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Investigating Study on Future Port Perception

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ABSTRACT

Ports plays a vital role of global economy by transporting 80% of trade and commerce of globe by value pass through them. The economic benefits are often less directly tied to port activities and more linked to the dynamics of the supporting supply chains. This operational support becomes beneficial and effective, playing a crucial role in enhancing national competitiveness. Smart ports are modern and highly facilitated port which uses digital, automated and other smart technologies to enhance efficiency, accountability, sustainability, competitiveness, monitoring, operations, and security. Smart ports frequently utilize digital tools such as sensors, data analytics, augmented reality, big data, digital twins, and automation to improve cargo movement, minimize waste and emissions, and provide superior services to shippers, shipping companies, customs authorities, local communities, and stakeholders. They may also feature renewable energy sources, electric charging stations, onshore power supply, sustainable to climate change, natural calamities, and smart infrastructure for better logistics and optimum transportation. This analytical paper will investigate the future development of port in contrast of history, global demand and advanced technology.

Keyword: Smart port, AI, ML, big data, IoT, 6GP

INTRODUCTION

Port in general or seaport in particular refers to various types of facilities that manage maritime vessels or vessels (Caves, 2004). More than 17,000 ports worldwide are part of larger social, technical, and physical systems that play an essential role in the movement of goods, people, and services and those ports are transported around 70% by volume and 80% by values global trade and commerce around the world and play an important role in international trade, economic growth, and employment generation (UNCTAD, 2021). Nowadays, many ports around the world are equipped with advanced technology and modern facilities. In the past, ports were simply harbors, but today's ports have evolved into vibrant multimodal distribution hubs, seamlessly connecting transportation by sea, river, canal, road, rail, and air routes (OECD 2011). Most successful ports are positioned to maximize access to an active hinterland (Hanson, 2001). Typically, all ports facilitate easy navigation for ships and give shelter from cyclones, tsunamis, and extreme weather. Ports are usually located in estuaries, characterized by shallow waters that require attention regular dredging (Khan, Khalil U, 2014). Deep water ports are very special and capable of accommodating larger ships with deeper drafts. Every modern port is equipped with advanced technology, including specialized cargo-handling tools and facilities like gantry cranes, portable heavy lift cranes, straddle carriers, reach stackers, and forklift trucks etc (Port Technology, 2017). Ports typically serve specialized purposes like passenger ferries or cruise ships, container traffic, general or bulk cargo, oil, liquid, gas, etc. Certain ports have significant roles for a nation's military or navy, and others cater to various other needs. In many developed countries, ports are usually either publicly owned or both the state and local cities or organization (Hossain, 2024e). Ship size has significantly increased since the 1990s, with the introduction of post-Panamax containerships. Increasingly, various types of merchant vessels such as containerships, bulk carriers, car carriers, and cruise ships necessitate specialized port terminal facilities. At present, the focus is shifting towards automation and other advanced technologies. These factors are exerting pressure on ports to enhance their services and capabilities (Rodrigue, 2017). 6th Generation Ports (6GPs) are envisioned as smart, sustainable, and socially responsible hubs that integrate advanced technologies to optimize operations, minimize environmental impact, and contribute to the well-being of their surrounding communities. Future port will be fully automation of container terminals and extensive use of digital and smart technologies for optimized operations, data management and better service. 6GPs will also be efficient and reliable transport links connecting the port to its inland hinterland, minimizing negative impacts on the surrounding environment. Those ports also need effective governance structures which can facilitate collaboration, innovation, and the efficient management of a smart port environment. However, smart ports utilize AI and other innovative technologies and facilities for successful and effective operation and management port. In the broadest sense, AI refers to the intelligence displayed by machines, especially computers systems (Hossain, 2025a).

AI has been utilized in various applications across industry and academia, including steam engines, internal combustion (IC) engines, and electricity or computers (McCorduck, 2004). Today, AI is a general-purpose technology with applications like automation, industrial robots, language translation, image recognition, decision-making, e-banking, e-health care, credit scoring, e-commerce, e-agriculture, and more sectors (ISPS, 2004). AI encompasses technologies that enable machines to perceive, understand, act, and learn within various scientific disciplines. The term "machine learning" (ML) gained popularity in 1959, thanks to Arthur Samuel. ML is a subset of AI that focuses on algorithms capable of learning from data to enhance the accuracy and performance of AI systems (Hossain, 2023a and 2024d). Again, Deep learning (DL) is a multi-layer neural network inspired by brain neurons. Artificial neural Networks (ANNs) are powerful tools that identify correlations between cause's factors (Kingston, 2003). So, DL is a subset of ML, which in turn, is a subset of AI, whereas Data Science (DS) integrates various techniques to analyze and derive insights from data (Hossain, 2023b). Today, autonomous ships monitor the ocean, powered by AI-driven satellite data analysis (Hino, 2018). Future port will be more giant and more equipped to accommodate and provide service 24/7 with high customer satisfaction. In future smart 6GPs is coming soon, and will be should capable to handle mega-ships with a capacity of 50,000 TEU (Twenty-foot Equivalent Units) and a ship's draft of 20 meters or more. This study will investigate the future development of port in contrast of history, global demand and advanced technology.

CHRONOLOGICAL PORT DEVELOPMENT HISTORY

The concept and extensive use of port has drastically changed since last two centuries. During the 19th century and first half of the 20th century the ports tended to be tools of state or colonial powers and port right of entry and way out was regarded as a means to manage and organize markets. Competition between ports was nominal and port-related expenditure was relatively unimportant in contrast to the high cost of sea transport and inland transport (Rossella, 2013). However, today seaports are the principal means of international trade and commerce, which facilitate to transport of merchandise between countries through water body or seas. They provide a cost-effective and efficient way to move large quantities of cargo and goods. A port typically serves as a marine facility with quays, jetties, or loading areas for ships to load and disembark passengers' cargo (AHD, 2025). Numerous port cities have experienced substantial multi-ethnic and multicultural transformations over history due to their roles as entry points for immigrants and soldiers during conflicts conflict (Caves, 2004). Ports are extremely important to the global economy; above 70% by value and around 80 % by volume of global goods or products trade and business passes through ports (Asariotis, 2017). Consequently, ports are often highly inhabited areas that supply labor for handling, processing, and other associated activities (Hanson, 2004).

Today, Asia is experiencing the greatest growth and development of ports, housing most of the world's largest and busiest ports, primarily in Singapore, China, and the UAE etc (Du Ke, et al, 2019). One of the busiest passenger ports in the world is the Port of Helsinki in Finland (Schlosberg, 2002 and Fuller, 2022). However, dredging, spills, and other pollutants can significantly harm local ecosystems and waterways, especially water quality. The shifting environmental conditions brought on by climate change have a significant impact on ports (Schlosberg, 2007 and Walker, 2016). From the history, sea ports were typically developed by ancient civilizations that participated in maritime trade. Nestled along the stunning shores of the Red Sea, Wadi al-Jarf boasts two of the world's earliest known manmade harbors, a remarkable testament to ancient engineering and maritime ingenuity (Rossella, 2013). However, Canopus, the main port in Egypt, and Guangzhou, which existed under the Qin Dynasty in China, are two instances of rare ancient ports. Once more in antiquity, the port of Piraeus in Athens served as the home port for the Athenian navy, which was instrumental in the defeat of the Persians at the Battle of Salamis in 480 BC (History Alive, 2004). Located in the Bhal region of today's Gujarat, Lothal was a significant port city of the Indus Valley civilization, dating back to 3700 BC (Rao s, et al, 1985). In addition to the neighboring port of Ostia, the port of Ostia Antica in ancient Rome was expanded by Trajan and constructed by Claudius with Portus (Finley, 1972).

Osaka was the greatest domestic port and the center of rice trade during the Edo period in Japan, while the island of Dejima served as the only port open for trade with Euro (Hale, 2009). Numerous renowned African trade ports, such as Mombasa, Zanzibar, Mogadishu, and Kilwa, were familiar to Chinese sailors like Zheng He and medieval Islamic historians, including the Berber voyager Ibn Battuta (Fordham, 2001). The development of seaports, especially those that handle containerized cargo, results in the establishment of an increasingly intricate web of relationships between the supply and demand sides of the port services industry. One way to describe the significance of seaports is to assign them to a particular port generation. Based with the UNCTAD model, ports can be classified as first, second, third, or fourth generations (UNCTAD, 2011). As a characteristic of the fifth generation port, M. Flynn (2011) proposed including two stakeholder groups: the local community and port users/customers (T Bebbington, 2009). P. Lee and J. Lam (2015) introduced the idea of classifying seaport generations, which is taken into consideration in the fifth generation seaports (A Beresford, et al, 2004).

The seaport classification system that is already in place describes the modifications that have already occurred in ports across the world. Such as: 1st Generation ports were close to cities, port-city model. 2nd Generation ports were Proximity to industrial areas for raw material supply. On the other hand, 3rd Generation ports were containerization and increased cargo handling capacity (Hossain, 2023)). Whereas, 4th Generation ports have given more focus on efficiency and cost reduction. Again, 5th Generation ports were concentrated on globalization, increased trade volumes, and the need for larger, more efficient ports. The future seaports to be categorized according to the present standards for a 4th or 5th generation port, are absent from the literature. Prior to the creation of the port supply center, there have been rapid changes in the area surrounding seaports, including the adoption of new IT, IoT and AI technologies, the growth of social networks, and new techniques for team and company management.

Consequently, ports generating models are developed in response to shifts in the world economy (Workport, 2000). Thus, it is necessary to update the port assessment standards under the INCTAD or EU workport initiatives. A. Beresford highlighted that several criteria could not have been considered since they had never been exist in the port's authenticity previously when comparing workport and UNCTAD (A Beresford, et al, 2004). According to the UNCTAD model, technological, organizational, and intelligent technology advancements made it possible to expand the range of services offered by 5th generation port (5GP) and the extent of their collaboration with stakeholder groups (P Lee, et al, 2024). In addition to serving as the hub for international maritime transportation, a 5GP benefits society and contributes to environmental preservation. The rapid advancement of innovative transport technologies and IT systems, in conjunction with the future maintenance of 50,000 TEU megaships, is expected to cause a change in cargo flows among ports. This shift will favor ports equipped to handle larger vessels, resulting in a significant rise in cargo traffic landside.

CONCEPT OF 6TH GENERATION PORTS (6GPS)

6GPs signify a conceptual framework for future ports which will be highly automated, competent, programmed, and will be familiar for sustainable development, social welfare, beside economic value creation. 6GPs go beyond current 5th Generation Ports by incorporating a higher degree of automation, integrating smart technologies like AI, ML, DL, IoT, big data, and focusing on a holistic, data-driven approach to port operations. The Strait of Malacca's depth of 25 meters now places restrictions on the size of the ships that can transport crude oil along that route in the form of ultra/very large crude carriers, or VLCCs. Vessels of the Malaccamax class have a 20 meter draft (Maritime, 2024). An alternate route for megaships is to cross the 250 meter deep Lombok Strait, which is close to the Indonesian island of Java, which is located 1734 kilometers southeast of Singapore.

Future container ships, such as those built after the Malaccamax, would have to add thousands of kilometers to their routes and so avoid some seaports (UNCTAD, 2021). Following dredging in June 2016, the maximum depth of the Panama Canal is now just 13.11 meters, allowing transit for boats up to the Neo-panamax class, which has a capacity of 13000 TEU. This limits the ability to operate the freshly planned megaships. Taking into consideration the restrictions on the maximum ship draught listed in the McKinsey report as well as the comments made by T. Notteboom and J. Rodrigue on land linkages with the hinterland, it would seem that the new, 6th generation ports should have the few important characteristics (T Notteboom et al, 2009). Such as: Capacity to manage cargo ships with a 50,000 TEU capacity and a maximum draft of 20 meters. Possess a completely automated container terminal that can handle a sizable number of loading and unloading tasks quickly with extensive use of smart technologies like the IoT, AI, ML, and big data analysis. 6GP need to manage the intermodal linkages with the hinterland that enable the low-cost, congestion-free transportation of containerized cargo.

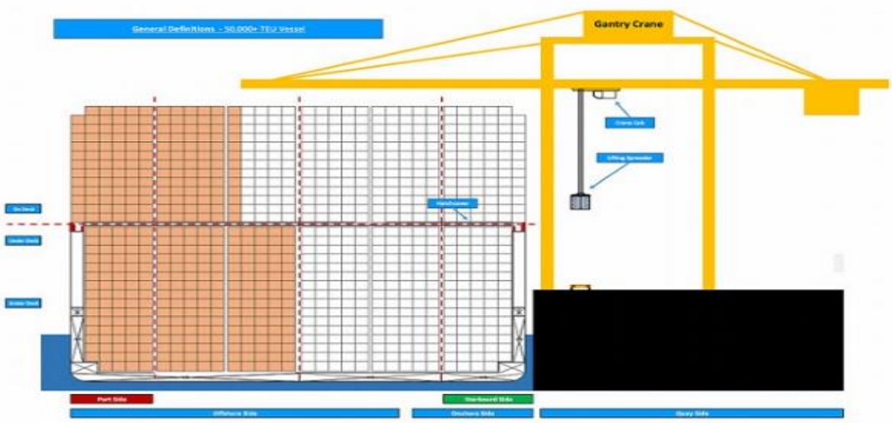

Figure 1: Limited capacity of 5GP crane to handle 23/24 row 50000 TEU mega-ship of 6GP (according to T. Bebbington in 2017)

For a port to reach the 6GP level of development characteristic, it must first transform into a 5th generation supply center. This will enable the four criteria for 5GP information technologies, significant development, port cluster, and hub port that were put out by P. Lee and J. Lam in 2016 to be excluded from the classification of 6GPs (P Lee, et al, 2016)). However, 6GP is theoretical and not yet universally adopted in anywhere of the globe. There are advancements and projects underway that could be considered steps towards the future. The idea of a 6GP envisions ports that can handle 50,000 TEU vessels with a 20 meter draft, utilize advanced automation, and have strong hinterland connections to minimize negative impacts. The 6GP framework proposes ports that can handle larger ships, implement advanced automation and have efficient transportation networks to support the increased cargo volume (Adam, 2028). Large-scale port expansion and development projects, like those underway in China, are pushing towards the capacity and infrastructure necessary for 6GP characteristics (Chinadaily, 2025). Today ports like Xiamen in China are mentioned as being able to handle mega-vessels and potentially considered to be moving towards 6GP capabilities (Gocomet, 2024).

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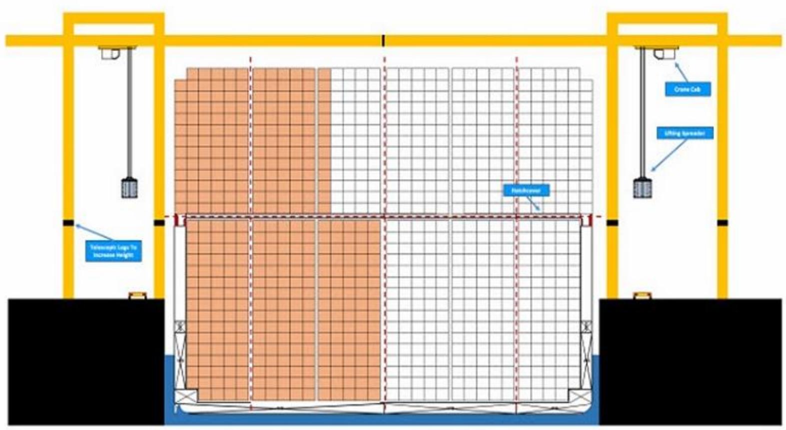

Figure 2: The visualization of handling a 50000 TEU ship with 23/24 row cranes for 6GPaccording to T. Bebbington (T Bebbington, 2017)

Alongside its role as a center for global maritime trade, a 5GP also supports society and helps protect the environment. The rapid advancement of transport technologies, IT, IoT, AI systems related to the upcoming 50,000 TEU megaships will likely lead to a change in cargo flows to ports equipped for larger vessels and a significant rise in landside cargo traffic. The 6GP builds upon the concepts of previous port generations, incorporating lessons learned and addressing new challenges and more facilities. The challenges of 6GP will be many more like to find the right balance between economic growth and environmental protection. Modern ports need to integrate new technologies like AI, ML, IoT, big data, blockchain, etc. into existing port infrastructure. Future ports need to address the increasing complexity of global supply chains and logistics (Hossain, 2023d). 6GP need to consider the social impacts of port operations and promoting community well-being. 6GP also need to prepare for future pandemics and disruptions to global supply chains. However, 6GP leverages digital technologies, data analytics, and automation to optimize port operations, enhance security, and improve decision-making. Moreover, de-carbonization efforts, reduced GHG emissions, and climate change adaptation are integral to the 6GP concept (S Saxon et al, 2017).

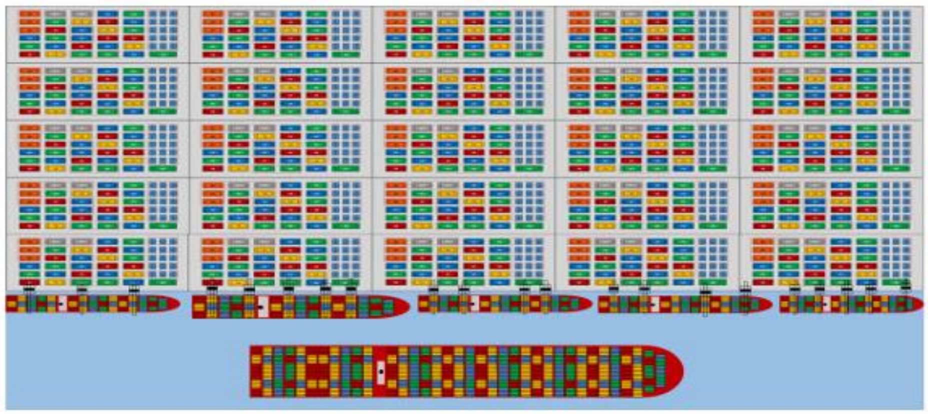

Figure 3: Comparison between 50,000 TEU and 18000 TEU ships (T. Bebbington)

CONCEPT AND ADVANTAGES OF SMART PORT

Ports link vessels and goods with importers, exporters, port-users, and stake-holders. Smart means the more beautiful, effective, user friendly and innovative with more intelligence in a competitive and viable sense. It may defined by being a technologically advanced seaport that integrates digitalization, automation, and data-driven solutions to optimize logistics, ease operation, improve efficiency, increase effectiveness, enhance security, ease operation, and reduce environmental impact. Smart ports are a new generation of digital ports that are designed to be more efficient, sustainable, and innovative than traditional ports. Smart ports are always augmented by smart and advanced technology. They use advanced technologies like internet of things (IoT), AI, ML, DL, DS, DM, big data, blockchain, and automation to improve their operations, optimize profits and reduce their environmental impact (Hino M, et al, 2018).

The concept of smart cities is gaining traction as technology and urban development evolve rapidly. At the forefront of this movement are automated or smart ports, which are crucial for international trade and sustainable urban environments. These ports leverage digital solutions, such as AI, IoT sensors, and blockchain, to enhance resource efficiency, reduce environmental impact, and improve operations (Chen, 2019). Key technologies include real-time cargo tracking, predictive analytics, cybersecurity, supply chain integration, and digital twin technology, among others (Splash247, 2025). Modern ports are upgrading their infrastructure to support smarter operations. This includes automated berths with mooring systems, shore power to reduce emissions, and energy-efficient lighting. Besides building and maintaining these facilities, smart ports focus on security. Effective port management software is essential, as it can help with yard management, berth scheduling, and terminal operations. Managing port facilities means operating and maintaining various services to ensure smooth cargo movement, safety, security, and environmental care. Digitalizing port operations and creating collaborative platforms for stakeholder engagement are key steps in using smart technologies. Examples include port community systems and real-time monitoring of cargo handling, infrastructure, and vessel movements (Hossain, 2024e). Smart technologies also use automation, sensors, and data analytics to improve efficiency and reduce delays in port operations.

Smart ports employ smart technology solutions to increase efficiency, effectiveness and security by making ports more environmentally sustainable, economically efficient and capable of handling increased port traffic (Portofrotterdam, 2021). To enhance efficiency and reduce delays, technology facilitates the integration of port operations, such as cargo handling, customs clearance, and vessel scheduling, needs to be developed. Port Community Systems (PCS) enable better collaboration and information exchange among stakeholders like port authorities, shipping lines, and logistics providers, improving commodity movement and operational transparency. Now, ports are using AI into their infrastructure worldwide. For instance, the Port of Shanghai and the Port of Singapore both employed AI to be recognized by the United Nations (UN) as the world's best-connected ports, while the Port of New York and New Jersey created a five-year plan to apply AI, and the Port of Hamburg has used ML modules. AI will keep making port improvements better.

Figure 4: A smart port and their unmanned activities (Splash247, 2024)

FUTURE PORT OPERATION AND SMART SOLUTION

Future smart ports will operate 24/7 through automation without human involvement intervention with higher efficiency and optimum output (Hossain, 2024a). This will enhance efficiency while simultaneously reducing labor costs (Hossain, 2024d). Data utilization is essential to enhance operations and maximize resource efficiency. Future ports will be designed to be more eco-friendly, often with the intent of minimizing their carbon footprint and protecting marine environments environment (JOE, 2024). They utilize renewable energy and sustainable and advanced technologies to lessen their environmental impact. Future smart ports will be crafted to enhance their connectivity with logistics and industries environments (Hossain, 2025a). They leverage advanced technologies to enhance the movement of goods and information among smart ships, cargo terminals, and other areas of the smart supply chain. Their open innovation mindset enables continual improvement of operations through the adoption of new technologies and concepts. Smart port is highly digitizes and uses smart technology for better efficiency and service. Smart ports are more effective, more performing, more user-friendly, and more competitive port. Smart ports consider residents a key stakeholder of their activities and operations (Hossain, 2023c). Due to the fact that port operations are repetitive, a large amount of both current and historical data are produced, which can be fed into the AI systems and algorithms (Basma, 2023). In future vehicles, lorries, equipments, and even a handful of the present port administration systems need to be automated by AI.

Future port need to enriched with advanced technology like specialized cargo-handling equipment and facilities, robotic cranes, automated straddle carrier, smart reach stackers, automated forklift trucks, etc as well as extensive use of AI, ML, DL, IoT, Blockchain, big data, digital twin, etc. One of the key features of smart ports is their automation and inclusion of AI, which allows them to operate 24/7 without human intervention (Finace, 2024). Future AI or ML powered solution can track vessel trade routes by integrating real-time data from blockchain databases and IoT sensors into AI algorithms. Future port will maximize berthing time by following a vessel's trade path, which would provide an accurate expected time of arrival (ETA). The application of AI technology will precisely schedule a ship's arrival and departure which will result in cost savings, minimize environmental effect and port congestion, and facilitate adherence to rules and standards (Hossain, 2025a). AI-driven Digital Smart Ports will manage freight and traffic more effectively, streamline staff work schedules, reduce human error, and boost supply chain efficiency (Stamford, 2021). Future port will use real time information, a collaborative management approach, provide more security, better service, more efficiency, save energy, and essentially provide more with less.

Figure 5: In future Smart Port will be game changer in any hub of the world (Sinay, 2024 Lloydslist, 2019)

In near future, by using AI algorithms, the maritime sector will be able to see their operations from every angle. Smart asset management systems utilize sensors, RFID tags, and GPS tracking to monitor port equipment like cranes and containers, promoting preventative maintenance and maximizing usage. Predictive maintenance algorithms analyze sensor data and performance to anticipate breakdowns, thereby enhancing safety and reliability while minimizing downtime and costs (Lloydslist, 2024). Making a port smart not only means digitally connecting everything inside the port, but also requires multilevel cooperation among government authorities, businesses, local communities and other relevant parties. The adoption of blockchain technology has improved freight movements traceability and transparency and building stakeholder trust (Hossain 2025b). The first step for potential customers interested in smart ports should be to launch the program. This can involve preparing an RFP, choosing a vendor, and managing the program for a pilot project. The purpose of the RFI is to gauge market interest and gather information about the kinds of specifications services and solutions providers might offer as end-to-end delivery. On the other hand, today a minor disruption in cargo flow within large maritime ports could lead to significant consequences. Grocery store shelves and service station gas tanks could be empty within days due to the failure of the zero-inventory, just-in-time delivery system that supports global commerce trade (Brookings, 2024). In future a cyberattack aimed at energy supplies would likely disrupt the global economy significantly.

CONCLUSION

Since a port benefits the local economy and society but is also subject to environmental restrictions, it typically presents a value proposition to the area notable increases in port traffic, especially in the industry that uses containers. Ports facilitate trade and sustain supply networks, which act as catalysts for economic growth. The global development of container ports, in particular their varying rates of expansion, reveals the forces behind off-shoring and local economic progress. It is feasible to manage vessels more than twice as big as those in operation now if sixth-generation ports are developed in the future. Traditional maritime operations are already being significantly transformed by smart ports. Smart technologies have been deployed by major ports worldwide to increase security, decrease environmental impact, and improve productivity. Smart port uses technologies like IoT, AI, ML, DL, big data, digital-twin, blockchain, and other technology to streamline operations, monitor cargo movements, and improve decision-making in real-time. Future 6GP aims to handle ships with a capacity of 50,000 TEU and a draft of 20 meters or more with full automation of container terminals is a key feature, streamlining operations and improving efficiency. However, 6GP represent a vision for the future of ports, aiming to create efficient, sustainable, and resilient maritime gateways that can meet the demands of global trade in the 21st century and beyond.

Today, more facets of port operations are incorporating AI. ML and DL can improve berth management, which will become even more crucial in the future as ships run on a variety of clean energy sources and have more specialized demands for port services. Furthermore, any port can envision a day in the future when AI-driven algorithms are trained to evaluate and forecast port congestion levels based, for example, on aerial pictures. It will assist ports in recognizing crucial circumstances and acting quickly to reduce traffic. Unquestionably, AI has the potential to help supply chains become smarter and more environmentally friendly. Therefore, In future extensive usage of AI in the marine industry need to be balanced with a deeper conception of the technology being produced, and that need to be ensure efficient and responsible port management training and skill development of employs. ETA forecasting is made possible by AI, which will transform port operations in near future. A precise and dependable forecast of the arrival of a vessel generates a cascade of advantages for the organization responsible for organizing and assigning ports of call. The advantages that come from effectively deploying smart technology will have an impact on nearly every facet of port operations like resource planning, port infrastructure, effective communication and paperwork, preventive maintenance, port administration, human labor skill development, smart handling equipment, berth allocation, and many more. Future smart and 6GPs will be designed to minimize their environmental impact through the use of green technologies, energy efficiency measures, sustainable operational practices and smart infrastructures.

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