

Article

Analysis of Smart Port Practices Across the Globe to Evaluate the Status of Bangladeshi Ports and Future Perspectives

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Abstract

Maritime routes ensure connectivity between nations, carrying a vast flow of goods across borders, while ports serve as the critical junctions within this network, managing a wide spectrum of commodities from raw materials to finished goods. Ports also generate employment across numerous sectors and underpin a broad range of allied industries. A seaport is a maritime facility equipped with docks, cranes, and storage infrastructure for international trade, where ships load and unload cargo, containers, and passengers. Key functions of seaports include customs processing, warehousing, and vessel services, with major global hubs such as Shanghai, PSA Singapore, DP World, and Rotterdam handling immense volumes of cargo each year. In contrast, Bangladesh's ports, Chittagong, Mongla, and Payra, play a vital role in sustaining regional commerce. Today, ports are widely recognized as essential capital infrastructure and prime movers of economic activity. Smart ports are automated facilities that leverage advanced digital technologies, including sensors, big data analytics, artificial intelligence (AI), machine learning (ML), deep learning (DL), augmented reality (AR), digital twins, the Internet of Things (IoT), and various automation systems, to optimize overall operational efficiency. These tools streamline cargo movement while embedding sustainable practices to protect the environment. Beyond operational gains, smart ports deliver faster, more advanced services to all stakeholders involved in port operations, including shipping companies, customs agencies, local communities, and other relevant parties. Renewable energy sources, electric vehicle charging stations, onshore power supply, and smart logistics infrastructure are among the defining sustainability features of smart ports in the present-day context. This study examines the current status and future development trajectory of Bangladesh's sea ports in relation to the broader global imperative toward smart port transformation.

Keywords: smart port; AI; big-data; IoTs; CPA; PCT; Matarbari; Bay Terminal



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1. Introduction

Global trade today moves through a maritime landscape that is larger, faster, and more congested than ever before. Vessels are growing in size, ports are handling rising volumes of cargo, and pressure on port infrastructure is mounting steadily. In this environment, the traditional model of port operations, built on manual coordination and periodic human oversight, is reaching its limits. This shift is part of a broader global movement in which countries are embedding Fourth Industrial Revolution (4IR) technologies into port infrastructure to remain competitive and sustainable [1]. Unlike conventional ports, which rely primarily on manual coordination and fixed procedures, smart ports use interconnected digital systems to sense, analyze, and respond to operational conditions with minimal

human intervention [2]. Smart technology is therefore no longer a competitive advantage confined to a handful of leading terminals; it is fast becoming a baseline requirement for any port that intends to remain relevant in global trade.

This shift matters because ports sit at a uniquely fragile point in the global supply chain. Because so much of world trade now runs on just-in-time delivery and lean inventory, even a short disruption at a major port can ripple outward into fuel and food shortages thousands of kilometers away. Conventional ports, coordinating cranes, storage, customs, and ship servicing largely through manual, sequential decision-making, are increasingly unable to absorb that pressure without delay. It is this specific fragility, not port infrastructure in general, that motivates the shift toward smarter ports.

A smart port applies four interlocking technology families to the daily business of moving cargo: artificial intelligence and machine learning for automated planning and decision-making; the Internet of Things for continuous, sensor-level visibility into equipment, cargo, and vessel movements; big data and analytics for demand forecasting and resource allocation; and high-speed connectivity, including 5G and digital twins, for real-time coordination and scenario simulation. Section 2 examines each of these technologies in detail; what matters here is how, together, they change the basic operating model of a port. Sensors and interconnected devices collect data continuously across terminals, feeding systems that plan berth allocation, track equipment, monitor security, and flag maintenance needs as conditions change, rather than at scheduled review intervals. The result is a port that runs on continuous, automated decision-making, directly addressing congestion, security risk, and environmental impact, the three chronic pain points of conventional port operations. The payoff shows up in cost and efficiency: because smart systems can assess which operations deliver the most value relative to their cost, ports are able to reduce labor and operational expenses without sacrificing throughput, while tighter data integration between ships, cargo handling, and the wider supply chain keeps cargo moving instead of sitting idle. In an industry that runs on tight margins and tighter schedules, this efficiency is what determines which ports stay competitive and which fall behind. The value of these technologies, in other words, lies not in their novelty but in the specific operational problems they solve within a port environment.

A substantial body of recent systematic and bibliometric reviews has already converged on a working definition of the smart port concept, examining its characteristics across operational, environmental, and governance domains [3–6]. This literature is, however, overwhelmingly derived from ports in East Asia, Europe, and the Middle East, where institutional capacity, capital availability, and regulatory maturity differ substantially from South Asia. Comparatively little empirical work examines how smart port technologies are adopted, resisted, or adapted within institutionally constrained, infrastructure-limited settings such as Bangladesh, where port governance, stakeholder coordination, and financing conditions diverge sharply from the contexts in which existing frameworks were developed.

For Bangladesh, this shift is not a distant, abstract trend. Chittagong Port remains the country's principal gateway for international trade, and alongside Mongla and Payra, it anchors a large share of the national economy. As competition among ports intensifies globally, and as automated terminals become standard elsewhere, ports that fail to modernize risk losing relevance within regional and international supply chains. Building smart capabilities into Bangladesh's ports is therefore not simply about keeping pace with technology; it is about protecting the country's position in global trade as the rules of competition change around it. Within this national port system, Bangladesh's ports also span markedly different developmental stages: an established high-volume terminal (Chittagong), a smaller developing port (Mongla), and an emerging greenfield deep-sea port (Matarbari), offering a comparative window that the existing literature has not systematically exploited.

Against this background, this study addresses that gap by examining the institutional, infrastructural, and stakeholder-level barriers and enablers of smart port adoption across these three ports, using primary qualitative evidence rather than relying solely on secondary technological description. Specifically, it focuses on the core enabling technologies, how they are applied at the terminal level, and what this means concretely for the current state and future trajectory of smart port development in Bangladesh. This study addresses several distinct research questions, and the findings provide answers to each of them.

- a. What factors are driving, or constraining, smart port development within Bangladesh's specific institutional and infrastructural context?
- b. What is the prevailing condition of sea ports in Bangladesh?
- c. What growth trends characterize Bangladesh's sea ports?
- d. What ongoing development is taking place at Bangladeshi seaports?
- e. What is the current state of the Matarbari deep-sea port?
- f. What is the scope for future development of Bangladesh's sea ports?
- g. How can Bangladesh's sea ports implement smart technology, given the institutional and stakeholder barriers identified in this study?

2. Literature Review

2.1. Key Enabling Technologies of Smart Ports

The transformation of a conventional port into a smart port relies on a range of digital technologies, each serving a distinct operational function within the terminal environment. Instead of presenting these technologies as a generic collection or reiterating their theoretical definitions, this section examines their practical applications and the specific operational challenges they address at the terminal level. The key enabling technologies are discussed below.

2.1.1. Artificial Intelligence (AI)

Artificial intelligence refers to systems capable of performing tasks that typically require human judgment, such as pattern recognition, planning, and adaptive response [7]. Within a port setting, AI is applied concretely in areas such as automated gate and security screening, where video analytics identify vehicles, containers, and anomalies without manual checkpoints; quay crane and yard equipment scheduling, where AI models sequence lifts and moves to minimize vessel turnaround time; and customs risk profiling, where AI flags high-risk shipments for inspection while allowing routine cargo to clear faster. These are not hypothetical capabilities; they are the operational layer that distinguishes a smart terminal from a conventional one.

2.1.2. Machine Learning (ML)

Machine learning, first introduced by Arthur Samuel in 1959, is a subfield of AI in which systems improve their performance by learning patterns from historical data rather than following fixed rules. In ports, ML is applied to predictive maintenance, where sensor data from cranes and reach stackers, such as vibration or temperature readings, is used to forecast equipment failure before it occurs, reducing unplanned downtime. ML also supports vessel traffic and cargo demand forecasting, using historical Automatic Identification System (AIS) and throughput data to anticipate congestion and inform berth allocation. In cybersecurity, ML algorithms analyze network traffic and documentation patterns to detect anomalies associated with fraud, cargo tampering, or piracy-linked activity.

2.1.3. Deep Learning (DL)

Deep learning, introduced by Rina Dechter in 1986 and substantially advanced by Yann LeCun and colleagues, uses layered Artificial Neural Networks (ANNs) modeled loosely on human cognitive processing to recognize complex patterns in large datasets [8]. In port operations, deep learning underpins computer vision systems that read container numbers through optical character recognition, automatically detect physical damage to containers during handling, and monitor yard congestion through camera feeds. Recurrent neural network variants are also used to forecast vessel arrival times and cargo throughput from time-series operational data, feeding directly into berth and yard planning decisions.

2.1.4. Data Science and Big Data

Data science draws on statistics, computer science, and domain expertise to convert large volumes of raw operational data into structured, actionable information [9]. In a port context, this translates into demand projection models that inform infrastructure investment decisions, real-time dashboards that give terminal managers a consolidated view of vessel, yard, and equipment status, and emissions and environmental reporting that aggregates sensor data to support ESG compliance and sustainability targets.

2.1.5. Internet of Things (IoT) and Digital Twins

IoT connects physical assets—containers, cranes, vehicles, and sensors—into a networked system that reports status in real time. Applied to ports, this includes RFID and GPS-based tracking of containers and equipment across the yard, environmental sensors that continuously monitor air quality, noise, and water conditions, and condition-monitoring sensors on reefer containers and cranes that flag maintenance needs immediately rather than during scheduled inspections. Digital twin technology extends this further by creating a virtual replica of the terminal that can simulate operational scenarios, such as a change in berth allocation or a spike in yard congestion, before any physical change is made, allowing managers to test decisions without operational risk.

Taken together, the convergence of AI, ML, DL, IoT, and data science is what transforms a conventional port into a smart port: a facility capable of continuous, data-driven decision-making across security, maintenance, scheduling, and sustainability functions simultaneously [10]. This convergence, rather than any single technology in isolation, is what determines a port's competitiveness in global trade.

2.2. Research Gap

While prior systematic and bibliometric reviews have established a robust conceptual and technological definition of the smart port [3–6], comparatively little empirical work examines how smart port technologies are adopted, resisted, or adapted within institutionally constrained, infrastructure-limited settings such as Bangladesh. As set out in Section 1, this study addresses that gap using primary qualitative evidence across three Bangladeshi ports at different stages of development, rather than relying solely on secondary technological description.

3. Research Methodology

3.1. Research Design

This study adopts an interdisciplinary, multi-scalar, mixed-methods design combining primary qualitative data collection with secondary data analysis. The qualitative component, comprising focus group discussions (FGDs) and semi-structured interviews, forms the primary evidence base, while secondary sources, including cargo growth projections, government and industry reports, and academic literature, are used to contextualize and

triangulate the primary findings. Chittagong Port and Mongla Port serve as the primary case studies, selected to represent, respectively, an established high-volume container port and a smaller, developing port; Matarbari deep-sea port is referenced as an emerging greenfield case. This case selection was designed to capture ports at different stages of development, and while the empirical focus is Bangladesh, the findings are intended to have broader applicability to other ports across South Asia and the Global South facing comparable institutional and infrastructural conditions.

3.2. Sampling Strategy and Participant Selection Criteria

Participants were selected using purposive, criterion-based sampling, supplemented by snowball sampling for internationally based experts who were reached through referrals from initial contacts. Inclusion criteria required that participants hold a direct professional, institutional, or operational role connected to Bangladesh's maritime and port sector, whether as an operator, regulator, technology provider, service user, or subject-matter expert, and be able to speak knowledgeably to port operations, technology adoption, or maritime policy in a professional capacity. Individuals without direct professional engagement in the sector were excluded. To reduce single-perspective bias and ensure heterogeneity of viewpoints, sampling was stratified across eight functional stakeholder clusters, spanning government and regulatory bodies, shipping lines, agencies and freight forwarders, technical and operational staff, business and finance, digital technology specialists, international experts, and civil society representatives (see Table 1).

Table 1. Summary of Participant Categories and Focus Group Composition.

Stakeholder Cluster	Representative Organizations	Professional Role/Category	FGD Sessions	Participants (n)
Port authorities and government agencies	Chittagong Port Authority, Mongla Port Authority, Payra Port Authority; relevant ministries and regulatory departments	Policymakers, regulators, port administrators	3	30
Global and local shipping lines	Maersk, MSC, CMA CGM, COSCO Shipping Lines, Hapag-Lloyd, ONE, Bangladesh Shipping Corporation	Ship owners, line representatives, fleet planners	3	28
Shipping agencies, freight forwarders and off-dock operators	Sea King Marine Services, SR Shipping, PIL Bangladesh, NYK Line Bangladesh, off-dock and warehouse operators	Agency managers, freight forwarders, warehouse owners	2	20
Port operations and technical personnel	Terminal operators, shipyards (ASSL, WMSL, KSY, BN Dockyard)	Equipment operators, technicians, engineers, workers (skilled/unskilled)	3	32
Business, trade and finance	FBCCI, BGMEA-affiliated exporters, banks, insurers, industry conglomerates	Maritime traders, bankers, insurers, fund providers	2	22
Digital technology specialists and academia	BUET, DU, CUET, KUET, Marine Academies; port IT/digital system vendors	System architects, AI/IoT engineers, faculty, researchers	3	28
International organizations, classification societies and experts	IMO, UNDP, World Bank, JICA, ADB, ABS, BV, NKK; partner universities (WMU, Osaka, Yokohama)	Foreign experts, classification surveyors, multilateral advisors	2	20
Civil society, labour and environmental representatives	NGOs, labour unions, environmental advocacy groups	Labour and environmental rights advocates	2	20
Total			20	200+

3.3. Focus Group Composition and Data Collection Procedures

Data collection took place between March 2024 and May 2026 through 20 focus group discussions and a set of supplementary individual interviews conducted where scheduling did not permit group participation. Each FGD comprised 6 to 10 participants drawn from

within a single stakeholder cluster to encourage open discussion among peers, and sessions were held online or in person depending on participant availability and location. In total, more than 200 individuals took part. Every session followed a consistent semi-structured guide (Appendix A), administered by the same moderator to maintain procedural consistency across sessions. Sessions were conducted in Bengali, English, or a mix of both depending on participant preference; sessions were audio-recorded with participant consent and transcribed, and where recording was declined, detailed contemporaneous notes were taken instead. Bengali-language transcripts were translated into English and checked for accuracy against the original recordings.

3.4. Ethical Considerations

This study engaged adult professionals on institutional, operational, and policy matters within their professional capacity, involving no vulnerable populations or sensitive personal information. It was therefore classified as a professional consultation rather than human-subjects clinical research, and formal ethics board review was not procedurally required. Given the scale of engagement—over 200 participants across 20 focus groups and supplementary interviews—informed consent was obtained from every participant, who were briefed on the study's purpose, voluntary participation, their right to withdraw, and anonymization of their responses. Findings are reported without attributing views to named individuals, with organizations referenced only where their role is already public record. This classification, consent protocol, and anonymized reporting together met the substantive standards of ethical engagement despite the absence of formal review.

3.5. Data Analysis: Thematic Analysis and Coding Procedure

Qualitative data were analyzed using thematic analysis following Braun and Clarke's six-phase framework. The transcripts were read repeatedly to identify meaningful patterns, and initial codes were developed inductively. Similar codes were grouped into broader themes corresponding to the study's research questions. The coding framework was refined iteratively throughout the analysis to ensure consistency and accurately represent participants' views.

3.6. Ensuring Credibility and Trustworthiness

The credibility of this study was enhanced by collecting data from diverse stakeholder groups across Bangladesh's port sector and comparing the findings with relevant academic literature, government publications, and industry reports. The researcher reviewed the transcripts repeatedly to identify recurring patterns and develop themes consistent with the study's objectives. As a qualitative study based on purposive sampling, the findings are intended to provide analytically grounded insights into smart port development in Bangladesh rather than statistically representative results. Illustrative graphics used in Section 6 that were AI-generated or otherwise not source-verified are labeled as such in their captions and are included solely for conceptual visualization; they are not presented as empirical or source-validated technical evidence.

4. Paradigm of Smart Ports and Its Performance

Smart ports are an integral node in the rapidly developing ecosystem of smart cities. These high-end ports utilize technological breakthroughs (blockchain, AI, ML, DL, DS, IoT sensors, computerization, DS, and real-time data analytics, etc.) for providing sustainable solutions to traditional problems and subsequently augment resource efficiency, minimize environmental impact and assist seamless operations. Innovations like these support oversight, cargo handling, vessel locomotion in real time and accommodation. Predictive analytics, IoT-enabled sensors, robust communication networks, cybersecurity frameworks,

and integrated supply chain platforms are some of the other features smart ports may integrate for flawless connectivity. In addition, digital twin technology, augmented reality (AR), virtual reality (VR), and interoperable systems may be used to ensure collaboration among diverse stakeholders. Today's smart ports are more effective, more efficient, more economically competitive and sustainable. Moreover, present days smart Ports consider residents a key stakeholder in their activities, connections, and operations. They use real-time information, a collaborative management approach, ensure safety and security, save energy, ease operation and help to decision making. Today's smart ports are green, digital, and well connected to logistics, industrial environments, related stake-holders and sustainable development resources. Those automated ports use advanced and sophisticated technologies that are very friendly to the environment and ecosystem.

Installing adequate infrastructure for smart ports requires the establishment of mechanized berths furnished with advanced mooring systems along with prioritizing advanced security. Further transformation of smart ports incorporates the rigorous assessment of capabilities that are a part of the port management software, such as yard management, berth scheduling, and terminal operating systems (TOS). In order to guarantee secure cargo flow, safety, security, and environmental sustainability, the port authority must emphasize the regular upkeep of infrastructure elements and support services. Shared stakeholder platforms, digitalization strategies, and the implementation of port community systems (PCS) highlight the inclusion of digital innovations, which expedite collaboration and transparency among clients, into smart port systems. Central port functions like cargo handling, customs processing, and vessel scheduling are made coherent and seamlessly harmonized combining several advanced technologies. For maximizing operational throughput, the Port Community System (PCS) is core to this combination. It fosters transparency and synchronizes port functions, thus improving the movement of cargo. PCS also enhances data exchange and joint ventures among vital stakeholders such as port authorities, shipping companies, terminal operators, customs agencies, and logistics providers. Crucial port properties are undergoing proactive maintenance to improve their durability and thus ideal asset management is ensured using progressive technologies. For instance, RFID tags, sensors and GPS tracking systems are utilized by modern asset management systems to oversee the operational health, position and output of motorized vehicles, containers and supporting infrastructure. Reinforced by advanced algorithms, preemptive upkeep strategies like predictive maintenance are employed to make port operations safe and dependable. This AI-driven application scrutinizes sensor data, maintenance history, and equipment performance to forecast equipment failures before they occur. Therefore, designated and timely action can be taken to reduce downtime and subsequent financial expenditures.

As shown in Figure 1, modern maritime port operations greatly rely on energy-efficient technologies to address operational bottlenecks and substantially curb carbon footprints. High-efficiency HVAC (Heating, Ventilation, and Air Conditioning) systems, modernized lighting, and micro-grid architectures are becoming a staple in smart ports. These digital apparatuses foster environmental stewardship, optimize electricity usage, mitigate peak demand, reduce operational utility costs and incorporate renewable energy sources. High-definition video cameras, perimeter intrusion detection systems, intelligent video analytics and sophisticated access control mechanisms flag anomalies and other security risks by observing exclusion zones and safeguard the port premises by alerting security personnel in real time. RFID tags, GPS trackers, and blockchain technology monitor cargo, vehicles and goods [11], which improves supply chain visibility. Optimized inventory management, limited larceny and live updates on shipment conditions are a direct outcome of implementing these technologies. In parallel, vehicular and cargo movements are monitored and coordinated using intelligent traffic management systems.

Traffic congestion and operational delays are optimized using these systems by tracking vehicle coordinates and managing truck queues, parking allocations and gate entry. For bridging communication gaps and enhancing collaboration by accumulating data from multiple stakeholders, including terminal operators, shipping lines, customs authorities, and logistics providers, a centralized port operations platform is utilized. A combination of mobile communication platforms, GIS mapping, and automated alert systems lies at the core of the crisis response system. These assist the port management in reacting instantly to emergency situations, protecting port personnel and undertaking appropriate measures during unexpected events.



Figure 1. A smart port and its unmanned activities. Adapted from Refs. [12,13].

5. Maximizing the Efficacy of Smart Port Infrastructure

Two structural pressures make efficacy, not just capability, the central question for smart port infrastructure. First, vessels are growing steadily larger, a trend accelerated since the arrival of post-Panamax containerships, and every additional meter of beam or draft increases the cost of an inefficient turnaround. Second, conventional port supply chain systems still rely on isolated data sources and static forecasting, which leaves terminals reacting to congestion after it forms rather than preventing it. Interactive dashboards, built on a four-pronged data model of storage, interaction, visualization, and security, address this directly by consolidating data from multiple streams into a single real-time view of supply chain movement. Adopting this kind of system is not a plug-and-play upgrade: it follows a structured procurement path, a Request for Information (RFI), a Request for Proposal (RFP), vendor selection, and pilot deployment, before it replaces the rigid, manual workflows of a conventional terminal.

Maximizing efficacy, in practice, means treating the components below as a coordinated portfolio rather than isolated upgrades:

Automation and Control Systems: Smart ports rely on mechanized technologies and robotics to amplify and refine port machinery. Remote-controlled cranes, automated guided vehicles (AGVs), smart mooring mechanisms, and automated container handling are central to this automated revolution.

Labor Relations: The high tendency of smart ports to rely on automation instead of manual labor makes labor relations more complex. Wage discussions and working-condition complexities must be neutralized by port management through a deliberate balance of automation technology and human labor.

Regulatory Compliance: Directives and legal mandates regarding port operations are continuously updated with sustainability and efficiency in mind. It is incumbent on the concerned authority to remain compliant and update regulations in a timely manner.

Supply Chain Integration: Ports are critical focal points in the global supply chain ecosystem; thus, they must synchronize their workflows with key logistical operations such as warehousing, distribution, and transportation. Procedural and technological dissimilarities among stakeholders, however, frequently complicate smooth integration.

Smart Terminal Operations: Adopting automation has become the norm for smart port terminals, as efficiency, workload management, security, and financial dealings all require urgent optimization. Relevant technologies include cargo handling systems, AGVs, and automated stacking cranes.

Collaborative Ecosystem: Partnerships and joint ventures among port authorities, shipping companies, and logistics firms are important for improving synergy. Innovative ideas and data exchange are a direct outcome of this collaboration.

Enhanced Safety and Security: Safety and accountability are major functions of port authorities, ensuring personnel protection, asset management, and cybersecurity. Key technologies in this regard include fencing systems, biometrics, integrated surveillance networks, and strengthened network firewalls.

Asset Management Solutions: These systems supervise the operational health of critical port infrastructure, including terminals, cranes, warehouses, and berths. Proactive maintenance and scheduled, timely checkups enhance proper usage and sustained performance.

Remote Monitoring and Control Systems: Centralized supervision and administration of port devices and components is possible through these tools. Regular, timely updates on operational data, equipment management, and secure handling of remote technologies further enhance seamless operation.

Digital Documentation and Port Community Systems: Port Community Systems (PCS) and national single-window platforms integrate customs, terminal operators, shipping lines, and freight forwarders into one digital interface, replacing duplicate manual filings with a single electronic submission [14]. The Port of Singapore's digitalPORT@SG platform, for instance, consolidates trade documents from multiple regulatory agencies into one standardized interface to shorten clearance times [15], while the Port of Hamburg's PCS, connecting more than 2500 companies, has served as a live testbed for blockchain-based paperless clearance since 2018 [16]. Evidence from Indian inland container depots similarly links PCS adoption to measurably faster documentation processing, though digital-literacy gaps among smaller stakeholders remain a limiting factor [17].

Predictive Maintenance Analytics: Machine learning models trained on sensor data, vibration, temperature, and load cycles, from quay cranes, rubber-tyred gantries, and AGVs, can flag component degradation well before failure occurs, allowing maintenance to be scheduled around actual equipment condition rather than a fixed calendar. A 2025 study using real operational data from a European container terminal found that such condition-based approaches meaningfully improve fault-prediction accuracy over traditional inspection schedules [18], and industry deployments report substantial reductions in unplanned crane downtime once these systems are operational [19].

Blockchain-Enabled Trade Documentation: Blockchain-based smart contracts allow bills of lading, customs declarations, and cargo manifests to be issued, verified, and updated on a shared, tamper-evident ledger rather than passed through paper or siloed digital copies. Academic case studies of port-level bill-of-lading workflows show this reduces document-cycle delays and lowers the risk of fraud or unauthorized alteration [20,21], and ports such as Rotterdam have used blockchain pilots to cut administrative turnaround time in live operations [22].

Cybersecurity and Cyber-Resilience Frameworks: As ports digitize, their attack surface expands in step with their operational capability, since cyber-physical systems that control cranes, gates, and berth scheduling become potential intrusion points [23]. A re-

silient smart port therefore pairs its automation investment with layered defenses, network segmentation, multi-factor authentication, and structured incident-response protocols, since analysis of recent port-sector incidents shows that legacy systems and fragmented governance, rather than a single point of technical failure, are the most common source of exposure [24].

Shore Power and Renewable Energy Integration: Managing energy consumption is core to sustainable development, which ports increasingly pursue through electric vehicles, LED lighting, and energy-efficient machinery. A particularly consequential measure is cold ironing, or shore-to-ship power, which allows a berthed vessel to shut down its diesel auxiliary engines and draw electricity from the shore grid instead. Optimization studies combining cold ironing with port microgrids and renewable generation have demonstrated reductions in berth-side emissions exceeding 90% for pollutants such as NO_x and SO_x when the shore power itself is drawn from clean sources [25], and real-port case studies report cold ironing can cut berthed-vessel energy costs by up to 75% relative to onboard diesel generation [26]. Ports can further diversify on-site generation through solar panels on unused rooftops, geothermal heating, hydroelectric capture from natural water currents, and biomass conversion, reducing dependence on grid electricity that may not itself be low-carbon [27,28].

5G and Private Network Connectivity: Automated cranes, AGVs, and terminal operating systems depend on sub-millisecond, high-reliability communication that conventional Wi-Fi struggles to sustain across large metal structures and constantly moving equipment. Private 5G networks address this directly: Shanghai's Yangshan Port coordinates over two dozen bridge cranes, more than a hundred automated guided vehicles, and over a hundred rail-mounted gantry trains on a private cellular network, supporting its status as the world's largest automated container terminal [29], while the Port of Antwerp and the Port of Liverpool have each deployed private 5G to automate key terminal activities and give real-time visibility into logistics movements across the yard [30,31].

Digital Twin-Based Scenario Simulation: Beyond the general sensing role of IoT, digital twins deliver efficacy specifically by letting terminal operators test scheduling and berth-allocation changes virtually before committing to them physically. A digital twin developed for a major South Korean container terminal has been used to model chained vessel-terminal scheduling and reduce the idle time and emissions caused by siloed decision-making among shipping stakeholders [32], and a related framework built for a national port authority has applied digital twin simulation to vessel tracking, terminal schedule optimization, and truck-flow management to ease yard congestion [33].

Together, these measures indicate that maximizing the efficacy of smart port infrastructure is not reducible to any single technology, but rather to how automation, documentation, maintenance, connectivity, security, and energy systems are integrated and sequenced. Ports that treat these as a coordinated portfolio, rather than isolated pilot projects, are best positioned to convert digital investment into measurable operational and environmental gains.

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

Artificial intelligence plays a pivotal role in contemporary maritime logistics, optimizing smart port and terminal operations, particularly through robotics. AI has already demonstrated transformative capacity in sectors such as healthcare, finance, and pharmaceuticals [34]; its adoption in smart ports is driven largely by the urgent need to decarbonize global supply chains and advance sustainability. Maritime operations such as towage, pilotage, and cargo movement are increasingly influenced by AI, which streamlines these processes considerably. Machine-learning predictive models are central to this shift,

analyzing historical data to forecast task durations for specific vessels and service requirements with high accuracy [35]. Variables such as vessel-specific pilot licensing, optimal tugboat configuration, and the logistical deployment of pilots to boarding stations are refined through these predictive insights, given the complexity of the underlying scheduling problem, allowing critical port resources to be allocated more effectively [36]. Although the proliferation of experimental programs and pilot projects makes AI's contribution to smart ports increasingly evident, further empirical research remains necessary to evaluate current practice and chart future trajectories [37]. AI's potential to transform maritime management can be organized around the following dimensions:

- Analyzing spatial-temporal traffic patterns and using predictive modeling on vessel arrival vectors can ensure proper marine traffic management. This helps with proactive traffic coordination, efficiently handling anchorage congestion and berth allocation.
- Systemic latency and workflow bottlenecks can be pinpointed through continuous monitoring of data streams during loading and unloading phases. Addressing these friction points coordinates scheduling and other disparate operations.
- IoT sensor networks are utilized to supervise terminal equipment to ensure asset reliability. Thus, operational flaws can be detected early to reduce downtime and increase operational resilience.
- Predictive insights regarding cargo handling operations help operators to anticipate resource requirements, minimize delays and develop container yard storage facilities.
- Various anomalies and security threats can be detected through surveillance cameras and sensors. Thus, industrial accidents can be prevented and global supply chain security is safeguarded.

As shown in Figure 2, AI increasingly underpins fully autonomous port operations, with the structural framework of these facilities built largely around AI-based applications. As global logistics enterprises turn their focus toward AI, the shipping and maritime sectors are being reshaped accordingly. The pervasive deployment of AI and ML algorithms enables the analysis of diverse operational variables and, in turn, improves ship arrival sequencing. This structured approach increasingly mitigates harbor congestion while reducing the carbon footprint associated with idling vessels. ML makes a particularly significant contribution to berth allocation, a highly complex constraint problem spanning multiple dimensions, including vessel size, hull classification, ship-to-shore crane availability, and shore-power infrastructure capacity [38]. As the maritime industry moves toward renewable energy, vessels arriving at port will present increasingly diverse servicing requirements, further underscoring the need for computationally efficient berth allocation to sustain port throughput.



Figure 2. AI will transform ports and AI will make ports more intelligent. Adapted from Refs. [35,37]. These are AI-generated conceptual illustrations compiled for visualization purposes only and are not source-validated technical drawings.

AI technologies support real-time performance diagnostics, forecast estimated times of arrival, and enable the construction of high-fidelity digital twins—virtual replicas of port operations that enhance oversight and supervisory control. AI-assisted analysis of aerial imagery may soon allow terminals to monitor and predict traffic congestion while accounting for environmental sustainability [39]. AI and ML, which already support sustainable maritime practices such as just-in-time arrivals, can work alongside predictive congestion modeling to advise incoming vessels on speed adjustments dynamically, reducing fuel costs while mitigating environmental impact. Modern AI-driven platforms depend heavily on the extensive datasets generated by IoT sensors deployed across ports and the wider shipping industry [19]; to derive maximum value from AI, ML, and DL architectures, the global supply chain must supply high-quality, uncorrupted data. Automated systems rely extensively on AI to manage horizontal freight movement and govern terminal operating systems, while AI-guided automated guided vehicles (AGVs) improve cargo movement under centralized management. Even as AI increasingly streamlines the autonomous and mechanized control of port operations, human oversight remains indispensable to supervising these systems.

AI has evolved from an experimental framework into a central pillar of smart port development. At the Port of Rotterdam, for instance, the AI model Pronto enhances the synchronization of container throughput by analyzing multiple data streams—including real-time vessel telemetry from Automatic Identification Systems (AIS) and port authority databases—to build self-learning, adaptive models. Data from the Rotterdam Port Authority indicate a 20% reduction in vessel detention periods as a result. Through these self-learning models, Pronto's machine-learning components improve forecasts of vessel arrival times and container processing intervals, raising the overall efficiency of port logistics and operations. In North America, the Port of Los Angeles has deployed a comparable predictive AI platform, Port Optimizer, which uses sensor networks and predictive analytics to streamline container scheduling and other port operations, anticipate future demand, and support proactive management. Singapore's Maritime Single Window serves a similar function in Southeast Asia, expediting customs and maritime immigration clearance; rather than relying on sensor networks, it applies natural language processing (NLP) alongside predictive analytics to improve transparency and processing speed, with ML subroutines categorizing and translating unstructured data from customs and shipping documentation to support macroeconomic port governance [40]. Together, this expanding integration of AI has produced several foundational benefits for maritime operations, including:

- **Data Availability Evaluation:** Since AI-driven platforms depend heavily on the quality of their underlying data, port authorities must ensure data availability through dedicated data-harvesting pipelines that eliminate gaps and capture data streams across the supply chain.
- **Operational Efficiency:** AI models can diagnose systemic latencies and identify their underlying causes, improving terminal productivity. Future generations of AI are expected to refine maritime shipping routes, optimize automated cargo handling, and help identify illicit activity.
- **Infrastructure Assessment:** Deploying advanced algorithms requires a thorough evaluation of existing infrastructure, a process AI itself can support. Existing computational assets, storage capacity, and network bandwidth must be adequate to support AI integration into smart ports.
- **Team Formation:** Effective human-machine co-management is essential to the transition from manually operated systems to automated ones. AI integration accordingly drives the formation of dedicated cross-functional teams to manage these systems [40].

- **Investment Analysis:** Large-scale digital deployment comes with financial risks, which can be pinpointed by AI predictive models. Thus, shareholders can analyze and invest accordingly.
- **Strategic Partnerships:** Collaborative alliances between expert AI firms allow ports to manage technicalities which integrate more software while developing onsite proficiency.

Integrating AI into the smart port ecosystem requires rigorous planning, implementation, and systematic evaluation, since not all AI platforms are equally effective. AI systems analyze the vast volumes of data generated by port operations using advanced algorithms modeled loosely on patterns of human cognitive processing. This capability has already enabled automated port operations through mechanized technologies such as autonomous cranes and trucks at the Port of Los Angeles and AI-powered operations at the Port of Rotterdam. AI-driven predictive analytics have advanced considerably in accurately forecasting a ship's Estimated Time of Arrival (ETA), a meaningful milestone given how frequently vessels currently arrive later than scheduled. Without AI-based intervention, the maritime sector faces considerable unpredictability: a 2020 report by the Danish firm Sea-Intelligence found that carrier on-time reliability across 34 global trade routes had fallen to just 50.1%—a level of disruption comparable to roughly half of all commercial flight arrivals being delayed by 24 h. Retrofitting port infrastructure with AI-driven software enhances logistical visibility, enabling stakeholders to analyze complex datasets to improve scheduling, cargo handling, and freight movement management. Nevertheless, integrating AI into daily port operations remains complex, owing to deeply embedded industry practices, heavy reliance on data quality, and a lack of established technical standards, all of which require AI models to be customized to specific port requirements [41]. Close collaboration between port authorities and AI professionals is therefore essential to developing standardized, adaptable measures capable of addressing the full breadth of the maritime network.

Several other leading shipping enterprises are similarly transforming the maritime landscape through AI, ML, and DL. Maersk, an industry pioneer, has developed Captain Peter, an AI model that optimizes fuel economy while addressing sustainability concerns. Likewise, CMA CGM has introduced Smart Containers, which enhance transparency through a client-friendly interface that allows customers to track the precise location of their containers along with associated environmental conditions. Hapag-Lloyd and MSC are advancing comparable capabilities: Hapag-Lloyd applies AI to identify the most cost-effective maritime routes based on meteorological and traffic data, while MSC's 'Safeguard' platform uses ML and data from multiple sources to issue safety alerts and help prevent adverse incidents. Evergreen Line's predictive-maintenance devices similarly anticipate equipment issues before mechanical failure occurs, and the company has developed a frictionless tracking interface that provides customers with instantaneous cargo-location information upon presentation of the relevant shipping credentials (e.g., booking reference, master bill of lading).

Unlike conversational applications of AI, where some scope for experimentation is tolerable, the margin for error is virtually nonexistent in matters of maritime safety and operational reliability. Achieving this level of reliability requires AI and ML models to be meticulously trained on tailored datasets against rigorous performance benchmarks, within a validation and feedback loop that compares projected timelines against each port's actual operational durations. This process allows the underlying algorithms to evolve and adapt to each port's specific requirements. Such precision has become increasingly necessary given the dramatic surge in container volumes that now shapes global maritime dominance. Historically, European and North American ports held the leading positions in global

shipping, as confirmed by 2005 data; by 2021, however, only the Port of Rotterdam remained among the world's top ten [23]. Data from the Hong Kong Marine Department lend support to the view that China has emerged as the new leader in the maritime sector, having set a new benchmark in modern shipping through the successful integration of advanced AI and digital infrastructure into its ports' administrative and operational functions [42].

As shown in Figure 3, Singapore's Port Authority (PSA) has introduced blockchain-based customs processing, AI-assisted berthing, and real-time port dashboards, contributing to a 30–40% reduction in processing time and a substantial reduction in costs [24]. Ports in the Netherlands, Australia, and China are adopting fully automated terminals that combine AGVs, AI-guided cranes, digital twins, IoT, and autonomous drones for monitoring, surveillance, and decision-making; these innovations have collectively reduced labor costs while improving performance, safety, and security standards [43]. China's Yangshan Port and Australia's Victoria International Container Terminal (VICT) are leading the sector's conversion to "Port 4.0," a roadmap guiding the industry's transition toward fully autonomous ports and, in turn, significantly lower operating expenses [44]. Rotterdam, meanwhile, has established a full-scale digital twin ecosystem that functions as a virtual, four-dimensional replica of its entire port operation. This infrastructure integrates real-time IoT sensors, weather data, and shipping information to continuously mirror real-world conditions and simulate future scenarios, supporting predictive cargo flows, activity monitoring, and emissions tracking, with corresponding gains in customer service and environmental performance [45]. Busan Port, for its part, is undertaking a major, multi-million-dollar AI-driven port transformation to position itself as a global smart-logistics hub in Asia, integrating real-time data, IoT, and ML across terminal operations and applying big-data analytics to forecast congestion patterns and optimize routing as it shifts toward predictive operations [46]. Ports such as Hamburg and Long Beach deploy IoT sensors to measure emissions in real time and use AI to adjust operations accordingly—practices increasingly demanded along eco-sensitive trade routes.



Figure 3. Smart ports will be a game changer in any hub of the world. Adapted from Ref. [43]. The right-hand panel is an AI-generated conceptual graphic compiled for illustration only, not a source-validated technical drawing.

7. Present Status of Bangladesh Sea Port

Bangladesh's sea ports are currently undergoing a significant phase of modernization and transformation. Chittagong Port handles over 90% of the nation's trade, while Mongla and Payra Ports are steadily expanding capacity. Key developments include the Matarbari Deep-Sea Port and the Bay Terminal, both aimed at increasing efficiency and reducing congestion. Chittagong Port is Bangladesh's main gateway and one of the busiest ports in South Asia, handling 98% of container trade and 90% of total export-import trade; the government has engaged foreign operators, primarily through Memoranda of Understand-

ing (MOU), including Denmark's APM Terminals and the Swiss firm Medlog, for terminal management to improve efficiency. Mongla Port serves as the country's second-busiest port, located in the southwestern region. Matarbari Deep-Sea Port, situated in Cox's Bazar, is under development as Bangladesh's first deep-sea port; designed to handle large, deep-draft vessels and built with Japanese support, it is expected to substantially enhance the country's maritime trade capacity. Payra Port, located in Patuakhali, is being developed to ease the operational burden on Chattogram Port, with major upgrades expected to be fully operational by 2027. The Bay Terminal—comprising three container terminals and thirteen jetties—aims to reduce congestion by accommodating ships of up to 6000 TEUs, including vessels with a draught exceeding 12 metres. Bangladesh's sea ports have historically faced congestion, at times exacerbated by political instability and flooding, resulting in supply-chain disruptions. Accordingly, current efforts remain focused on expanding terminal capacity and developing new, deeper ports to support the country's growing maritime trade, particularly given continued growth in the apparel and other export sectors.

Chittagong Port is Bangladesh's principal seaport and a vital economic engine, handling 92% of the nation's total seaborne trade and roughly 98% of its containerized trade. Operated by the Chittagong Port Authority (CPA) and administered by the Ministry of Shipping (MOS), the port's history extends as far back as the 4th century BC. It developed through British colonial governance under the Port Commissioner's Act of 1887 and began its modern institutional existence in 1960 as the Chittagong Port Trust; following the Liberation War, it gained semi-autonomous status and was renamed the Chittagong Port Authority in 1976. Given the strategic importance of the landlocked regions surrounding Bangladesh—Northeastern India, Nepal, Bhutan, and parts of Myanmar and China—the Port of Chittagong, with adequate inland connectivity, has the potential to serve as a shipping link connecting the wider region to the rest of the world. While it is unlikely to become an international hub, given natural constraints and its distance from major international sea routes [47], the port has considerable potential to develop into a major regional hub. Chittagong Port nonetheless faces a capacity constraint and must expand to accommodate the growing volumes of containers and other cargo anticipated in the coming years.

Chittagong Port achieved record performance during January–December 2025, handling 3,409,069 TEUs of containers, 138.15 million metric tons of cargo, and 4273 vessels. According to the Chittagong Port Authority (CPA), this represents substantial growth over 2024, with container handling rising by 4.07%, vessel handling by 10.5%, and cargo throughput by 11.43% [22]. Although limited automation, customs delays, strikes, and political unrest slowed operations at points during the year, the port nonetheless stabilized its performance and continued to expand its role as an indispensable part of the national supply chain—reflected in a 13.2% increase in bulk cargo and a 6.02% rise in container volume, with total cargo handled reaching 138.15 million metric tons. Despite these technological and political headwinds, Chittagong Port's growth did not falter in 2025; vessel-holding durations were, in fact, optimized. During January–November 2025, average vessel turnaround time improved to 2.53 days and average container dwell time to approximately 9.44 days, marking a substantial improvement in port lead time. This progress enables importers and exporters to trade considerably more efficiently, with anticipated reductions in logistics overheads expected to drive export competitiveness and yield substantial benefits for the Readymade Garments (RMG) sector [22].

As shown in Figure 4, Chittagong Port's continued cargo volume growth mirrors the nation's broader economic expansion, as it is the main maritime gateway. Containerized traffic in the port registered an 11% growth rate while overall port throughput grew at a rate above 8% across the last decade. The port is forecasted to undergo an increase in container handling, evolving from 2.7 million TEUs in 2017–2018 to 10.7 million TEUs by 2043 under

baseline economic growth forecasts. Hence, substantial capital investment is essential for increasing its capacity and optimizing operational performance, given its pivotal role and systemic importance in the Bangladesh economy. The statistics of cargo, container and vessel handling by Chittagong Port during 2024 and 2025 are shown in Table 2, and the growth of cargo, container and vessel handling by Chittagong Port for the last two years is shown in Figure 5 below:



Figure 4. Geographical locations of existing sea ports of Bangladesh. Prepared by the author.

Table 2. Cargo, container and vessel handling by Chittagong Port during 2024 and 2025.

Calendar Year	Cargo (In M/Ton)	Difference	Container (In TUEs)	Difference	Vessel (In No)	Difference
2024 (Jan–Sep)	91,950,584	10,753,675	2,441,825	121,625	2864	297
2025 (Jan–Sep)	102,704,259		2,563,450		3161	
Growth (%)	11.70%	-	4.98%	-	10.37%	-

As shown in Figure 5, Mongla Port, situated in Mongla Upazila, Khulna, is historically recognized as a premier maritime hub of the Bengal delta. It is Bangladesh’s second-largest seaport and lies in close proximity to the Bay of Bengal. Founded in 1950 on the Pashur River in Khulna Division under the original name Chalna Port, it serves the southwestern region of East Bengal. With Chittagong Port continuing to face congestion, several maritime enterprises now favor Mongla as a strategic and increasingly economical alternative; the construction of the Padma Bridge has further strengthened its commercial viability alongside growing domestic and regional demand. Beyond its commercial functions, Mongla Port serves as a gateway for tourists, providing access to the Sundarbans, a UNESCO World Heritage mangrove forest. The port hosts the Mongla Export Processing Zone (MEPZ) and comprises 11 jetties, 8 warehouses, and 12 deep-river swinging moorings. Operating 24 h a day, seven days a week, it has an unconstrained anchorage channel capable of accommodating up to 33 ships simultaneously, and can handle vessels up to 225 metres in length with a maximum draught of 6 metres.

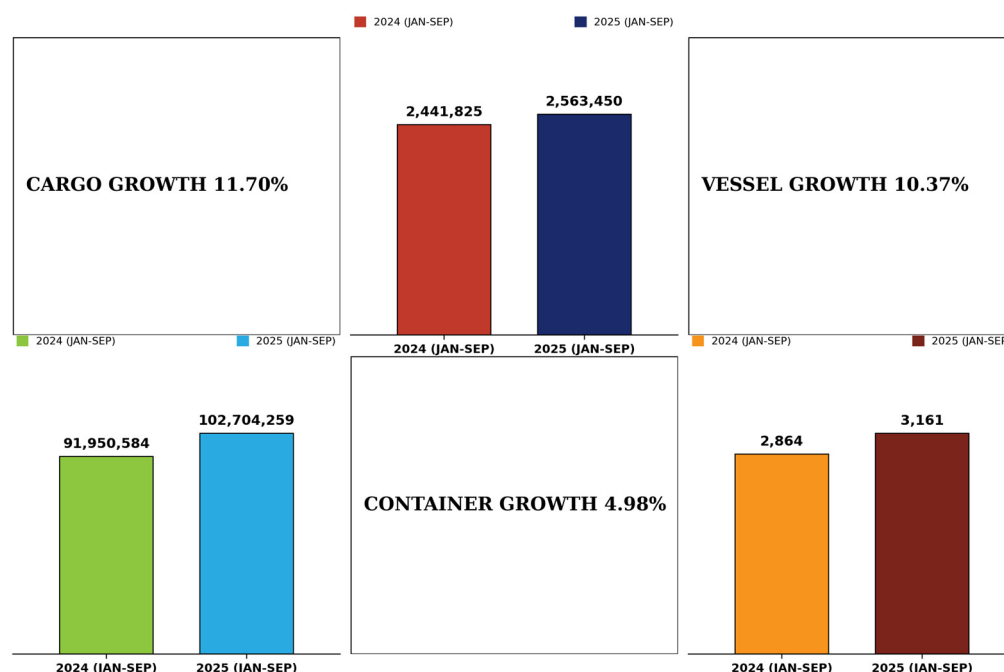


Figure 5. Growth of cargo, container and vessel handling by Chittagong Port over the last two years (2024–2025). Prepared by the author.

Payra Port was legislatively established in 2013 by an Act of Parliament and formally inaugurated in 2016. Located in Kalapara Upazila, Barisal Division, it lies in close proximity to the Bay of Bengal. To secure deep-sea access for the under-construction port, the Payra Port Authority (PPA) partnered with the Belgium-based dredging company Jan De Nul (JDN) to oversee capital and maintenance dredging of its 75-kilometre main channel. JDN completed capital dredging operations in March 2023, opening the port access channel to commercial vessels with a draught of up to 10.5 metres. The project has since entered its maintenance phase, in which JDN deploys three trailing suction hopper dredgers to the Rabnabad Channel to sustain the required navigational depths. The port is central to the nation's maritime trade strategy, with plans to develop it into a major economic hub through modern terminals, deeper channels for larger vessels, and enhanced cargo-handling capacity. Despite ongoing challenges with navigability and operational efficiency, authorities continue to address these issues through infrastructure development and dredging.

8. Bangladesh's Port Infrastructure and the Case for Smart-Port Investment

Bangladesh's rapid economic growth has placed increasing pressure on its seaport infrastructure, which remains the country's primary channel for imports and exports. As South Asia's second-largest economy, Bangladesh depends heavily on trade-driven sectors—most notably ready-made garments (RMG), which account for over 80% of total exports—making efficient port operations a direct determinant of national economic performance. Yet despite this dependence, none of Bangladesh's ports currently meet the standard of a fully automated “smart port,” a gap that grows more consequential as cargo volumes rise and international shipping demands intensify.

This gap is visible even amid recent gains. As of early 2026, Bangladesh's sea ports have posted record-breaking performance: Chattogram Port, for example, recorded its highest-ever cargo and container volumes in 2025, aided by efficiency improvements and reduced vessel waiting times. But these improvements are incremental rather than

structural, and the port continues to face limitations that manual, non-digitized operations impose at scale.

The scale of the challenge is evident in forward projections. The Chattogram Port Authority forecasts that the port must handle 8.63 million TEUs annually by 2035, rising to 11.41 million TEUs by 2040 (Table 3, Figure 6). Meeting this demand will require not only physical upgrades—deeper drafts and extended berths to accommodate larger Panamax and post-Panamax vessels—but also improved transportation links and, critically, the digitization and smart-technology integration needed to cut turnaround times and reduce delays. Several upcoming port projects are expected to come online in the near term and should contribute directly to this capacity growth.

These figures are published capacity-planning targets from the Chattogram Port Authority and associated infrastructure planning documents, built up from the phased delivery schedules of specific terminal projects—including the Bay Terminal, the Patenga Container Terminal, and Matarbari Port—rather than derived from a disclosed statistical or trade-elasticity forecasting model. As such, they represent planned capacity rather than an independently modeled demand forecast. Given the 14-year horizon, actual volumes will depend on the on-schedule completion of these projects, sustained trade growth, and stable regional shipping demand, and could diverge materially from the projected figures. We treat these numbers as directional indicators of expected growth and infrastructure need rather than precise predictions.

The projections in Table 3 should be read with three further caveats regarding their derivation. First, the per-port allocation of volume (e.g., the split between GCB/CCT/NCT, PCT, the Bay Terminal, and Matarbari) reflects the individual capacity design of each terminal as published in project planning documents, rather than a modeled distribution of expected trade flows across facilities—actual allocation will depend on shipping-line routing decisions, tariff structures, and relative operational efficiency once these terminals are operational. Second, the historical data period underlying the base-year figures (2027) is not separately disclosed in the source material; we treat 2024–2025 CPA-reported throughput as the effective baseline, consistent with the volumes cited earlier in this section. Third, because the published figures represent a single deterministic trajectory rather than a probabilistic forecast, we do not treat them as a precise prediction. Where authors have access to the underlying growth assumptions, we recommend presenting baseline, conservative, and high-growth scenarios (for example, ± 15 –20% around the published baseline by 2035 and 2040) to reflect the compounding uncertainty of infrastructure delivery timelines and trade-demand growth over a 14-year horizon; we note this as a direction for methodological refinement rather than a claim resolved in the present figures.

Table 3. Predicted container handling volume (in million TEUs) in Bangladesh, projected to 2040.

Year	Total Container Volume of Bangladesh (Million TEUs)	Chittagong Port (GCB + CCT + NCT) (Million TEUs)	PCT of Chittagong Port (Million TEUs)	APM or Laldia Terminal of Chittagong Port (Million TEUs)	Bay Terminal of Chittagong Port (Million TEUs)	Matarbari Port (Million TEUs)	Mongla Port (Million TEUs)	Pyra Port (Million TEUs)
2027	4.97	3.1	0.25	0	-	0.12	0.12	0.08
2030	6.20	3.45	0.40	0.55	1.80	0.29	0.19	0.12
2035	8.63	3.63	0.50	0.90	3.30	0.34	0.35	0.22
2040	11.41	3.85	0.50	1.00	3.60	0.63	0.63	0.39

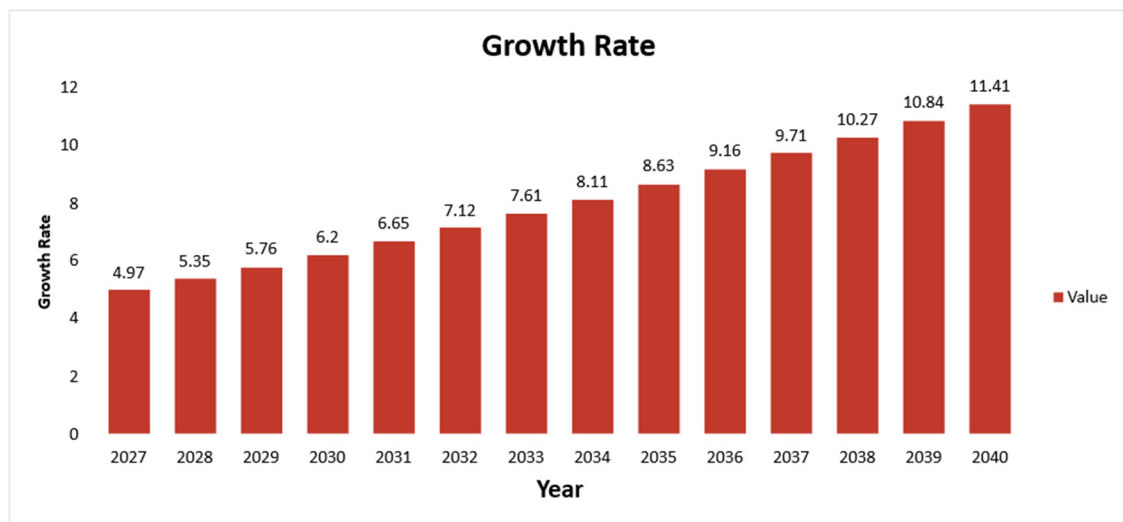


Figure 6. Prediction of container handling growth by volume (in million TEUs) in Bangladesh.

9. Development Plans and Future Projects of Bangladesh's Sea Ports

Efficient infrastructure and expanded capacity are key prerequisites for success in an increasingly globalized economy. In Bangladesh's context, the ports and shipping sector are critical to sustainable economic development and growth, and the government has recognized both the country's substantial economic potential and its growing need for robust port infrastructure. Following Chittagong, Mongla, and Payra Port, Matarbari will become the country's fourth seaport and first deep-sea port, designed to establish a reliable, low-cost logistics infrastructure for seaborne cargo handling and transport services that keeps Bangladeshi products competitive internationally. Among the deep-sea port locations in the Bay of Bengal, only Matarbari has the capacity to serve the wider hinterland region. Bangladesh occupies a strategically important geographic position, with the Bay of Bengal playing a notable role in regional affairs; the country is well placed to function as a nodal point connecting nations worldwide via efficient overland transit routes to deep-water ports, thereby substantially reducing operational costs and transit times [32,33]. The Matarbari deep-sea port may also serve as a transit port for neighboring regions, including Bhutan, Nepal, China, and India's northeastern states, with its location shaped by a range of compelling geopolitical and diplomatic considerations. Given its sufficient depth to accommodate larger vessels, Matarbari is expected to develop into a transshipment hub comparable to Colombo, Singapore, and Hong Kong. Regarding plans for Chattogram Port, Shipping Minister Shaikh Rabiul Alam has clarified that the ministry does not intend to cede full control of the port to foreign entities; rather, both domestic and international enterprises remain eligible to compete for terminal operator roles. He further noted that terminal management will follow a formal, structured framework in which public–private partnerships (PPP) and government-approved models are used to leverage foreign expertise [14]. The following upcoming projects and facilities are expected to become operational and contribute to this development in the near term.

- Matarbari Port Development Project (MPDP);
- Bay Terminal;
- Laldia Container Terminal (LCT);
- New Mooring Container Terminal (NCT);
- Patenga Container Terminal (PCT).

Current State of Development of Matarbari Sea Port is as follows:

- 1st Deep-Sea Port of Bangladesh;

- Channel- Length 14.3 km, Width 350 m, Depth 16 m (CDL);
- North Breakwater 2.15 km and South Breakwater 670 m;
- Operation Started: December 2020;
- Expected Date of Completion: 2028;
- Financed Through JICA Loan and the project is running.

Plans to Develop Bay Terminal are as follows:

- The marine infrastructure (breakwater and access channel) and developing connecting transportation infrastructure (Roads and Railway) will be financed by CPA (6 KM Access channel and 6.2 KM Breakwater). This will be financed by WB Loan.
- The development and operation of Container Terminal 1 is expected to be undertaken by Singapore Port Authority (PSA) Consortium under a long-term concession through a direct G2G PPP agreement. Terminal size: 1225MX750M. Primary MOU has been done and hope to be operated by PSA, Singapore through PPP G2G Agreement in future.
- The development and operation of Container Terminal 2 is expected to be undertaken by DP World under a long-term concession through a direct G2G PPP agreement. Terminal size: 1225MX750M. Primary MOU has been done and hope to be operated by DP World through PPP G2G Agreement in future.
- The development and operation of Multipurpose Terminal is expected to be carried out by an international terminal operator under a long-term concession through a PPP open tendering process. Terminal size: 1500MX750M. The terminal operator will be chosen through a tendering process in the near future.

Plans to Develop Laldia Terminal are as follows:

- Total Land Area: Block C: 32 Acres and Block B: 07 Acres;
- Future Commitment: Block A: 10 Acres;
- Jetty Length: 600 Meters;
- There is possibility to operate by APM Terminals through PPP G2G Agreement (BV-Maersk Group) in future.

Plans to Develop PCT are as follows:

- Operation Started: June 2024;
- Annual Throughput Capacity: 5,00,000 TEUs;
- Two Jetties-Total Length 600 M;
- It may be operated by Red Sea Gateway Terminal (RSGT), Saudi Arabia, through PPP G2G Agreement in future.

Plans to Develop NCT are as follows:

- Constructed—2007;
- Length—950 m; 5 Ships take berth simultaneously;
- Draft—10 m;
- Equipment-14 Quay Gantry Crane (QGC), 30 Rubber Tiered Gantry Crane (RTG) & Other handling equipment;
- Throughput capacity: 1.3 m TEUs Containers;
- There is possibility to operate by DP World, UAE, through PPP G2G Agreement in future.

Adequate port facilities, export diversification, seamless global trade access, and well-developed land connectivity are among the essential prerequisites for holistic economic growth. Energy, infrastructure, and transportation form the cornerstones of success not only in the economic sphere but also in human development, education, and social progress; accordingly, Bangladeshi policymakers and administrators are working to es-

establish a sustainable transport mechanism and a secure energy-supply infrastructure [15]. Among Bangladesh's three seaports, Chittagong Port handles 92% of all transported goods, resulting in significant congestion of containers and vessels and a consequent increase in turnaround time. Chittagong Port's 9.5-metre draft limitation forces Bangladesh to rely on feeder vessels routed through Southeast Asian ports such as Singapore, Port Klang (Malaysia), and Colombo (Sri Lanka), increasing both transportation costs and transit times. Deep-sea ports have therefore become a strategic imperative for Bangladesh to remain competitive globally and to attract foreign direct investment. Beyond meeting domestic demand, Bangladesh stands to generate substantial foreign currency by providing maritime access to its landlocked neighbors, Nepal and Bhutan, while also maintaining logistical corridors to China and Northeast India. If properly implemented, these connecting corridors, together with a functioning deep-sea port, could meaningfully enhance Bangladesh's GDP. Given that Bangladesh is geographically situated in a region highly vulnerable to environmental degradation and natural disasters, project coordinators and policymakers overseeing port development and expansion initiatives—including the Bay Terminal and Matarbari deep-sea port—should incorporate forward-looking contingency planning and sustainable management practices to mitigate the impact of natural calamities on both the projects themselves and the livelihoods of surrounding communities.

The Bangladesh Single Window aims to integrate the functions of 19 customs-affiliated agencies into a centralized framework to streamline and facilitate trade operations. The unified system is designed to expedite and standardize essential bureaucratic procedures, including the issuance of permits, licenses, certifications, and customs declarations; by incorporating advanced technologies into import, export, and empty-container handling, it seeks to reduce paperwork, ease vessel congestion, and lower costs. Chittagong Port is actively utilized by India, Nepal, and Bhutan owing to its strategic significance and close proximity to the ocean. World Bank data highlight persistent logistical inefficiencies in Bangladesh's maritime trade, with domestic logistics costs fluctuating between 4.5% and 48%—substantially higher than elsewhere in South Asia. Nevertheless, short-to-medium-term structural reforms could raise national export earnings by as much as 19%; notably, even a 1% reduction in logistics costs could increase global demand for Bangladeshi exports by up to 7.4% [48]. Bangladesh's ports continue to face operational strain from rising cargo volumes: Chittagong Port handled approximately 3.05 million TEUs in 2023, rising 6.8% to 3.26 million TEUs in 2024 [48]. This operational pressure is reflected internationally, with the World Bank's Container Port Performance Index 2023 ranking Chittagong Port 337th out of 405. Bangladesh's mean RMG supply lead time stands at 95 days—markedly less efficient than Vietnam (60 days) and China (32.5 days).

As part of this capacity expansion, the Patenga Container Terminal was fully funded by the CPA at a cost of BDT 12.30 billion (USD 100.8 million). The CPA subsequently signed a 22-year Memorandum of Understanding (MOU) in December 2023 with Red Sea Gateway, Saudi Arabia, to scale container-handling capacity from 250,000 to 600,000 TEUs. Complementing this initiative, an ADB-funded project will upgrade the 11.5-kilometre Chattogram Port Access Road—linking the Dhaka-Chattogram highway to the port—into a multi-lane configuration with an additional service road. Similarly, the Bay Terminal project, budgeted at BDT 149.1 billion (USD 1.22 billion) and scheduled for completion by 2030, is designed to double the port's overall handling capacity and alleviate congestion; upgraded berthing parameters will enable it to accommodate vessels with a 12-metre draught and 280-metre length, a major advance on current capacity (10-metre draught, 200-metre length). Against an existing threshold of approximately 2000 containers, the Bay Terminal is expected to enable berthing of vessels with nearly three times that capacity (6000 containers). In parallel,

the Matarbari deep-sea port mega-project, slated for completion by 2029, requires a capital investment of USD 2 billion (BDT 243.81 billion), with JICA as the principal financier, contributing USD 1.06 billion (BDT 128.93 billion), while the government and Port Authority co-finance the remainder. The project will raise handling capacity from a current threshold of 20,000–30,000 metric tons to 80,000–100,000 metric tons, substantially improving bulk-cargo throughput, and is expected to manage 1.4 to 4.2 million TEUs by 2041. Matarbari is projected to reduce transit times to the United States from 45 to just 23 days, while establishing new trade corridors with Europe. Data from the Chattogram Port Authority suggest that these projects could prove economically successful, with the accommodation of larger, deeper-draft vessels potentially reducing overall freight transportation costs by 15% [48].

10. Results

The findings presented in this section are drawn from thematic analysis of 20 focus group discussions and supplementary individual interviews conducted across the eight stakeholder clusters described in Section 3. Four dominant themes emerged from the coding process, corresponding to the study's research questions on drivers and constraints, governance conditions, workforce implications, and infrastructure priorities. Illustrative statements are reported anonymously, consistent with the ethical protocol described in Section 3.4; where a stakeholder cluster is identified, this reflects the participant's professional category rather than any individually identifying detail.

10.1. Perceptions of Smart Technology Adoption

Across nearly all stakeholder clusters, participants expressed broad conceptual support for smart port technologies, but this support was consistently qualified by scepticism about feasibility within the current operating environment. Representatives from the digital technology and academic cluster were the most unambiguously positive, framing automation, predictive maintenance, and AI-based scheduling as overdue rather than aspirational. One systems engineer from this cluster observed that the underlying data infrastructure required for these tools already exists in fragmented form across Chittagong Port's terminal operating systems, but that it has never been consolidated into a usable analytical layer.

Port authority and government participants were more cautious, tending to frame smart technology adoption as a long-term ambition contingent on prior reforms to procurement and staffing structures rather than an immediate operational priority. Several regulators drew a distinction between Chittagong, where they felt automation was operationally justified given cargo volume, and Mongla, where participants questioned whether the throughput currently handled would justify the capital outlay for comparable systems. This distinction recurred across multiple clusters and is discussed further in relation to infrastructure priorities in Section 10.4.

Shipping line and freight-forwarding participants generally welcomed the prospect of AI-enabled customs risk profiling and automated gate processing, citing existing delays at container examination points as a recurring operational cost. However, several agency representatives voiced concern that partial digitization, where only some port functions are automated while others remain manual, could introduce new bottlenecks rather than resolving existing ones, a concern that several technical staff participants echoed with reference to past experience of underused digital systems introduced without corresponding changes to workflow.

A recurring cross-cutting observation, raised independently in FGDs across the port authority, shipping line, and technical personnel clusters, was that perceptions of smart technology were shaped less by unfamiliarity with the technology itself and more by prior

experience with previous modernization initiatives that had stalled after an initial rollout phase. This pattern of qualified optimism, tempered by institutional memory of incomplete implementation, was among the most consistent findings across the dataset.

10.2. Governance and Regulatory Barriers

Governance and regulatory constraints emerged as the most frequently coded theme across the dataset, cutting across nearly every stakeholder cluster. Participants from the port authority and government cluster most often located the barrier not in technology cost but in the fragmented distribution of regulatory authority across multiple ministries, port authorities, and customs bodies, each with distinct approval processes and, in some cases, overlapping jurisdiction over digital infrastructure decisions. Several policymakers noted that a single automation initiative could require sign-off from port authority engineering divisions, national customs authorities, and, where foreign technology vendors are involved, additional ministerial clearance, a sequencing process participants described as slow relative to the pace of technological change it is meant to govern.

International experts and classification society participants situated this within a broader comparative frame, observing that comparable regulatory fragmentation exists in other South Asian ports but that Bangladesh's approval timelines were, in their professional assessment, longer than regional peers with similar institutional structures. Several of these participants also noted the absence of a dedicated national policy instrument specifically addressing smart port or port digitalization standards, in contrast to sector-specific digitalization roadmaps they had encountered elsewhere.

Business, trade, and finance participants raised a related but distinct concern: regulatory uncertainty around data ownership and cybersecurity liability, particularly for privately financed digital systems operating within a state-controlled port. Several bankers and insurers indicated that this uncertainty complicates financing structures for smart port investment, since lenders and insurers require clarity on liability allocation that current regulation does not yet provide.

Civil society and labour representatives, while raising governance concerns of a different character (addressed further in Section 10.3), also noted a consultation gap: several participants from this cluster indicated that they had not been formally consulted on prior digitalization initiatives at either Chittagong or Mongla, and viewed this as symptomatic of a broader governance pattern in which technology decisions are made administratively rather than through structured multi-stakeholder consultation.

10.3. Workforce and Social Implications

Workforce implications were raised extensively by the port operations and technical personnel cluster, as well as by civil society and labour representatives, and were characterized by a tension between anticipated efficiency gains and concern over employment displacement. Equipment operators and technicians generally did not oppose automation in principle; several described current manual processes, particularly gate and yard operations, as physically demanding and error-prone. However, participants in this cluster consistently raised the absence of a clear reskilling or transition pathway as a primary source of concern, distinguishing their position from outright resistance to technology.

Labour union representatives were more critical, framing the current absence of a formal workforce transition policy as a governance failure rather than a technical one, and linking it directly to the consultation gap identified in Section 10.2. Several participants from this cluster argued that without a negotiated transition framework, automation initiatives at Chittagong in particular risk generating labour disputes that could disrupt operations more significantly than the operational inefficiencies automation is intended to resolve.

Digital technology and academic participants offered a complementary perspective, noting that Bangladesh's technical and engineering education institutions, several of which were represented directly in this cluster, are producing graduates with relevant digital and systems engineering skills, but that a structured pathway connecting this graduate talent pool to port sector employment does not yet exist. Several participants described this as a missed opportunity rather than a structural barrier, suggesting that workforce concerns raised by operational staff and the skills gap identified by educators could, in principle, be addressed through the same set of interventions.

Environmental and civil society participants extended the workforce discussion into broader social terms, raising concerns about community impacts of port expansion, particularly around Matarbari, where displacement and livelihood disruption associated with greenfield construction were raised as an active concern distinct from, but related to, the automation-driven employment concerns raised elsewhere.

10.4. Infrastructure and Investment Priorities

Infrastructure and investment priorities varied substantially by port, reflecting the differentiated developmental stages set out in Section 3.1. For Chittagong, participants across the shipping line, agency, and technical clusters converged on yard and gate congestion as the most immediate infrastructure constraint, with several participants specifically identifying real-time container tracking and automated gate processing as the highest-priority near-term investments given the port's existing cargo volume.

For Mongla, participants were more divided. Port authority representatives described a strategic ambition to position Mongla as a secondary hub with growing capacity, while several business and finance participants questioned whether current throughput justified prioritizing smart infrastructure investment ahead of more foundational infrastructure, such as berth depth and inland connectivity. This divergence reflects the broader distinction, raised in Section 10.1, between participants who framed smart technology as scale-contingent and those who viewed it as a precondition for attracting the volume growth Mongla is intended to capture.

Matarbari was consistently discussed as a distinct case rather than an extension of the Chittagong or Mongla conversation. International experts and government participants both noted that, because Matarbari is being constructed as a greenfield facility, it presents an opportunity to embed smart infrastructure, including IoT-based monitoring and digital twin capability, into the port's design from the outset rather than retrofitting it into existing operations, an approach several participants argued would avoid the integration difficulties raised elsewhere in relation to partial digitization at Chittagong. However, participants from the business and finance cluster cautioned that Matarbari's financing structure, and the involvement of external development partners, introduces its own coordination requirements that could affect the pace at which this design-stage opportunity is realized.

Across all three ports, a recurring investment-related concern, raised primarily by business, finance, and international expert participants, was the absence of a clearly sequenced, publicly available national investment roadmap for port digitalization, which several participants indicated complicates private co-investment planning even where individual investors are otherwise favourably disposed toward smart port initiatives.

11. Discussion

The findings set out in Section 10 indicate that the barriers to smart port adoption in Bangladesh are, in the main, institutional and coordinative rather than technological. This is a materially different picture from that suggested by the East Asian, European, and Middle

Eastern literature reviewed in Section 2, where the enabling role of AI, ML, deep learning, and IoT is generally treated as a function of capital availability and technical readiness. In the Bangladeshi case, participants across every stakeholder cluster demonstrated a working familiarity with these technologies and, in most cases, a favourable disposition toward their adoption; the constraint lies instead in the regulatory fragmentation, consultation gaps, and financing uncertainty documented in Sections 10.2 and 10.4. This distinction supports the study's central premise, set out in Section 1, that existing smart port frameworks developed in institutionally mature contexts do not transfer directly to infrastructure-limited, institutionally constrained settings, and that governance capacity, rather than technological capacity, should be treated as the primary variable of interest in such contexts.

The differentiated findings across Chittagong, Mongla, and Matarbari also suggest that a single national smart port strategy may be analytically and practically insufficient. Chittagong's constraints are those of an already-congested, high-volume facility in which automation is operationally urgent but institutionally difficult to sequence; Mongla's constraints are those of a developing port where the case for smart infrastructure investment is contingent on volume growth that has not yet materialized; and Matarbari's position as a greenfield site presents a genuinely different opportunity, namely the ability to design smart capability into the port from inception rather than retrofitting it, though this opportunity is itself bounded by the coordination demands of its multi-partner financing structure. Any policy or investment roadmap that treats these three ports as a single undifferentiated case is therefore unlikely to reflect the conditions under which stakeholders in each context are actually operating.

The workforce findings in Section 10.3 point to a further governance dimension that is comparatively underexamined in the existing smart port literature, which tends to treat automation's labour implications as a downstream effect rather than a precondition for successful adoption. In this study, the absence of a negotiated workforce transition framework was raised, independently, by both operational staff and labour representatives, as a factor that could materially affect the feasibility of automation initiatives at Chittagong specifically. This suggests that workforce transition planning is not a peripheral social consideration but a core adoption condition in this context, and that its omission from current digitalization planning represents a substantive gap rather than an oversight of secondary importance.

Taken together, these findings support an answer to the study's final research question, on how Bangladesh's sea ports might implement smart technology given the barriers identified. The evidence suggests that sequencing matters as much as investment: consolidating fragmented regulatory authority, establishing a formal multi-stakeholder consultation mechanism of the kind civil society and labour participants indicated is currently absent, and developing a negotiated workforce transition pathway would address governance-level barriers common to all three ports, while port-specific investment sequencing, incremental automation at Chittagong, volume-contingent infrastructure development at Mongla, and design-stage smart infrastructure integration at Matarbari would address the developmental divergence documented in Section 10.4. This combination of governance-level and port-specific measures offers a more context-sensitive pathway than the largely technology-first frameworks that dominate the existing literature.

These findings should be read in light of the study's qualitative, purposive design, as noted in Section 3.6. The findings are not statistically representative of the sector, and the study's transferability to other South Asian and Global South port contexts, while plausible given the institutional similarities several international expert participants noted, remains a boundary condition rather than an established claim and would benefit from comparative empirical testing in future research.

12. Recommendations and Way Forward: A Phased Smart-Port Implementation Roadmap

Bangladesh's sea ports, particularly the Chattogram Port Authority (CPA) and Mongla Port Authority (MPA), face mounting pressure to manage growing cargo volumes, meet demands for faster turnaround, and comply with tightening global environmental and ESG mandates [17]. Current operations remain a mixture of manual and semi-automated systems across berth allocation, customs clearance, and cargo documentation, with minimal digital integration, disjointed IT architecture across terminals and agencies, and no national Port Community System (PCS) [16]. This has produced measurable inefficiencies: studies estimate that the lack of digital integration raises operating time and costs by 10–20% through duplication, delay, and inaccuracy [20], while globally, PCS implementation has been linked to 25–40% reductions in dwell times [28]. Structural constraints—limited financing, institutional fragmentation, unclear digital mandates, and workforce skills gaps [49]—mean that wholesale technology adoption is unlikely to succeed; a phased, incremental approach tailored to Bangladesh's operational and regulatory capacity is more sustainable. The roadmap below sequences the recommendations across three phases, each defined by priority technologies, the responsible institution, prerequisites, implementation timeline, measurable KPIs, financing pathway, cybersecurity requirements, and key risks.

Phase 1—Foundational Digitization and Governance (Years 0–2)

Priority technologies: Basic digitization of cargo documentation; pilot Port Community System (PCS) and Terminal Operating System (TOS); baseline IoT container-tracking; automated berth-scheduling notifications.

Responsible institutions: Ministry of Shipping (MOS), through a newly established National Smart Port Governance Authority; CPA and MPA IT divisions; national maritime academies (for early workforce training).

Prerequisites: Legal establishment of the National Smart Port Governance Authority; enactment of a digital/smart-port legislative framework to clarify institutional mandates and reduce agency overlap; baseline budget allocation.

Timeline: Years 0–2.

Measurable KPIs: % of customs/cargo documentation digitized; PCS/TOS pilot rollout at ≥ 1 terminal; reduction in average vessel waiting time (baseline vs. Year 2); number of staff completing digital-literacy training.

Financing: Government budget allocation; concessional grants and technical assistance from ADB and World Bank digital-transformation programs [25].

Cybersecurity requirements: Establish a baseline data-protection and access-control policy for new digital systems; initial gap assessment against IMO MSC.428(98).

Significant risks: Institutional resistance to centralized governance; delays in legislative enactment; underfunding relative to pilot scope; low digital literacy among port workforce slowing adoption.

Phase 2—Core Smart Operations and Interoperability (Years 2–5)

Priority technologies: IoT sensors for equipment condition-monitoring and environmental metrics (noise, emissions); AI-assisted berth and yard planning; predictive maintenance via ML; pilot digital-twin simulation for one major terminal; national-scale PCS/TOS rollout with interoperable, open-API architecture across CPA, MPA, and inland ports.

Responsible institutions: National Smart Port Governance Authority (coordination); CPA/MPA operations and IT departments; private terminal operators (e.g., PSA Singapore, DP World) as co-investors and technology partners; technology vendors under certified procurement.

Prerequisites: Phase 1 governance structure and legal framework operational; baseline cybersecurity policy in place; workforce trained on foundational digital systems; interoperable data-architecture standards agreed across agencies.

Timeline: Years 2–5.

Measurable KPIs: Reduction in vessel turnaround time (target: meaningful % improvement over Phase 1 baseline); % reduction in unplanned equipment downtime via predictive maintenance; national PCS/TOS operational across all three sea ports; emissions-monitoring dashboard live at ≥ 1 port.

Financing: Public–private partnership (PPP) models with terminal operators; JICA and ADB infrastructure loans; blended finance combining public investment with private terminal capital (as seen in Bay Terminal and Patenga Container Terminal financing).

Cybersecurity requirements: Formal adoption of a maritime cybersecurity framework aligned with IMO MSC.428(98); establishment of the Port Cyber Resilience Taskforce under MOS to oversee threat monitoring, incident response, and vendor certification [18].

Significant risks: Integration failure between legacy manual systems and new digital platforms; cybersecurity exposure during system interconnection; cost overruns in PPP arrangements; uneven adoption pace between CPA (higher capacity) and MPA (lower capacity).

Phase 3—Full Smart-Port Integration and ESG Alignment (Years 5–10+)

Priority technologies: Full-scale digital-twin deployment for scenario planning and energy-efficiency modeling; blockchain-based documentation for customs, bills of lading, and trade finance; 5G-enabled automated guided vehicles (AGVs) and automated cranes; AI/ML-driven emissions and ESG-compliance dashboards linked to carbon-border reporting requirements.

Responsible institutions: National Smart Port Governance Authority (policy and compliance oversight); MOS (national climate and trade-strategy alignment); international technical partners (UNCTAD, ESCAP, MIT CTL) and regional peer-learning partnerships (China, Singapore, UAE, India, Vietnam, Indonesia) [18].

Prerequisites: Phase 2 systems fully operational and interoperable; cybersecurity framework matured and independently audited; ESG compliance criteria formally linked to port concession licensing.

Timeline: Years 5–10 and beyond (continuous refinement).

Measurable KPIs: Verified reduction in port-level carbon emissions against baseline; improvement in global port performance rankings (e.g., Lloyd's List); % of port concessions/licenses meeting linked ESG performance metrics; blockchain-documentation adoption rate across customs and trade-finance transactions.

Financing: ESG-linked and green bond financing; carbon-credit and climate-finance mechanisms; continued multilateral co-financing; private-sector investment incentivized through tax relief for SME and logistics-operator technology adoption [28].

Cybersecurity requirements: Continuous third-party security auditing; mandatory vendor certification for all new digital/AI systems; resilience testing against system-wide disruption scenarios, consistent with Port Cyber Resilience Taskforce oversight established in Phase 2.

Significant risks: Technology obsolescence given the pace of global smart-port innovation; shifting international ESG/carbon-border regulation outpacing domestic compliance capacity; geopolitical or trade-policy shifts affecting financing partners; risk of over-investment in unproven technologies without adequate phased validation.

13. Conclusions

In the present global context, sea ports exert substantial influence over international trade, accounting for approximately 80% of trade by volume and 70% by value, while also underpinning national security as a cornerstone of the blue economy. Contemporary smart ports leverage AI, ML, digital twins, and blockchain technology to enhance reliability, efficiency, traceability, and stakeholder trust, thereby optimizing nearly every dimension of port operations. Modern technology holds the potential to refine virtually every facet of port administration, from automating heavy machinery and berth scheduling to equipment maintenance, workforce management, and training. Financial and administrative considerations no longer constrain sustainability efforts, as smart ports increasingly adopt renewable energy alternatives and eco-friendly procedures with due regard for the marine ecosystem and carbon footprint. This continued adoption of newer, streamlined technologies reflects a sustained commitment to innovation; however, the principal concern accompanying AI adoption remains cybersecurity vulnerability, given that a cyberattack on essential systems—such as power grids—could trigger a ripple effect across the global economy. To secure its competitive edge and support national stability, Bangladesh must confront these security challenges directly and invest substantially in automation, AI-based monitoring, and resilient infrastructure, thereby strengthening its long-term economic position internationally. The integration of AI, ML, IoT, big data, 5G, and other smart technologies is transforming seaports into smart ports, driving gains in efficiency, security, operational ease, safety, and sustainability. These technologies enable real-time monitoring, predictive maintenance, improved security, enhanced logistics, effective energy management, and more informed decision-making. As seaports continue to evolve, the adoption of smart technologies will remain essential to meeting the demands of global trade while ensuring the sustainable growth of the maritime industry as a whole. This ongoing wave of digital innovation will position modern ports at the forefront of technological advancement, paving the way toward a smarter, faster, more profitable, and more sustainably connected future. Accordingly, Bangladesh's major sea ports should undertake a quantitative assessment of AI, ML, IoT, big data, and PCS/TOS technologies to determine their impact on port efficiency, cost savings, safety, security, cargo throughput, and decision-making.

Local sea ports may also explore blockchain integration to enable end-to-end customs transparency, trade documentation, and digital trade finance, thereby improving service delivery to businesses and maritime trade stakeholders. A simulation-based port operations model could similarly be introduced to improve efficiency and cost-effectiveness, guiding top management in predictive berth scheduling, real-time yard optimization, energy-efficient routing, safety and security, and cost savings. Bangladesh occupies an important geostrategic position within the global economy and, owing to its large, untapped blue economy, holds an advantageous position relative to landlocked countries. Having secured its maritime territory following the resolution of border disputes with Myanmar (14 March 2012) and India (7 June 2014), Bangladesh now holds sovereign rights over its territorial waters; robust maritime security and resource exploitation will be essential to realizing the full potential of these waters, with ports such as the Bay Terminal and deep-sea facilities such as Matarbari well positioned to support such activities. In the twenty-first century, naval power remains paramount to securing these maritime economic hubs, requiring the Bangladesh Navy to expand its presence around existing and future maritime projects. To secure a critical geostrategic advantage in regional trade with its neighbors and the Middle East, Bangladesh's deep-sea ports must be coupled with adequate supporting infrastructure, including link roads and modern telecommunications. More than USD 100 billion in trade currently circulates through small feeder vessels, compelling Bangladesh to pay a premium for imported goods routed via secondary vessels and causing mother vessels to

incur higher costs and longer delays. The operationalization of the Matarbari deep-sea port and Bay Terminal will address these bottlenecks by accommodating deep-draft mother vessels directly, substantially reducing import- and export-related expenses. This maritime development is also expected to raise living standards by accelerating macroeconomic growth, generating employment, and modernizing local communication networks. The successful completion of current and future port projects, together with smart operations, efficient port management, and sound strategic government decision-making, can therefore deliver substantial benefits for national economic growth; the government should accordingly prioritize the timely completion of these two strategic mega-projects—the Matarbari Deep-Sea Port and the Bay Terminal. Ultimately, smart ports represent a prerequisite for handling cargo efficiently and continuously, in line with the global standards expected of the maritime sector in the twenty-first century.

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Abbreviations

Abbreviation	Full Form
AI	Artificial Intelligence
ML	Machine Learning
DL	Deep Learning
IoT	Internet of Things
DS	Data Science
AR	Augmented Reality
VR	Virtual Reality
ANN	Artificial Neural Network
5G	Fifth Generation Mobile Network
BDA	Big Data Analytics
ICT	Information and Communication Technology
GIS	Geographic Information System
GPS	Global Positioning System
RFID	Radio Frequency Identification
AIS	Automatic Identification System
AGV	Automated Guided Vehicle
OCR	Optical Character Recognition
API	Application Programming Interface
ERP	Enterprise Resource Planning
ITS	Intelligent Transportation System
PCS	Port Community System
TOS	Terminal Operating System
VTS	Vessel Traffic Service
EMS	Environmental Management System
KPI	Key Performance Indicator
JIT	Just-in-Time

TEU	Twenty-foot Equivalent Unit
CPA	Chittagong Port Authority
MPA	Mongla Port Authority
PPA	Payra Port Authority

Appendix A. Semi-Structured FGD and Interview Guide

The following guide was used consistently across all focus group discussions and individual interviews. Questions were adapted in wording, not substance, to suit each stakeholder cluster, and moderators used follow-up probes to elicit elaboration where needed.

- A. *Concept and Awareness*
 - How would you define a “smart port,” based on your own professional experience?
 - Which technologies do you associate most strongly with smart port operations?
- B. *Current Operations and Constraints*
 - How would you describe the current state of technology adoption at your port or organization?
 - What operational, infrastructural, or institutional constraints have you encountered in adopting digital or smart systems?
- C. *Technology Adoption*
 - Which specific technologies, such as AI, IoT, digital twins, or big data, have you seen applied, piloted, or discussed for adoption in Bangladesh’s ports?
 - What has been the outcome, or expected outcome, of these initiatives?
- D. *Governance and Policy*
 - How would you assess coordination among the agencies and institutions involved in port governance?
 - What regulatory or policy changes would most support smart port development?
 - How is compliance with ESG and public–private investment requirements currently handled?
- E. *Workforce and Social Impact*
 - How do port workers and operators perceive the shift toward automation and digital systems?
 - What training or capacity-building needs do you see as most urgent?
- F. *Environmental and Sustainability Considerations*
 - How is environmental performance, such as emissions, noise, or energy use, currently tracked at your port?
 - What role could smart technology play in improving environmental outcomes?
- G. *Future Outlook*
 - What do you see as the most important next step for Bangladesh’s ports over the next five to ten years?
 - What lessons from international ports do you think are most transferable to the Bangladeshi context?

References

1. Rodrigue, J.P. Transport and Development. In *The International Encyclopedia of Geography*; Richardson, D., Castree, N., Goodchild, M.F., Kobayashi, A., Liu, W., Marston, R.A., Eds.; John Wiley & Sons: New York, NY, USA, 2017.

2. Sinay. What is a Smart Port? 2024. Available online: <https://sinay.ai/en/maritime-glossary/smart-port/> (accessed on 9 May 2024).

3. Pham, T.Y. A smart port development: Systematic literature and bibliometric analysis. *Asian J. Shipp. Logist.* **2023**, *39*, 57–62. [CrossRef]

4. Li, K.X.; Li, M.; Zhu, Y.; Yuen, K.F.; Tong, H.; Zhou, H. Smart port: A bibliometric review and future research directions. *Transp. Res. Part E Logist. Transp. Rev.* **2023**, *174*, 103098. [CrossRef]
5. Paraskevas, A.; Madas, M.; Zeimpekis, V.; Fouskas, K. Smart Ports in Industry 4.0: A Systematic Literature Review. *Logistics* **2024**, *8*, 28. [CrossRef]
6. Rahman, M.S.; Siddiqui, S.A.; Haque, T. Institutional voids and the challenges of smart port governance in South Asia. *Asian J. Shipp. Logist.* **2021**, *37*, 245–258.
7. Copeland, J. *The Essential Turing: The Ideas that Gave Birth to the Computer Age*; Clarendon Press: Oxford, UK, 2004.
8. Hernandez, G.; Floret, C.P.; Cardozo De Almeida, K.F.; Da Silva, V.C.; Papa, J.P.; Da Costa, K.A.P. Phishing Detection Using URL-based XAI Techniques. In Proceedings of the 2021 IEEE Symposium Series on Computational Intelligence (SSCI), Orlando, FL, USA, 5–7 December 2021. [CrossRef]
9. Deng, L.; Yu, D. Deep Learning: Methods and Applications. *Found. Trends Signal Process.* **2014**, *7*, 197–387. [CrossRef]
10. Kingston, K.S. Applications of Complex Adaptive Systems Approaches to Coastal Systems. Ph.D. Thesis, University of Plymouth, Plymouth, UK, 2003.
11. Breakbulk News. 2024. Available online: <https://breakbulk.news/techtalk-china-sets-global-benchmark-with-automated-port-expansion/> (accessed on 7 May 2025).
12. LA Classification. 2024. Available online: <https://www.togo-port.net/la-classification-des-ports-selon-sur-leur-statut-juridique/> (accessed on 6 May 2025).
13. Seaspace. 2025. Available online: <https://www.seaspace-int.com/importance-of-seaports-for-international-trade/> (accessed on 11 April 2025).
14. FICCI. Chattogram Port: Bangladesh's Gateway to Blue Economy and International Trade, FICCI Monthly Bulletin March. 2025. Available online: <https://www.ficci.org.bd/ficci-stories/chattogram-port-bangladeshs-gateway-to-blue-economy-and-international-trade> (accessed on 23 March 2026).
15. Shipping Minister Says Port Remains Under State Control Despite Foreign Terminal Operators, 22 April 2026. Available online: <https://bdnews24.com/bangladesh/63efd89ce946> (accessed on 25 April 2025).
16. Chowdhury, M.M.H.; Munim, Z.H. Dry port location selection using a fuzzy AHP-BWM-PROMETHEE approach. *Marit. Econ. Logist.* **2022**, *25*, 301–329. [CrossRef]
17. Notteboom, T.; Van Der Lugt, L.; Van Saase, N.; Sel, S.; de Langen, P. The role of seaports in green supply chain management: Initiatives, attitudes, and perspectives in Rotterdam, Antwerp, North Sea Port, and Zeebrugge. *Sustainability* **2020**, *12*, 1688. [CrossRef]
18. Afshar, U.J.; Tamim, F.S.; Mamun, M.H. Sustainability Focused Industry Trends in Global Research. In Proceedings of the International Conference on Economics, Business and Technology Management, Dhaka, Bangladesh, 14–15 November 2025. Available online: <https://icebtm.iub.edu.bd> (accessed on 23 March 2026).
19. Maritime Data Solution. 2021. Available online: <https://sinay.ai/en/what-is-artificial-intelligence-in-smart-port-operations/> (accessed on 12 May 2024).
20. Chu, F.; Gailus, S.; Liu, L.; Ni, L. *The Future of Port Automation*; McKinsey & Company: New York City, NY, USA, 2018. Available online: <https://www.mckinsey.com/industries/logistics/our-insights/the-future-of-automated-ports> (accessed on 23 March 2026).
21. MIT CTL. MIT Center for Transportation & Logistics (MIT CTL), Port Digital Maturity Index. 2022. Available online: <https://ctl.mit.edu> (accessed on 7 May 2025).
22. Hossain, K.A. Bangladesh's Ship Recycling Industry in the Global South: Readiness, Regional Competition, and Reform Imperatives. *Sustainability* **2025**, *17*, 10998. [CrossRef]
23. Duc, T.L.; Leiva, R.G.; Casari, P.; Östberg, P.O. Machine Learning Methods for Reliable Resource Provisioning in Edge-Cloud Computing: A Survey. *ACM Comput. Surv.* **2019**, *52*, 1–39. [CrossRef]
24. Notteboom, T.E.; Haralambides, H.E. Port management and governance in a post-COVID-19 era: Quo vadis? *Marit. Econ. Logist.* **2020**, *22*, 329–352. [CrossRef]
25. Heilig, L.; Lalla-Ruiz, E.; Voß, S. Digital transformation in maritime ports: Analysis and a game theoretic framework. *NETNOMICS Econ. Res. Electron. Netw.* **2017**, *18*, 227–254. [CrossRef]
26. Chen, Y.; Wang, L.; Zhang, X. Smart ports: A technology-driven approach to sustainable maritime logistics. *Sustainability* **2019**, *11*, 4123. [CrossRef]
27. Lam, J.S.L.; Notteboom, T. The greening of ports: A comparison of port management tools used by leading ports in Asia and Europe. *Mar. Pollut. Bull.* **2014**, *76*, 25–34.
28. Elkafas, A.G.; Seddiek, I.S. Application of renewable energy systems in seaports towards sustainability and decarbonization: Energy, environmental and economic assessment. *Renew. Energy* **2024**, *228*, 120600. [CrossRef]
29. Top Private Networking Providers in Ports. STL Partners (Yangshan Port Private 5G/LTE Case). Available online: <https://stlpartners.com/articles/private-cellular/top-private-networking-providers-in-ports/> (accessed on 23 March 2026).
30. 5G Powers Smart Port Transformation. Orange Business (Port of Antwerp). Available online: <https://www.orange-business.com/en/magazine/land-ahoy-5g-powering-smart-port-transformation> (accessed on 23 March 2026).

31. Transforming Port Operations with Private 5G: Peel Ports Case Study. Logicalis (Port of Liverpool). Available online: <https://www.logicalis.com/insights/revolutionising-port-operations> (accessed on 23 March 2026).
32. Eom, J.O.; Yoon, J.H.; Yeon, J.H.; Kim, S.W. Port Digital Twin Development for Decarbonization: A Case Study Using the Pusan Newport International Terminal. *J. Mar. Sci. Eng.* **2023**, *11*, 1777. [CrossRef]
33. Saragani, C.; Garrido, J.; Sauri, S. Digital twin adoption in port authorities: A structured framework for use case assessment. *J. Shipp. Trade* **2026**, *11*, 12. [CrossRef]
34. IBM. *Improve IT Systems Management Productivity, Application Performance and Operational Resiliency with AIOps*; IBM: Armonk, NY, USA, 2024. Available online: <https://www.ibm.com/it-infrastructure/z/capabilities/it-operations-management> (accessed on 13 December 2025).
35. Innovez One. 2024. Available online: <https://www.innovez-one.com/post/3-ways-ai-will-transform-ports> (accessed on 11 December 2025).
36. Khan Khalil, U. *Stevedoring & The Role of Stevedores in Shipping*; International Institute of Marine Surveying: Fareham, UK, 2014. Available online: <https://www.iims.org.uk/the-role-of-stevedores-in-shipping/> (accessed on 13 December 2025).
37. PierNext. 2023. Available online: <https://piernext.portdebarcelona.cat/en/technology/will-ai-take-over-port-management/> (accessed on 11 May 2025).
38. Masood, A.; Hashmi, A. AIOps: Predictive Analytics & Machine Learning in Operations. In *Cognitive Computing Recipes: Artificial Intelligence Solutions Using Microsoft Cognitive Services and TensorFlow*; Apress: New York, NY, USA, 2019; pp. 359–382. [CrossRef]
39. PierNext. 2024. Available online: <https://piernext.portdebarcelona.cat/tecnologia/ospac-oceanografia-operacional-para-puertos-y-ciudades/> (accessed on 12 March 2024).
40. Port De Barcelona. Why the European Maritime Single Window Raises Doubts. 2025. Available online: <https://piernext.portdebarcelona.cat/en/logistics/european-maritime-single-window/> (accessed on 13 September 2025).
41. Hossain, K.A. Evaluation of local industry of Bangladesh including shipbuilding. *Glob. Sci. J.* **2023**, *11*, 2320–9186.
42. Marine Digital. The World's Biggest Shipping Hubs. 2024. Available online: https://marine-digital.com/article_eeo-biggest_shipping_hubs (accessed on 15 May 2024).
43. Lloydlist. Smart Port Solutions Demand Unilateral Approach. 2019. Available online: <https://www.lloydlist.com/LL1126611/Smart-port-solutions-demand-unilateral-approach> (accessed on 16 May 2025).
44. Valourconsultancy. Emergence of Unmanned Technology in Major Ports. 2026. Available online: <https://valourconsultancy.com/smart-yet-portly/> (accessed on 26 May 2026).
45. Marinelink. Port of Rotterdam Unveils Phase 2 of Digital Twin Project. 2026. Available online: <https://ports.marinelink.com/ports/port/cairo/news/port-of-rotterdam-unveils-phase-2-of-digital-twin-project> (accessed on 15 May 2026).
46. Sim, S.; Kim, D.; Park, K.; Bae, H. Artificial Intelligence-based Smart Port Logistics Metaverse for Enhancing Productivity, Environment, and Safety in Port Logistics: A Case Study of Busan Port. *arXiv* **2024**. [CrossRef]
47. Hossain, K.A. An Initiative to Evaluate the Entrepreneurship Creativity in China with Contest of Economic Development and Growth of a Great Nation. *IOSR J. Bus. Manag.* **2026**, *28*, 1–55. [CrossRef]
48. Zaman, M.A. *2026 is Year Without Job Security in Bangladesh*; Asia News Network: Singapore, 2025.
49. Hasnat, M.A. The Feasibility and Challenges of Implementing a Green Port Policy Framework in Bangladesh. Master's Thesis, World Maritime University, Malmö, Sweden, 2024.

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