitigate supply chain disruptions but also to optimize logistics in real time. Although these advantages are written with these advantages, a commitment of huge infrastructure and workforce upskilling is needed for the adoption

of AI in port management as well as stringent regulatory structures to minimize the potential ethical problems associated with automation and joblessness.

Using Blockchain technology, transparency and security in port logistics have been transformed tapping the benefits of tamper proof documentation, secure financial transactions using good tech and automation of customs clearance via smart contracts. Nonetheless, on the blockchain, we do not rely as much on the intermediaries which in turn means reduced instances of fraud, data manipulation, and inefficiency in trade documentation. In addition, digital ledger and real time cargo tracking systems also builds up the trust between various supply chain participants and enhances the respective chain's accountability. However, high implementation costs, regulatory uncertainty and the requirement of a common global framework to adopt blockchain create a stumbling block for the adoption.

Smart port automation and real-time data exchange link have made available through 5G connectivity. 5G networks' ultra low latency and high bandwidth power remote controlled operations, autonomous shipping, and high speed communication between port networks. This is especially important for real time monitoring of vessels, environment as well as predicting when the port equipment needs to be maintained. In addition, 5G contributes to the functionality of the IoT devices by facilitating real time data processing and seamless inclusion of the AI fueled analytics. But, in 5G's potential in maritime logistics, one should also take into account the problems with infrastructure costs, cybersecurity vulnerabilities and a global implementation gap.

In addition to technological advancement, smart port is also key to sustainability, and environmental responsibility. As the carbon emission, energy efficiency and eco friendly R&D logistics solutions are highly demanded in the modern era, the maritime industry is under the increasing pressure. The implementation of smart port technologies helps to make cargo handling equipment electric, to use renewable energy, and to track real time emissions. AI driven optimization provides the vessel route optimization and derives from combining the digital twin simulations, IoT enabled monitoring to reduce the fuel consumption that collectively contribute to environmental sustainability. Obtaining green port status is after all only possible through considerable investments in infrastructure and adherence to strict environmental requirements.

However, many challenges persist in the way of the full smart port implementation. Smart ports transition require a lot of financial investment for infrastructure, technology and human capital. The majority of ports are using legacy systems that are not compatible with today's digital solutions, making the system upgrade and system overhaul expensive. More so, the growing dependence on interdependent digital platforms has eliminated the cybersecurity risks and threats in order to secure the sensitive trade data from cyber attacks as well as hacking attempts. Another challenge is the lack of standardization in digital port technologies due to the fact that different ports and regulations have different protocols and hence may lead to inefficiency in the global trade.

In addition, the human factor is an important issue for the smart port transition. Automation for the greater efficiency comes at the cost of automatic displacement of the workforce and hence demands for reskilling the port labor. With this, workers should be trained and proper policies provided that would help adopt the technologies smartly and integrate into the new changing digital work environment. These socio economic challenges necessitate collaborative initiatives among stake holders within the maritime industry; the governments, port authorities and private sector to tackle them while promoting inclusive maritime industry growth.

The future of smart ports is seen as bright if further innovation, policy adaption and global cooperation will continue. As AI and 5G draw more advanced, blockchain continues to improve and creates the perfect scenario for automating, predictive analytics and real time decision making. In addition, quantum computing and edge computing may set the new trend for processing and leveraging the data in maritime logistics. Autonomous ships, drone assisted port surveillance and AI driven supply chain management may likely become a standard to be followed for securing global trade to being the best it can be in terms of efficiency.

In the end, the metamorphosis of the ports into smart ports is an unavoidable and requisite one for maritime logistics. However, as global trade volumes keep on growing, ports must change over into robotized transition strategies for better productivity, maintainability, and resilience. However, smart ports benefits such as promoting economic productivity, providing security of supply chain, and reducing environmental impact outweigh obstacles. To unleash the true potential for smart ports, governments,

industry leaders, and technology developers must work together to develop digital infrastructure, align regulations and be prepared from the cyber security point of view.

The conclusion is that the digitization of ports is not a technological upgrade but tipping points in global trade operations. Owing to its ability to improve efficiency, enhance security, and take care of the environment, the implementation of IoT, AI, Blockchain, and 5G has already been proven. For smart ports, the success depends on moving forward with further investment in, strategic policymaking for, and global cooperation among those elements..

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