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Evaluation of History and Development of Smart Port

Dr Hossain KA
Vice Chancellor, Bangladesh Maritime University (BMU), Dhaka, Bangladesh

* Corresponding Author: **Dr Hossain KA**

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Abstract
Ports are essential for local and international trade, connecting countries and facilitating the movement of goods. It plays a vital role of global economy as 75% of trade and commerce of planet by value passes through the port. Actually, ports are always considered as capital infrastructures and those cover wide range of financial associates. Smart ports are modern and highly facilitated port which uses digital, automated and other smart technologies to enhance efficiency, accountability, sustainability, security, and competitiveness in monitoring, operations, management and effective 24/7 service. Smart shipping and 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, freight-forwarders, local communities, stakeholders and others. They may also feature renewable energy sources, electric charging stations, onshore power supply, and smart infrastructure for logistics and transportation. 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, and playing a crucial role to enhancing national and international competitiveness. This analytical paper will assess the history and development of ports in the context of advanced technology. Today's smart ports and shipping are always used smart technology like AI, ML, DL, data science, etc. and facilities for effective and efficient service, safety, operation and better management.

Keywords: Port, PCS, smart port, 6GP, AI, ML, DL

1. Introduction

Ports hold immense significance for human civilization. The term 'port' or 'seaport' refers to various types of facilities that manage maritime vessels or vessels (Caves R W, (2004) [8], whereas river a port facilitates river traffic, including barges, coasters, and other shallow-draft vessels. An inland port refers to a port situated on a navigable lake, river, or canal that connects to the sea. In contrast, a seaport typically lies directly on the shore of a body of water sea (Fulcrumslgroup, 2024). However, a cargo port is quite distinct from cruise ports, as it manages a different type of cargo that must be loaded and unloaded either manually or through mechanical means. In contrast, a cruise home port is where passengers board and disembark from cruise ships. A fishing port serves as a location for landing and distributing catch fish (Hattendorf John, 2007) [38]. A marina serves as a port for recreational activities boating (MARINA 2015) [54]. 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) [39]. Typically, all ports facilitate easy navigation for ships and provide refuge from cyclones, tsunamis, or rough waves. Ports are usually located in estuaries, characterized by shallow waters that require attention regular dredging (Khan 2014 and Hossain 2024e) [46, 31]. Deep water ports are rarer 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 2019). Ports typically serve specialized purposes: some focus mainly on passenger ferries and cruise ships, while others specialize in container traffic or general and bulk cargo. 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 partly owned by both the state and local cities themselves (Rotterdam, 2024).

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. Currently, the focus is shifting towards automation and other advanced technologies. These factors are exerting pressure on ports to enhance their services and capabilities Rotr (Rodrigue 2017) [63]. Smart ports represent a new era of digital ports, designed to be more efficient, sustainable, and innovative than their traditional counterparts. They are enhanced by cutting-edge technology, utilizing advanced tools like artificial intelligence (AI), machine learning (ML), deep learning (DL), the internet of things (IoT), big data, data science (DS), blockchain, and automation to optimize operations and minimize environmental impact (Sinay, 2024 and Hossain, 2025a) [70, 32]. Smart ports operate 24/7 through automation without human involvement intervention (Finance, 2024). This enhances efficiency while simultaneously reducing labor costs (Smartportalliance, 2024). Data utilization is essential to enhance operations and maximize resource efficiency. Smart ports are designed to be eco-friendlier, often with the intent of minimizing their carbon footprint and protecting marine environments environment (JOC, 2024). They utilize renewable energy and sustainable technologies to lessen their environmental impact. Additionally, smart ports are crafted to enhance their connectivity with logistics and industries environments (Basma *et al*, 2023). They leverage advanced technologies to enhance the movement of goods and information among ships, cargo terminals, and other areas of the supply chain. Their open innovation mindset enables continual improvement of operations through the adoption of new technologies and concepts (Hossain 2025b) [33]. 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, 2021) [7]. A cyberattack aimed at energy supplies would likely disrupt the global economy significantly. AI and other smart technologies will contribute to sustainability efforts and better solution in the maritime industry by optimizing fuel consumption, reducing emissions, enhancing the efficiency of supply chains, efficient port operation, effective shipping management, ensuring safety and security and many more concern related to modern shipping and port management.

In the broadest sense, AI refers to the intelligence displayed by machines, especially computers systems (Copeland, 2004). AI has been utilized in various applications across industry and academia, including steam engines, internal combustion (IC) engines, and electricity or computers (Hossain, 2024d and McCorduck, 2004) [30, 55]. 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 sector (Hossain, 2024a) [27]. AI encompasses technologies that enable machines to perceive, understand, act, and learn within various scientific disciplines. The term 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, 2025a and Du Ke *et al*, 2019) [32]. ML, or a powerful algorithm, enhances AI systems and helps combat spam, scams, and phishing (Galego *et al*, 2021) [22]. Conversely, the term DL was brought to the ML community by Rina Dechter in 1986. Then, in 1989, Yann LeCun and others utilized the standard back-propagation technique algorithm (Trentonsystem, 2024) [75]. DL is a multi-layer neural network inspired by brain neurons. A neural network consists of interconnected neurons that receive input signals in the form of data and process them to transmit information to other neurons (Hossain, 2024d, MIT, 2024 and Deng *et al*, 2014) [13, 56]. Artificial neural Networks (ANNs) are powerful tools that identify correlations between causes factors (Kingston, 2003) [45]. ANNs are tailored to evaluate extensive datasets that represent natural phenomena and their potential influencing factors. DL is a subset of ML, which in turn, is a subset of AI. Additionally, Data Science (DS) is an essential field that warrants significant focus. DS integrates various techniques to analyze and derive insights from data. Today, autonomous ships monitor the ocean, powered by AI-driven satellite data analysis (Hossain 2025 and Hino *et al* 2018) [32, 26]. This study analyzes the history and development of ports alongside advancements in technology. Modern and smart ports utilize AI and other smart technologies and facilities for successful and effective operation, better management and safety of ships and ports. This is an analytical study to evaluate the development of port on the basis of history and technological advancement.

Chronological Development and History of Ports

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 passenger's cargo. 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, R. W., 2004) [8]. Ports are extremely important to the global economy; 70% by value and 85% by volume of global goods or products trade and business passes through ports (Asariotis, Regina, *et al*, 2017) [1]. Consequently, ports are often highly inhabited areas that supply labor for handling, processing, and other associated activities (Hossain, 2024a) [27]. 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 (Eurostat, 2024) [14]. However, dredging, spills, and other pollutants can significantly harm local ecosystems and waterways, especially water quality (Fuller Richard, *et al*, 2022) [16]. The shifting environmental conditions brought on by climate change have a significant impact on ports (Walker Tony R., 2016 and Schlosberg David, 2007) [81, 73].

Let's look back from 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 Lorenzi, 2013) [65]. 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) [40]. 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*) [66]. 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, Moses 1972) [19]. 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 John R, 2009) [36]. 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 (42 Fordham, 2011) [20].

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) [80]. As a characteristic of the fifth-generation port, by M. Flynn (2011) proposed including two stakeholder groups: the local community and port users/customers (T. Bebbington, 2017) [77]. P. Lee *et al*, (2016) [61] introduced the idea of classifying seaport generations, which is taken into consideration in the fifth-generation seaports (A. Beresford, *et al*, 2004) [4]. UNTCTAD states that the primary characteristic of a first-generation seaport. Taking advantage of its dominant position and often monopoly in the local market, it makes little effort to meet user wants (P Lee, *et al*, 2016) [61]. The 1st generation port's document, statistics, and information systems run independently of the port users. The port city and the seaport have loose relations that they do not need to coordinate their plans for spatial growth (Hossain Tahazzud, *et al*, 2019) [34]. In the port regions, several entities' operations are likewise disorganized. Because of the low stevedoring rate and poor cargo displacement prior to containerization, ports must make decisions independently of one another. Seaports that served liquid and bulk cargoes and were situated close to natural resource extraction sites were an exception to this rule. Here, intermodal cargo displacement onto ships; either by conveyor or pipeline—was conducted (H. Klimek, *et al*, 2003) [35].

First-generation ports are located in uncontested hinterlands that are able to transport freight without facing competition because of political or economic reasons. Seaports and ports that handle raw materials should both fall under this category (A. Paixão, *et al*, 2004) [3]. Little seaports like fishing ports and marinas don't need large storage spaces, costly information systems, or coordinated planning for activities. Even yet, we cannot ignore their significance for the economic advancement of developing nations as well as for the smooth operation of local communities in industrialized nations. UNCTAD states that 2nd generation ports use their transportation, industrial, and commercial functions to interact with their surroundings. Industrial parks are established within the port areas to accept imported raw materials, such as iron ore, steel, crude oil, aluminum, copper, paper pulp, artificial fertilizers, sugar, flour, and other agricultural commodities, that are transported by sea. In the 1960s, the usage of massive tankers and bulk carriers for sea transportation forced the ports to deepen their water areas (T. Notteboom, 2009) [76]. The potential for increased value created in ports has been enhanced by broadening the scope of port operations to encompass industrial and commercial activities sectors (R. Zahorski, 2017) [64]. The expansion of industrial operations is closely tied to the availability of labor and utilities, such as power and water, as well as land accessibility and efficient transportation links. However, the increase in industrial production has had a negative impact on the natural environment. From an operational perspective, effective coordination with the port city and the surrounding region is essential for the efficient functioning of the port supply center. As port activities and cargo volumes grow, the need for collaboration among various service providers within the harbor becomes increasingly important to manage cargo effectively (Saxon *et al*, 2017) [68].

2nd generation ports usually cooperated with their immediate environment, the transportation industry, and local government in a limited capacity. In actuality, seaport operations were restricted to the specific microenvironments (Gospodarkamorska, 2024) [24]. As far as we are aware, electronic data exchange systems were not considered in the 1960s and 1970s information exchange process with the environment (Lloydslist, 2023). The third generation of seaports emerged in the 1980s during a time of rapid growth in the number of containerized cargo, the construction of an intermodal connections network, and rising demands brought on by the expansion of international transportation. These ports are known for being busier than their predecessors when it comes to cargo searches thanks to the development plan. 3rd generation ports are distinguished in the operational domain by a significantly wider range of services encompassing four business operating areas (UNCTAD, 1992) [78]. The first makes use of contemporary technology, organization, and administration to provide stevedoring, storage, and navigation services. This generation places a high value on knowledge, skills, and electronic data interchange and processing. The second sector consists of the extension of the ports' industrial function into environmental functions related to the operation of ships and equipment required for environmental protection in the second generation. The ports are surrounded by industrial zones and well-known export processing zones where imported commodities are refined and exported via the harbor (K Misztal, *et al*, 2019) [44]. The third section consists of the port's required financial, insurance, and legal services, as well as an efficient administrative and commercial management of cargo information. UNCTAD notes that a rise in non-tariff trade barriers may be caused by the burdensome documentation and regulatory requirements as well as the disorganized port service work schedule. The new distribution system for logistics role that arises from integrating seaports into the combined notion of the network of land-sea transportation is the subject of the fourth area (Lloydslist, 2024).

In order to provide just-in-time delivery, the 3rd generation seaport's distribution service entails efficient administration of the cargo stream and information related thereto. Quick intermodal connections and container rotation within the harbor hinder the ability to add value to the cargos there. Port distribution centers have the potential to enhance the range of port services offered, facilitate cargo deconsolidation for LCL (less than container load) shipping, plan land-based cargo distribution, and facilitate the return of the empty containers to the port. The development approach cannot be implemented by third-generation ports and refuse to collaborate with national, regional, and port city authorities. Because of the large amount of containerized cargo that ports handle, they need modern warehouses and distribution parks, high-quality road and rail connections with nearby facilities, and a complete symbiotic relationship between the port and the city to ensure efficient resource use and cooperative spatial planning (A Paixao, 2003 and Lloydslist, 2024). The fact that the port supply center operates independently of the distribution chain poses a particular vulnerability for third-generation ports. Insufficient stakeholder participation may result in business decisions that are advantageous for the port. The UNCTAD classification of seaports does not include the stevedoring capacity as a developmental criterion. Even with a small cargo volume, tiny ports may find it difficult to guarantee high-quality ship handling, which in developing nations may prove insufficient to justify the expensive investments, notably in IT. Decision-makers at the port are actively engaged in exploring modern cargo handling technologies, which includes implementing organizational and informational enhancements an additional requirement set by UNCTAD categorization (A Paixao *et al*, 2003). The rapid advancement in computer sciences since the 1980s renders the EDI data exchange systems from that era outdated in the 21st century for two main reasons. First, they restricted Internet usage, which has evolved into a globally embraced platform that facilitates international finance and trade. Additionally, it is crucial to update the processes and systems associated with online information security to ensure that participants involved in port turnover are protected against hacker attacks, which could threaten the port's ability to perform stevedoring operations temporarily or permanently entirely (Port Technology, 2024 and Lloydslist, 2023).

The definition of a 4th-generation port was established by UNCTAD in 1999. A few significant factors have been taken into account, including the level of port services, the use of IT, the growth of the port community, the existence of the port cluster and logistics center, and the effectiveness of the linkages with the foreland and hinterland on the seaside and landside, respectively (UNCTAD, 1999) [79]. Unlike the third-generation ports, the fourth-generation ports serve as the primary regional hub from which goods are delivered by sea to smaller outlying ports, so forming a super-regional function. A common operator of the container terminal or a common administration may serve as the link between port authorities. UNCTAD highlights that private sector entities, particularly powerful multinational organizations with expertise in managing port terminals, primarily container terminals, are typically responsible for implementing investments in port hubs. However, UNCTAD suggests that port authorities refocus their focus from seaport operations to more long-term forms of influencing their future in light of the aforementioned trend of direct private sector participation with seaports. These consists of carrying out strategic and ownership responsibilities in a few areas, This includes creating port policies, enforcing regulations on service providers, licensing to ensure fair competition, addressing issues like excessive tariffs from private operators, and ensuring a minimum standard of quality for security services. It also involves monitoring the port's vicinity, promoting the port externally, and hiring and training the necessary personnel for service provision operations.

In 1999, UNCTAD suggested that such ports may be developed, but it did not provide any particular measurements that could be used to categorize ports as belonging to the fourth generation. The UNCTAD port classification may change again soon because of how quickly IT technology, the Internet, smart-phones, and social networks are developing at the beginning of the twenty-first century. The literature on the subject has questioned the UNTCAD's categorization of seaports into generations, citing glaring oversimplifications. It appears that the port classification is now imprecise, hazy, and unrepresentative of the actual functioning. Port generation in accordance with the UNCTAD model disregards elements that, in A. Beresford's opinion, are crucial and influence the degree of development of commercial facilities. Key elements are the port's size, location, and the involvement of public or private sectors in its operation services (A. Beresford, (2004) [4]. According to A. Beresford, the advantages of the port's location also have an impact on plans for future growth, market strategies, and the range of services the port offers. The port is less technologically advanced in that sense. Once more, because of its ideal location in relation to the hinterland, it would be suitable for managing the current cargo stream while maintaining the low-cost level. As a result, it doesn't appear necessary to build ports of the newest generation to replace the ones that already exist everywhere.

The workport study project has financed by the European Union 1998–1999, demonstrated how seaports were changing in contrast to the UNCTAD model from 1990. Since the 1960s, ports in Europe have developed in an evolutionary manner. This means that, in terms of terminals, individual supply centers in ports coexisted with ports, or more specifically, container terminals of different generations according to the UNCTAD concept. Dubai is one example of a port that combines elements of the first and fourth generations. In the old area of the city, next to the contemporary Jebel Ali container terminal is a first-generation port that is still in use. Here, sacks and packages are transshipped from small vessels in the same way as they were decades ago. The UNCTAD models failed to take into account the port differentiation criteria, which are important for the growth of ports in Europe. These factors include environmental protection, organizational culture, worker safety and health, and the evolving circumstances for handling larger vessels. As ports become more automated, mechanized, and computerized, it is necessary to modify worker skill levels, implement training initiatives, and pay attention to enhancing organizational culture. Through a collaborative work structure with a high degree of decision-making autonomy, the work port project emphasizes the human side of organizational success while enabling the flexible provision of port services and utilizing the multi-skilled nature of its members. It appears that the work port, which was introduced in March 2000, considers a significantly greater number of criteria and their interrelationships than the UNCTAD port generation model (Workport, 2000) [82]. Because of its emphasis on the management and executive roles that port employees play in the evolution of the port, the work port model appears to be anthropocentric. Aspects of work quality were also addressed in the project as part of the ongoing effort to improve port service quality.

J. Semenov saw that as 4th-generation ports evolved, port employees' perspectives on their work had to shift from one of passively carrying out stevedoring activities to one of participating in the global economy (J. Semenov, 2003) [43]. An important factor to raise the competitiveness of Polishports is the port's perception as a unified system that integrates information technologies, superstructure, and infrastructure in order to maximize suitability for port users (ISPS, 2004). According to J. Semenov, a 4th-generation port must be able to adapt to new kinds of operations, create added value, and serve as a logistical center. Ports with containers, like Rotterdam, Singapore, or Hong Kong, are excellent examples in this regard. Usually J. Semenov's port lacks the capacity to manage the largest ships, particularly container ships classification (J. Semenov, 2003) [43]. In significant European container ports like Gothenburg and Hamburg, the depth of the quay basins and port approach turning basins practically limit the handling of the largest cargo ships. Such a seaport has to explain why it isn't allowed to take part in the navigation services between Asia and Europe or why it can't accommodate a ship that is completely loaded (OECD, 2017). Authors A. Grzelakowski and M. Matczak claim that the characteristics of a 4th generation port are in line with what makes a contemporary container port that is connected to international supply chains through a computer network. However, they avoid discussing the matter of port basin depth, much as J. Semenov's classification. Therefore, the reasons behind the notable rise in container turnover in recently built ports such as Wilhelmshaven, Germany, or the DCT in Gdańsk, Poland, cannot be explained by this classification. They were built because the existing container ports in Hamburg, Gdynia, or Gothenburg were not deep enough. A. Grzelakowski and M. Matczak presented a novel characteristic of the 4th generation port in 2012, accounting for a few factors as mention below (A Grzelakowski, *et al*, 2012) [25].

- The major cargo stream is containerized.
- The strategy for port development is founded on enhanced automation and information technology.
- The range of services offered includes multimodal transportation, information standards, and complete port integration with the transportation, forwarding, and logistics sectors.
- The features of the management system that highlight the global nature of port operations.
- Orientation towards supply chain management (SCM)
- Monitoring the state of the natural environment,
- Using techniques such as process management, service process automation, human resources management (HRM) approach, and total quality management (TQM), port services are provided.
- Information, technologies, and innovation are fundamental development factors.

The 4th and 5th generation ports provide a significant logistical platform. Large volumes of commodities may be transported to the distribution chain (Mckinsey, 2024) [53]. Moreover, the traditional positions of port logistics chains are transformed and given value by the emerging network economy. Port operations have undergone major changes in this new setting, which shortens the time required for door-to-door transportation and loading and unloading (Francois Xavier *et al*, 2018). So, Smart or advanced technologies such as AI, ML, DL, DS, digital twin, and others are used to digitally connect the 5th generation ports to other ports. Where, a Port Community System (PCS) is an open, impartial platform that links several systems, facilitatisng the intelligent and safe sharing of data amongst the various entities that comprise an airport or seaport community (Customscity, 2024) [9]. The PCS becomes essential for developing smart ports as the emphasis on globalization and the sea transportation industry's rapid digital transformation increase (Hossain, 2024a) [27]. The events with the COVID-19 pandemic have verified it. PCS are usually use at the largest ports worldwide, already have demonstrated their effectiveness in supporting flexible port enterprises by tying together the different systems utilized by the numerous actors that make up a complex network. However, selecting the ideal instrument becomes more difficult as the selection grows. The top ten port community systems worldwide are listed below. Through the integration of as many public and commercial stakeholder systems as possible, the finest port community systems are able to handle large volumes of data flows.

It is possible to objectively examine Singapore Port using the 5th generation port (5GP) standards (which offers 24-hour customs and administrative clearance, but still need development taking into account once more the dire circumstances in Poland, where the nation has crossed over. A fresh conceptual framework for the 6th generation port (6GP) has been designed and put out. Strong hinterland transport links that minimize negative externalities, semi- or fully automated container terminals, and ports that can accommodate 50,000 TEU vessels at a depth of 20 meters are among the requirements for 6GP. Since none of the current ports meet the requirements for the 6th Generation Port (6GP) still today. The working paper by T. Bebbington has been closely analyzed to offer additional insights into the technical and financial challenges related to port strategy, planning decisions, and the future development and management of such operations port. A distinct approach to the transportation, environmental, and city-forming functions characterizes fifth generation ports, which were produced as a result of the dynamic expansion of containerization. Ships with a capacity of 50,000 TEUs will be able to be handled by 6GP.

The seaport classification system that is already in place describes the modifications that have already occurred in ports across the world. The findings of predictive studies, which would allow 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 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. 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 (Hossain, 2025a) [32]. According to the UNCTAD model, technological, organizational, and intelligent technology advancements made it possible to expand the range of services offered by 5th-generation seaports and the extent of their collaboration with stakeholder groups (P. Lee, 2016) [61]. In addition to serving as the hub for international maritime transportation, a 5th-generation port 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 Port (6GP)

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. (Marine insight, 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 (*Walker Tony R. 2016*) [81]. 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 13 thousand 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, (T. Notteboom, *et al*, 2009) [76] it would seem that the new, 6th generation ports should have the three important characteristics. 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. Over the past 50 years, information technology has also advanced significantly. The foundation for sustaining the speed at which information technology and IT are developing over the next 50 years is the continuous pace of development of new technologies like the Internet of Things, AI, ML, and big data analysis.
- Managing the intermodal linkages with the hinterland that enable the low-cost, congestion-free transportation of containerized cargo.

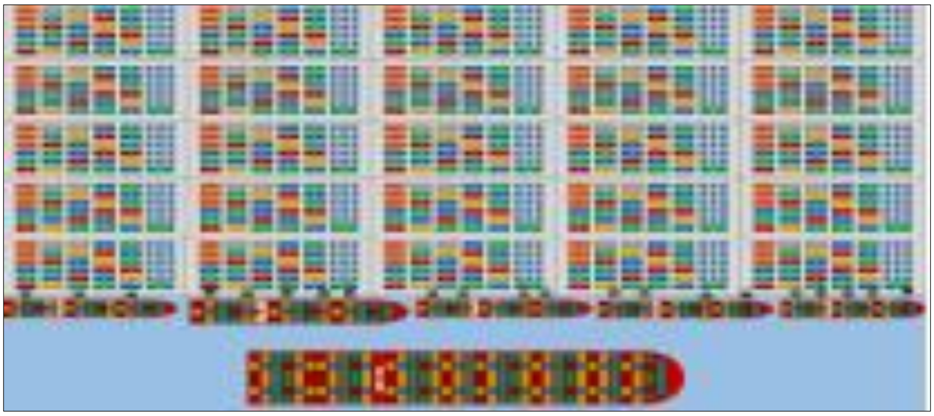

Fig 1: The depiction of a call from a 50,000 TEU vessel at a quay that accommodates 18 TEU ships, as noted by T. Bebbington (T Bebbington, *et al*, 2017) [77].

Alongside its role as a center for global maritime trade, a 5th-generation port also supports society and helps protect the environment. The rapid advancement of transport technologies and IT 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. 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 5th-generation ports 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 6th-generation ports. 6th generation ports (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 (Hossain, 2024b) [28]. Large-scale port expansion and development projects, like those underway in China, are pushing towards the capacity and infrastructure necessary for 6GP characteristics (Hossain, 2024d) [30]. Today ports like Xiamen in China are mentioned as being able to handle mega-vessels and potentially considered to be moving towards 6GP capabilities (Chinadaily, 2024).

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 5th-generation ports 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 6th-generation ports. 6th generation ports (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 Kaliszewski, 2018) [5]. Large-scale port expansion and development projects, like those underway in China, are pushing towards the capacity and infrastructure necessary for 6GP characteristics (Stanford News, 2021) [69]. Today, ports like Xiamen in China are mentioned as being able to handle mega-vessels and are potentially considered to be moving towards 6GP capabilities (Gocomet, 2024) [23].

Concept of Automated or Smart Port

Ports link vessels and goods with importers, exporters, port-users, and stake-holders. Smart port is highly digitizing and uses smart technology for better efficiency and service. Smart means the more beautiful, effective, user friendly and innovative with more intelligence in a competitive and viable sense. It may define 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. It uses technologies like IoT, AI, ML, DL, big data, digital-twin, blockchain and 5G or 6G technology to streamline operations, monitor cargo movements, and improve decision-making in real-time (Hossain, 2024b, 2025b) [28, 33]. Smart ports are more effective, more performing, more user-friendly, more-effective, and more competitive port. Smart ports consider residents a key stakeholder of their activities and operations. They use real time information, a collaborative management approach, provide more security, better service, more efficiency, save energy, and essentially provide more with less.

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. Key technologies include real-time cargo tracking, predictive analytics, cybersecurity, supply chain integration, and digital twin technology, among others (Splash247, 2024 and Hossain, 2025b) [71, 33]. 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. 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 (Paris innovation review, 2024). 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 (Splash247, 2024) [71]. Smart asset management systems utilize sensors, RFID tags, and GPS tracking to monitor port equipment such as 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. 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.

Fig 2: An automated port (Splash247, 2025) [72] and their unmanned activities (Pulse, 2025)

Use of AI for Smart Solution and Safe Port Operation

All modern ports are enriched with advanced technology like specialized cargo-handling equipment and facilities, like gantry cranes, portable heavy lift crane, straddle carrier, reach stackers, forklift trucks, etc as well as with AI-power (Port Technology, 2017). Ports usually have specialized functions like some cater mainly for passenger liners, ferries and cruise vessels; some specialize in container traffic; some cater general cargo or bulk; some ports mainly play an important role for nation's military or navy; some focus for any other purpose. Now, it is normal for ports to be either publicly owned in may developed countries, or port may be owned both by the state partly and by the partly cities themselves (Portofrotterdam, 2021). 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 (Sinay, 2024) [70]. 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 (Finance, 2024). AI or ML powered solution can track vessel trade routes by integrating real-time data from blockchain databases and IoT sensors into AI algorithms. A port might 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 to precisely schedule a ship's arrival and departure could result in cost savings, minimize environmental effect and port congestion, and facilitate adherence to rules and standards (Hossain, 2024e) [31]. AI-driven Digital Smart Ports can manage increased freight and traffic, streamline staff work schedules, reduce human error, and boost supply chain efficiency. Actually, by using AI algorithms, the maritime sector will be able to see their operations from every angle (Hossain, 2025a) [32].

Fig 3: Smart port will be game changer in any hub of the world (Sinay, 2024 and Lloydslist, 2019) [70]

AI helps to Develop Effective Vessel Traffic System (VTS) and Maritime Safety

The safety and efficiency of vessel traffic are paramount and act as heart of modern maritime operations. NeuralBoost is an AI based vessel traffic system invented by MakarenaLabs (Hossain, 2024d) [30]. It enhances vessel traffic services by offering real-time analysis of maritime data, significantly improving safety measures. Such modern and advanced technology swiftly pinpoints potential collision risks, navigational hazards, and anomalies, enabling proactive steps to avert accidents and guarantee the uninterrupted flow of vessel traffic (Hossain, 2024e) [31]. Integrating NeuralBoost advanced tools into any vessel traffic services is necessary and useful to oversee and manage the complexities of modern maritime traffic (Pietrzykowski, 2011) [59]. NeuralBoost's technology transforms the way maritime data analyzed and turning vast amounts of information into actionable insights and that ensures vessel traffic services work effectively and can anticipate or mitigate risks before they escalate. It also ensures fostering a safer maritime environment. It ensures a safer, more efficient pathway through the busiest waters, protecting vessels, cargoes, and crews against the dynamic challenges at sea. It is providing the clarity, but more foresight needed to navigate the future of maritime operations confidently (Hossain, 2024e) [31]. However, few benefits of NeuralBoost for vessel traffic services have been given below.

- It can help to identified risk and detects potential dangers in real-time, from collision risks to navigational hazards for marine platforms or vessels.
- It can enhance navigational safety for vessel by make sure comprehensive insights to navigate away from hazards and ensure vessels operation in safe waters.
- It can help to optimized traffic flow and use as aids in maintaining a smooth and efficient movement of vessels and minimize delays and improve operational timelines.

Fig 4: AI transforming shipping sector (Manik Tanwar, 2024) [51] and future port operation (All-Forward, 2024) [2]

Benefits of AI in Smart Shipping and Smart Port

The rapid advancement of AI has begun to transform various industries, from healthcare to vehicle, banking, agriculture, finance, industry, transportation, entertainment and many more. One of the most fascinating and potentially radical applications of AI and smart technology is in the dominion of maritime transportation. Smart or autonomous shipping, powered by advanced AI and other smart technologies, is balanced to redesign the future of global trade, commerce, service, and naval operations. Conventionally, maritime transportation is the backbone of international commerce, business, and responsible for the movement of goods across the world by the oceans. However, it is critically importance, the industry faces numerous challenges, including human error, piracy, management, and environmental concerns. Smart shipping aims to address these issues by leveraging AI, ML, DL, blockchain, and other smart technology to create safer, efficient, user and environmentally friendly maritime operations with safety and optimum service (FPGA Insights, 2024 and Hossain, 2025a) [15]. So, AI in smart or autonomous shipping is revolutionizing the maritime industry entirely and bringing significant benefits in terms of safety, efficiency, service, and environmental sustainability. By leveraging advanced technologies like ML, DL, data science, computer vision, and predictive analytics, smart ships can navigate more accurately, avoid collisions, and optimize routes in real time. This reduces human error, lowers operational costs, and minimizes the environmental footprint of maritime industry in general and maritime transportation in particularly. As AI continues to evolve, its role in smart shipping will expand, further enhancing the safety, efficiency, capabilities and resilience of the maritime sector. The ongoing advancements promise to transform global trade, commerce, operation, making it more efficient and sustainable. Embracing these AI or smart technology driven innovations will be vital for stakeholders aiming to stay competitive and navigate the future of maritime operations and management successfully (FPGA Insights, 2024) [15].

AI, ML, DL, data science, and other smart technologies are revolutionizing the freight forwarding industry and driving efficiency, and enabling major cost savings. By leveraging AI algorithms and smart technologies, forwarders can optimize routes, improve visibility, enhance warehouse operations, manage risks, and automate document handling. Implementing these technologies will be crucial for freight forwarders to stay competitive and embrace the future of shipping and maritime business. Again, the implementation of AI and automation also creates or has some challenges. There are a high initial investment costs, data privacy concerns, and the need for skilled personnel to manage and interpret AI systems. As AI continues to advance and new smart solutions emerge, the role of these technologies in freight forwarding will only continue to expand and provide better solution. Forward-looking and positive-thinking forwarders must proactively embrace these advancements and continuously adapt to the evolving technological landscape to secure their position as industry leaders (All-Forward, 2024) [2]. One of the biggest challenges maritime leaders face is managing concerns over AI adoption. Some employees fear job displacement, while others worry about AI and other smart technology's impact on workplace culture (Hossain, 2024d, 2025b) [30, 33]. To successfully integrate AI while maintaining a motivated workforce, maritime leaders must priorities clear and transparent communication. The best organizations will proactively address concerns by explaining how AI will support roles rather than replace them. AI are providing real-world examples of AI augmenting rather than eliminating jobs can go a long way in helping ease uncertainty. Transparent communication, clear career development pathways, and ongoing training will be critical in ensuring AI and other smart technology are viewed as an enabler, not a threat (Splash247, 2025) [72].

AI and smart technology driven predictive analytics optimize shipping routes, reduce fuel consumption, and improve vessel utilization. By analyzing vast amounts of data, AI algorithms identify the most efficient routes, taking into account factors such as weather conditions, sea currents, and port congestion. AI and smart power powered predictive maintenance systems monitor the condition of ship components in real-time, predicting potential failures before they occur. This proactive approach reduces downtime, lowers maintenance costs, and extends the lifespan of critical equipment. Smart ships and AI-based navigation systems enhance safety at sea by reducing human error and improving decision-making. AI algorithms can process real-time data from various sensors to detect and respond to potential hazards, such as collisions and adverse weather conditions. AI models analyze historical data and market trends to provide accurate shipping rate forecasts. This enables stakeholders to make informed decisions regarding fleet management, chartering, and investment strategies (Hossain, 2024e) [31]. AI improves supply chain visibility and coordination, enabling better inventory management, demand forecasting, and logistics planning. This leads to reduced operational costs and enhanced customer satisfaction.

Challenges, Real-World Applications and Future of Smart Technology in Global Shipping

To implementing AI, ML, DL, data science and other smart technologies requires significant investment in hardware, software, and skilled personnel. Small and medium-sized shipping companies may find it challenging to meet the expense of these initial costs. The integration of AI and other smart technologies involve collecting and analyzing vast amounts of data and raising concerns about data privacy, safety, and security. Ensuring that data is protected from cyber threats is crucial for the successful adoption of AI (Hossain, 2025a) [32]. The maritime industry is subject to various international regulations, and the implementation of AI and smart technologies must comply with these standards. Navigating the regulatory landscape can be complex and time-consuming. The introduction of AI and other smart technologies may lead to job displacement for certain roles within the shipping or maritime industry. Training and developing required skill is the workforce to work alongside AI and other smart technologies are essential to mitigate this impact. Companies like Rolls-Royce and Kongsberg are developing autonomous or smart ships that can navigate and operate without human intervention. These vessels use AI algorithms to process data from sensors, cameras, and radar systems to make real-time decisions. Shipping companies are using AI and other smart technologies to monitor the health of critical equipment, such as engines and hull structures. AI algorithms analyze data from sensors to predict when maintenance is needed, reducing the risk of unexpected breakdowns.

AI and other smart technologies driven route optimization systems are helping shipping companies reduce fuel consumption and transit times. Today, Maersk has implemented AI technology to optimize the routes of its container ships, resulting in significant cost savings and better management. Smart port uses AI and other smart technologies to provide accurate shipping rate forecasts, enabling stakeholders to make informed decisions about fleet management and chartering. By analyzing historical data and market trends, AI models predict future shipping rates with high accuracy and better forecast (Pulse, 2024). Today, AI and other smart technologies advances, we can expect to see more autonomous vessels operating in international waters. These smart ships will enhance safety, reduce operational costs, manage effectively, and improve efficiency. Digital technology and IoT will play a significant role in the future of AI in shipping. IoT devices will provide real-time data on vessel performance, cargo conditions, and environmental factors, which AI algorithms will analyze to optimize operations (Hossain, 2025b) [33]. AI will contribute to sustainability efforts in the maritime industry by optimizing fuel consumption, reducing emissions, and enhancing the efficiency of supply chains. AI driven solutions will help shipping companies to meet environmental regulations and achieve their sustainability goals. The future of AI and other smart technologies in shipping and maritime industry will see the development of more advanced predictive analytics tools. These tools will provide deeper insights into market trends, enabling stakeholders to make data driven decisions and stay ahead of the competition.

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. To establishing a narrow range of high-level criteria seems to provide a chance to stabilize the requirements for a 6th generation port over time, while also allowing for the identification of the world's major ports for the next fifty years. 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. The adoption of blockchain technology has improved freight movements' traceability and transparency, building stakeholder trust. 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.

Today, more facets of port operations are incorporating AI. For instance, ML 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 artificial intelligence (AI)-driven algorithms are trained to evaluate and forecast port congestion levels based, for example, on aerial pictures. It might 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, but not all AI is created equal. Therefore, increased usage of AI in the marine industry should be paired with a deeper comprehension of the technology being produced, as well as making sure port management trains and employs it in an efficient and responsible manner. 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. Vehicles, Lorries, and even a handful of the present port administration systems have already been automated by AI. 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 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. ETA forecasting is made possible by AI, which will transform port operations in the long run. 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 and maintenance, human labor (such as dockers or stevedores), materials (such as cranes or handling equipment), administrative duties and paperwork, berth allocation, and port administration overall.

Smart ports need to encompass communities and ecosystems. Smart ports are usually green, digital, and more connected to logistics, industrial environments, and sustainable development resources. They are highly automated ports and are using advanced technologies while caring more for the marine environment. Smart Ports encompass IoT, AI, ML, DL, Big Data, blockchain technology, and 5G or 6G connection. In this era where efficiency, speed, and precision are paramount in logistics, the freight forwarding industry is turning to AI and automation to revolutionize its operations. Such advanced technologies are already shaping the present and future of freight forwarding, in different ways. AI and automation are revolutionizing the freight forwarding industry, driving efficiency, and enabling significant cost savings. By leveraging AI algorithms and automation technologies, forwarders can optimize routes, improve visibility, enhance warehouse operations, manage risks, and automate document handling. Implementing these technologies will be crucial for freight forwarders to stay competitive and embrace the future of shipping. The impact of AI on global shipping is profound, offering numerous benefits such as enhanced operational efficiency, improved safety, and accurate market forecasting. While there are challenges to overcome, the potential of AI to transform the maritime industry is immense. As technology continues to evolve, AI will play an increasingly vital role in shaping the future of global shipping. Companies that embrace AI-driven solutions will be well-positioned to thrive in the dynamic and competitive maritime landscape. The integration of AI in autonomous shipping offers numerous benefits that address some of the maritime industry's most pressing challenges. These advantages range from enhanced safety and operational efficiency to significant environmental and economic impacts. Here are the key benefits of AI in autonomous shipping.

Author

Vice Chancellor of a specialized public university named Bangladesh Maritime University (BMU). Email: kahossain756@gmail.com and admiraldrakhter@bmu.edu.bd

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