2025 Volume: 01 Issue: 07 www.ijrpa.com ISSN 2456-9995 **Research Article**

International Journal Research Publication Analysis

Page: 01-24

A STUDY ON MODERN PORT PLANNING.

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Article Received: 10 November 2025
Article Revised: 30 November 2025
Published on: 20 December 2025

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ABSTRACT

Modern port planning increasingly relies on smart technologies, automation, and simulation-based approaches to improve operational efficiency, safety, and sustainability. This study integrates CAD-based port layout design using AutoCAD with agent-based simulation modeling in "AnyLogic" software to evaluate port infrastructure performance and vessel operations. Detailed layouts of berths, container yards, access roads, and navigation channels were developed and assessed against functional standards. The "AnyLogic" simulation modeled real-time port dynamics, including vessel movements, cargo handling processes, and resource utilization, enabling analysis of vessel turnaround times, congestion, and process efficiency. Results demonstrate that simulation-driven planning and path-based vessel navigation significantly reduce congestion and improve operational performance. The study highlights the value of integrating digital design and simulation technologies to support data-driven decision-making in the development of smart and sustainable ports.

KEYWORDS:

Smart ports; Port planning; Agent-based simulation; AnyLogic; AutoCAD; Vessel navigation; Infrastructure optimization; Digital port design; Operational efficiency; Sustainable port development

INTRODUCTION:

Ports play a pivotal role in global trade by serving as key interfaces between maritime transportation and inland distribution networks. Nearly 80–90% of global trade by volume is carried by sea, making ports essential components of international supply chains. Traditionally, port planning emphasized geographical suitability, natural harbor conditions, navigational depth, and basic cargo-handling infrastructure. While these factors ensured operational feasibility, they often failed to address long-term adaptability, technological advancement, and environmental sustainability. With increasing globalization, larger vessel sizes, evolving trade patterns, and heightened environmental awareness, the scope of port planning has expanded significantly.

Modern port planning has become a multidisciplinary and integrated process that incorporates engineering, logistics, environmental management, and advanced digital technologies. The adoption of tools such as BIM, GIS, digital twins, artificial intelligence, and the Internet of Things has led to the emergence of smart ports that enhance efficiency, safety, and resilience through automation and real-time data-driven decision-making. At the same time, sustainability has become a core objective, with growing emphasis on green port initiatives, emissions reduction, renewable energy, and community engagement. Consequently, contemporary port planning focuses on developing future-ready infrastructure that balances economic growth, environmental responsibility, and social well-being.

EVOLUTION OF MODERN AND SMART PORTS:

Advances in technology, the expansion of global trade, and the demand for faster and more reliable shipping have fundamentally transformed the role of ports. Initially, ports functioned primarily as locations for cargo handling and ship berthing. However, beginning in the mid-20th century, innovations such as mechanization and containerization revolutionized port operations. The introduction of standardized containers, pioneered by Malcolm McLean in 1956, significantly reduced handling costs, improved efficiency, and accelerated cargo movement. This transformation enabled ports to handle rapidly increasing trade volumes and laid the foundation for modern logistics-driven port systems.

In recent decades, ports have evolved further into smart, integrated logistics hubs. The adoption of automation, digital tracking systems, and advanced technologies such as the Internet of Things, artificial intelligence, digital twins, and blockchain has enhanced operational efficiency, safety, and transparency. At the same time, sustainability has become a key priority, with ports incorporating renewable energy, energy-efficient equipment, and environmentally responsible designs. Today’s ports operate as interconnected nodes within global transport networks, supporting trillions of dollars in trade annually while striving to balance economic performance with environmental and technological sustainability.

PORTS IN INDIA:

India's maritime infrastructure has undergone a major transformation, with modern ports emerging as efficient, technology-driven hubs aligned with global standards. Key ports such as Jawaharlal Nehru Port Trust and Chennai Port have benefited from infrastructure upgrades, automation, and improved inland connectivity, enabling faster ship turnarounds and higher cargo handling capacity. The Sagarmala Project has further accelerated port-led development through modernization, new port construction, coastal economic zones, and digital systems like the Port Community System. Alongside sustainability initiatives such as solar energy and advanced waste management, these efforts have strengthened India's global trade position, reduced logistics costs, supported the "Make in India" initiative, and made ports more customer-centric and competitive.

NECESSITY FOR THE STUDY OF SMART PORTS:

As global trade expands and demand for faster, cheaper delivery rises, ports are adopting smart technologies to stay competitive. Using tools such as IoT sensors, big data analytics, automation, and AI, modern ports reduce ship delays, improve cargo handling, and strengthen supply chains, as seen in ports like Rotterdam and Singapore. Digital systems help save fuel, space, and costs while enabling better decision-making through real-time data. At the same time, ports are embracing green practices—such as solar power and reduced emissions to meet environmental regulations and climate challenges. Overall, smart and sustainable ports are becoming essential hubs for efficient, resilient, and future-ready global logistics.

THEORY

FAVOURABLE SITE CONDITIONS:

An ideal port location offers natural advantages that lower construction and maintenance costs while ensuring safe and efficient navigation. A naturally deep and sheltered harbor minimizes the need for dredging and allows large vessels to berth securely. Protection from strong waves, currents, and prevailing winds enables smooth ship movement, while a stable seabed of sand or firm soil provides strong support for heavy port infrastructure with minimal ground preparation.

The site should have minimal sedimentation to reduce the need for frequent dredging and to maintain adequate navigation depth over time. Gentle offshore slopes are preferred, as they allow vessels to approach closer to the shore and lower channel construction costs, while sufficient waterfront space is essential to support future port expansion.

From a connectivity perspective, close access to hinterland transportation networks such as highways, railways, and industrial corridors greatly improves a port's efficiency and economic viability. Reliable availability of fresh water, power supply, and communication infrastructure is also essential to ensure smooth and uninterrupted port operations.

Finally, favorable meteorological conditions such as low fog occurrence, moderate tidal ranges, and minimal exposure to cyclones or storm surges greatly enhance navigational safety and port reliability. Combined with suitable natural and infrastructural features, these factors create an optimal environment for developing a cost-effective, resilient, and high-performing port.

PORT FACILITIES:

Port facilities form the core infrastructure of docks, equipment, and supporting networks that allow ports to function efficiently in handling goods and passengers. On the water side, facilities such as piers, berths, cranes, and breakwaters enable ships to berth safely, protect them from waves, and allow for the quick loading and unloading of cargo. These elements are crucial for minimizing vessel waiting time and ensuring smooth maritime operations. On the land side, ports are supported by warehouses, container yards, paved storage areas, security gates, and terminal buildings that connect maritime activities with road and rail transport. These facilities help store, organize, and transfer goods to trucks and trains while also managing customs and security procedures. When water-side and land-side facilities work in coordination, ports reduce congestion, lower logistics costs, and support global supply chains, employment, and economic growth, making them vital to international trade and transportation. they are as follows:

Harbor Basin: A harbor basin is the sheltered water area within a port where ships can anchor, maneuver, and carry out loading or unloading operations safely. It is typically enclosed by protective structures such as breakwaters, quays, and jetties that reduce the effects of waves, currents, and wind, creating calm conditions for vessel movement. The basin is carefully designed with sufficient depth, width, and turning radius to accommodate different types and sizes of vessels, allowing them to berth and maneuver without difficulty. To maintain safe navigation depths, regular dredging is carried out to prevent sediment buildup. The harbor basin also connects to approach channels that guide ships from the open sea into the port. A well-planned harbor basin improves navigational safety, reduces vessel waiting time, and plays a vital role in enhancing the overall efficiency and performance of port operations.

Breakwaters: Breakwaters are protective structures built to shield harbors from waves, currents, and storms, creating calm water conditions for safe anchoring, berthing, and cargo handling. They are usually constructed parallel or at an angle to the shoreline and may be detached offshore or connected to land, using materials such as rock armor, concrete blocks, or caissons. By reducing wave energy, breakwaters protect harbor structures and improve navigational safety, though their design must carefully consider wave forces, sediment movement, and environmental impacts.

Turning Basin: A turning basin is a widened water area within a port or harbor that allows vessels to safely turn, maneuver, and align with berths or channels. It is especially important for large ships such as container vessels, bulk carriers, and tankers, providing enough space to avoid grounding or collisions. The size and design depend on the largest vessel using the port, along with factors like tides, wind, and currents. Usually located near berthing areas or at the ends of approach channels, turning basins are dredged to suitable depths and equipped with navigational aids. By enabling smooth ship movements, they reduce congestion, minimize delays, and improve overall port efficiency and safety.

Quay/ Wharf/ Jetty/ Pier: Quays, wharves, jetties, and piers are key waterfront structures in a port that support the berthing, loading, and unloading of ships. A quay is a continuous structure along the shoreline where vessels moor directly for cargo or passenger handling, while a wharf is a similar but often larger area with multiple berths and related facilities. A jetty usually extends out from the shore and is used for ship berthing or for protecting harbor entrances from waves and currents. A pier is a pile-supported platform projecting into the water, allowing ships to dock on one or both sides, especially where nearshore depths are insufficient. Built from materials such as reinforced concrete, steel, or stone, these structures are equipped with fenders, bollards, cranes, and mooring systems, forming the essential link between sea-based and land-based port operations.

Berths: A berth is a specific area in a port or harbor where a ship is moored for loading, unloading, or other services. It is designed for particular vessel sizes and types and is located along quays, wharves, jetties, or piers. Berths are equipped with fenders, bollards, and cargo-handling facilities, and may be classified as container, bulk, oil and gas, Ro-Ro, or passenger berths. Proper berth design and planning ensure safe operations, reduce waiting time, and improve overall port efficiency.

Terminal: A terminal is a specialized facility within a port dedicated to handling specific types of cargo or passenger operations. Each terminal is equipped with appropriate infrastructure, machinery, and storage areas to ensure the efficient transfer of goods or passengers between ships and land transport systems. Common types include container terminals with cranes and automated systems, bulk cargo terminals for materials such as coal, grain, or petroleum, Ro-Ro terminals for vehicles that roll on and off ships, and passenger terminals for cruise ships and ferries. Terminals typically include berths, storage yards, warehouses, conveyors or pipelines, and strong road and rail connections. Modern terminals also use digital technologies, automation, and port management systems to improve operational efficiency, safety, and environmental performance, making them the central operational hubs of a port.

Cargo handling equipment: Cargo handling equipment includes the machines and tools used in ports to load, unload, move, and store goods safely and efficiently. Common equipment includes ship-to-shore cranes, gantry cranes (RTG and RMG), forklifts, reach stackers, and straddle carriers for container handling. Bulk cargo is managed using conveyor belts, grab cranes, hoppers, and pipelines for liquid cargo. Modern ports increasingly use automated and digitally controlled systems to improve efficiency, accuracy, and safety.

Navigational Aids: Navigational aids are systems and devices installed in and around ports to ensure the safe and efficient movement of vessels. They help mariners determine position, identify hazards, and navigate safely through channels and harbor areas, even in poor visibility. Common aids include lighthouses, buoys, beacons, and lighted markers, while modern ports also use radar, AIS, and Vessel Traffic Management Systems to monitor and control ship movements in real time. Proper installation and maintenance of these aids are essential for preventing accidents and ensuring smooth port operations.

Approach Channel: An approach channel is a designated and carefully maintained waterway that guides vessels safely from the open sea to a port or harbor. It is designed with adequate depth, width, and alignment to accommodate the size and draft of ships using the port. Approach channels are regularly dredged and marked with navigational aids such as buoys and lights to ensure safe navigation, reduce the risk of grounding or collision, and allow smooth and efficient vessel movement into and out of the port.

Dredging and Reclamation areas: Dredging and reclamation are vital activities in port development and maintenance. Dredging involves removing sediments from channels, basins, and berths to maintain sufficient water depth for safe vessel movement, while reclamation uses the dredged material to create or expand land for port facilities such as terminals and storage areas. Together, these processes improve port efficiency, support future expansion, and require careful environmental management to reduce ecological impacts.

Roads and Rail links: Roads and rail links are key land-side infrastructure elements of a port, providing vital connectivity with the hinterland. Internal roads support smooth movement of cargo, vehicles, and equipment within the port, while external road networks connect the port to highways, industrial areas, and cities for efficient cargo distribution. Rail links enable the cost-effective and environmentally friendly transport of large volumes of goods over long distances. Well-planned integration of road and rail systems with port operations reduces congestion, lowers transport costs, and enhances overall port efficiency and competitiveness.

Ship repair and maintenance: Ship repair and maintenance facilities are specialized port areas that support the inspection, servicing, and repair of vessels to ensure safe and efficient operation. These facilities include dry docks, floating docks, slipways, and workshops for activities such as hull cleaning, painting, structural repairs, and engine maintenance. By offering skilled labor, spare parts, and fueling services, ports help extend vessel life, ensure compliance with safety and environmental standards, and strengthen their role as complete maritime service hubs.

DREDGING:

Dredging is a critical maritime engineering activity essential for maintaining safe navigation depths, operational efficiency, and competitiveness of modern ports. It involves removing sediments from approach channels, basins, and berths to counter natural sedimentation and accommodate increasingly large vessels. Using specialized equipment such as trailing suction hopper dredgers, cutter suction dredgers, and grab dredgers, ports carry out both maintenance and capital dredging for expansion and development. Modern dredging follows strict environmental management practices, including turbidity control, safe handling of contaminated sediments, and beneficial reuse of dredged material for land reclamation or habitat restoration. Overall, effective and sustainable dredging ensures reliable port operations, supports global supply chains, and underpins long-term economic growth.

DREDGING AND SEDIMENTATION CONTROL

Dredging and sedimentation are closely linked processes that directly affect the smooth operation of ports and harbors. Sedimentation occurs when silt, sand, and clay carried by rivers, tides, and coastal waves settle in navigation channels, turning basins, and berthing areas. Over time, this buildup reduces water depth, creating risks for large, deep-draft vessels and causing delays in port operations, as seen in busy ports like the Port of Los Angeles. Without intervention, reduced depths can restrict ship movement, increase grounding risks, and lead to significant economic losses.

Dredging counteracts sedimentation by removing accumulated material and restoring required depths for safe navigation. Using equipment such as cutter suction and trailing suction hopper dredgers, ports maintain channels, basins, and berths to accommodate modern vessels with deep drafts. Regular dredging also improves water circulation, supports port expansion through land reclamation, and enhances environmental management when done responsibly. Modern practices focus on minimizing ecological impacts through careful monitoring, controlled operations, and beneficial reuse of dredged material, helping ports remain efficient, competitive, and environmentally sustainable.

SOFTWARES USED IN EXISTING MODERN PORTS

1. GEOGRAPHIC INFORMATION SYSTEM: Geographic Information Systems (GIS) play a vital role in modern port planning by integrating, analyzing, and visualizing spatial data to support informed decision-making. In the early planning stages, GIS aids site selection and feasibility studies by assessing coastal topography, bathymetry, environmental constraints, land use, and hinterland connectivity. During the design phase, it helps develop efficient port layouts by analyzing spatial relationships between berths, terminals, channels, storage areas, and support infrastructure. GIS also improves maritime safety through mapping navigational routes, identifying hazards, and monitoring vessel traffic patterns.

In addition, GIS is essential for environmental management and operational efficiency. It supports environmental impact assessments by analyzing coastal erosion, water quality, and ecological sensitivity, while also assisting daily port operations through asset tracking, infrastructure monitoring, and maintenance planning. GIS enhances supply chain optimization by evaluating freight flows and transport networks and strengthens disaster risk management through hazard mapping and vulnerability analysis. By providing clear maps, 3D models, and visual dashboards, GIS improves coordination among stakeholders and acts as a comprehensive decision-support system for efficient, sustainable, and resilient port development.

2. BUILDING INFORMATION MODELLING: Building Information Modeling (BIM) plays a crucial role in modern port planning by providing a collaborative, data-driven digital platform that supports the entire lifecycle of port infrastructure. During the planning and design stages, BIM enables the creation of detailed 3D and 4D models of port components such as terminals, berths, breakwaters, and utility systems, allowing better visualization, coordination, and early detection of design conflicts. It also supports simulations for construction sequencing, cost estimation, and operational workflows, helping planners optimize layouts for efficiency, safety, and future expansion while ensuring environmental and regulatory compliance.

During construction and operation, BIM enhances project management through real-time progress tracking, quality control, and improved communication among stakeholders, reducing delays and cost overruns. Once operational, BIM serves as a powerful facility management tool by storing asset data, maintenance schedules, and system information, enabling predictive maintenance and longer asset life. When integrated with technologies like GIS, IoT, and digital twins, BIM further supports continuous monitoring, performance analysis, and resilience planning, making it a vital tool for efficient, sustainable, and resilient port development.

3. DIGITAL TWINS: Digital twins play a transformative role in port planning by creating a dynamic virtual replica of the physical port that integrates real-time data, simulations, and predictive analytics. During the planning stage, they allow engineers and port authorities to visualize port layouts, test design alternatives, and assess the performance of infrastructure such as berths, channels, breakwaters, and storage areas without physical changes. By combining data from IoT sensors, AIS tracking, surveys, and weather forecasts, digital twins help optimize vessel traffic, improve navigational safety, and identify operational bottlenecks in advance.

Throughout construction and operation, digital twins support progress monitoring, resource optimization, and early detection of deviations from plans. Once the port is operational, they enable predictive maintenance, efficient energy and equipment management, and continuous environmental monitoring. Through scenario-based simulations of extreme weather, sea-level rise, and operational stress, digital twins enhance port resilience and sustainability. Overall, they provide a unified, data-driven decision-support platform that reduces costs, improves efficiency, and supports the development of smart, future-ready ports.

4. ARTIFICIAL INTELLIGENCE: Artificial Intelligence (AI) plays an important role in modern port planning by enabling data-driven analysis, prediction, and automation. During planning, AI analyzes traffic, cargo trends, vessel movements, and environmental data to forecast demand and optimize the layout of berths, terminals, storage areas, and navigation channels. AI-based simulations improve navigational safety, logistics efficiency, and environmental assessments, while also supporting climate-resilient and energy-efficient designs. During construction and operations, AI uses real-time sensor data to monitor performance, predict maintenance needs, and enhance safety. Overall, AI helps reduce uncertainty, improve efficiency, and support the development of smart, sustainable, and future-ready ports.

INTERNET OF THINGS: The Internet of Things (IoT) plays a key role in modern port planning by enabling real-time data collection, monitoring, and connectivity across port infrastructure. IoT sensors provide continuous information on vessel movements, environmental conditions, tides, weather, and infrastructure performance, helping planners make accurate decisions on port layout, channel design, and berth planning. IoT also supports resilient and climate-adaptive designs by assessing system behavior under heavy traffic and extreme weather conditions. When integrated with GIS, analytics, and digital twins, IoT enhances spatial planning and operational efficiency. Overall, IoT enables the development of smart, efficient, and sustainable ports through data-driven planning and proactive management.

AUTOMATED TECHNOLOGIES USED IN PORT CONSTRUCTION AND MANAGEMENT

Automated technologies play a vital role in modern port construction and management by improving efficiency, safety, and sustainability. During construction, tools such as laser-based surveying systems, drones, autonomous dredging equipment, BIM, and GIS help create accurate designs, monitor progress, reduce risks, and optimize planning. These technologies allow early detection of design conflicts, precise execution of works, and better coordination among teams. Once operational, automation enhances daily port activities through automated cranes, AGVs, IoT sensors, RFID tracking, and digital twins. These systems speed up cargo handling, reduce errors, enable real-time monitoring, and support predictive maintenance using AI. Although automation requires high initial investment and workforce reskilling, it delivers long-term benefits through lower costs, higher productivity, and environmentally efficient operations, supporting the development of smart and future-ready ports.Some such technologies are explained below:

Automated Dredging equipment: Automated dredging equipment has transformed port and waterway maintenance by using sensors, GPS, and computer-controlled systems for precise sediment removal with minimal human intervention. These systems monitor depth and position in real time, improving accuracy, safety, and efficiency in hazardous marine environments. When integrated with GIS and digital twins, automated dredgers optimize operations, reduce fuel use and environmental impact, and make dredging more cost-effective.

Automated surveying and mapping: Automated surveying and mapping technologies have become essential tools in modern port construction and management, providing highly accurate and efficient spatial data collection. These systems use advanced instruments such as drones, LiDAR, multibeam echo sounders, and GPS-based equipment to automatically capture topographic and bathymetric information. Automation eliminates much of the manual effort involved in traditional surveying, allowing large and complex areas to be mapped quickly and safely, even in challenging marine environments. The collected data is processed and integrated into Geographic Information Systems (GIS) and Building Information Modeling (BIM) platforms, enabling engineers to visualize terrain, monitor construction progress, and detect changes over time. Automated surveying and mapping not only improve accuracy and efficiency but also support better decision-making in design, dredging, and maintenance operations, ultimately leading to smarter and more sustainable port development.

3D printing for construction: 3D printing is an emerging technology in port infrastructure development that creates structural components layer by layer using materials such as concrete or composites. It enables the precise fabrication of customized elements like quay sections and seawall blocks with minimal material waste. By reducing labor needs, speeding up construction, and supporting the use of sustainable materials, 3D printing especially when integrated with BIM and GIS promotes efficient, accurate, and environmentally responsible port construction.

Remote controlling and piling systems: Remote controlling systems in port construction allow heavy machinery such as cranes, excavators, and piling rigs to be operated from a safe distance using digital and wireless technologies. This improves worker safety by limiting exposure to hazardous areas and enhances accuracy through GPS, sensors, and real-time monitoring. By reducing human error and labor requirements, remote-controlled systems increase efficiency, precision, and speed in port infrastructure construction.

Automated Guided Vehicles (AGVs): Automated Guided Vehicles (AGVs) are self-driving vehicles used in ports and terminals to transport containers and cargo efficiently without human intervention. Guided by sensors, GPS, magnetic tracks, or laser navigation systems, AGVs move along pre-defined routes to transfer goods between ships, storage yards, and loading areas. These vehicles operate high. Precision, reducing accidents, fuel consumption, and waiting times compared to traditional truck-based Transport. In smart ports, AGVs are integrated with terminal operating systems (TOS) and IoT networks, enabling real-time coordination with cranes and other automated equipment. They enhance productivity, ensure 24/7 operations, and contribute to a cleaner and safer working environment by minimizing human involvement in high-risk areas.

Automated Stacking Cranes (ASCs): Automated Stacking Cranes (ASCs) are advanced, computer-controlled cranes used in container terminals for the precise stacking and retrieval of containers in storage yards. Operated through automated control systems and guided by sensors, GPS, and cameras, ASCs can efficiently handle containers with minimal human supervision. These cranes work in coordination with Automated Guided Vehicles (AGVs) or trucks to optimize yard space and ensure smooth cargo flow. The automation reduces human error, increases stacking density, and enhances operational speed and safety. In modern smart ports, ASCs are integrated with terminal management systems to enable real-time tracking, energy-efficient operation, and predictive maintenance. This technology not only boosts productivity but also contributes to sustainable and intelligent port operations.

Robotic Container Inspection: Robotic container inspection involves the use of autonomous or semi-autonomous robots to examine shipping containers for damage, security threats, or compliance with customs regulations. These robots are equipped with high-resolution cameras, sensors, and sometimes Xray or infrared scanning systems to detect structural defects, leaks, or hazardous materials without manual intervention. Using AI and image analysis, the system can quickly identify irregularities, record inspection data, and transmit it to port authorities in real time. This automation significantly reduces inspection time, enhances accuracy, and minimizes human exposure to unsafe or high-risk environments. In smart ports, robotic inspection systems are integrated with digital platforms and databases, enabling faster cargo clearance, improved safety, and greater efficiency in port operations.

IoT-Based Asset Tracking: IoT-based asset tracking systems use interconnected sensors and wireless communication technologies to monitor the real-time location, condition, and status of assets such as containers, vehicles, cranes, and cargo handling equipment within a port. These Internet of Things (IoT) devices collect and transmit data on movement, temperature, humidity, and vibration to a central monitoring platform. This allows port operators to track assets accurately, prevent loss or theft, and optimize equipment usage. By integrating IoT tracking with GIS and Port Community Systems, ports can achieve greater visibility across their logistics chain, improve scheduling, and reduce operational delays. Overall, IoT-based asset tracking enhances efficiency, transparency, and safety, making it a key technology in the digital transformation of modern smart ports.

Digital Traffic Management Systems: Digital Traffic Management Systems (DTMS) are advanced, technology-driven solutions used to coordinate and control the movement of ships, vehicles, and cargo within and around port areas. These systems use real-time data from GPS, Automatic Identification Systems (AIS), radar, and IoT sensors to monitor vessel traffic, truck flow, and terminal operations. Artificial intelligence and predictive analytics help optimize berth allocation, route planning, and scheduling to minimize congestion and waiting times. DTMS also support automated communication between port authorities, pilots, and shipping operators for safer navigation and efficient turnaround of vessels. By integrating with Port Community Systems (PCS) and digital twins, these systems enhance situational awareness, reduce delays, and improve overall operational efficiency. In smart ports, digital traffic management ensures smooth, coordinated, and sustainable movement across all modes of transport.

Autonomous Surface and Underwater Vehicles: Autonomous Surface Vehicles (ASVs) and Autonomous Underwater Vehicles (AUVs) are robotic systems used in port construction, maintenance, and environmental monitoring without the need for direct human control. ASVs operate on the water’s surface, while AUVs function below it, both equipped with sensors, sonar, cameras, and GPS for navigation and data collection. These vehicles are widely used for hydrographic surveying, seabed mapping, inspection of underwater structures like quay walls and pipelines, and monitoring water quality. They can operate in hazardous or hard-to-reach areas, ensuring safety and precision while reducing operational costs. By integrating with GIS and digital twin systems, ASVs and AUVs provide accurate real-time data that supports construction planning, dredging operations, and long-term port maintenance. Their use enhances efficiency, safety, and environmental sustainability in modern smart port management.

BENIFITS OF AUTOMATION TECHNOLOGIES IN PORT CONSTRUCTION AND MANAGEMENT:

Automation tools play a vital role in both the construction and operation of modern ports by improving efficiency, safety, and sustainability. During construction, robotic systems for piling, dredging, and foundation work use sensors and laser guidance to achieve high precision while reducing human error and keeping workers out of hazardous environments. These technologies significantly speed up construction timelines and lower risks, as seen in advanced ports such as Singapore. In day-to-day port operations, automation enables round-the-clock activities through automated cranes, smart gates, and computer-controlled container handling systems, reducing labor costs and workplace injuries. Technologies like IoT, AI, and digital twins support real-time monitoring, predictive maintenance, and performance optimization, cutting downtime and improving reliability. With added support from cloud computing and blockchain for secure data sharing, automation enhances coordination, resilience, and environmental performance, helping ports become smart, efficient, and future-ready hubs of global trade.

CHALLENGES AND LIMITATIONS OF AUTOMATED TECHNLOGIES IN PORT CONSTRUCTION AND MANAGEMENT:

Automation offers major benefits to ports by improving speed, safety, and efficiency, but it also presents significant challenges. High initial investment costs for robotic systems, sensors, and software make automation difficult for smaller and developing ports, while integrating new technologies with outdated legacy systems often causes delays and technical issues. In addition, automation requires skilled professionals in areas such as AI, robotics, and data analysis, and the global shortage of such expertise increases training costs and slows adoption.

Cybersecurity risks, high maintenance demands, and limited flexibility during unexpected events such as storms further complicate automation efforts. Resistance from workers concerned about job security, along with inconsistent regulations across countries, also slows implementation. While automation clearly enhances port performance and competitiveness, its long-term success depends on addressing financial constraints, technical integration, workforce development, and regulatory coordination.

STRATEGIES TO MITIGATE CHALLENGES OF AUTOMATED TECHNOLOGIES IN PORT CONTRUCTION AND MANAGEMENT:

Ports face challenges in adopting automation due to high costs, skill shortages, cybersecurity risks, and difficulties integrating new technology with older systems. These issues can be addressed through phased investments that spread costs over time, focusing first on critical operations such as cargo handling. Public–private partnerships also help share financial and technical risks, making automation more affordable and practical.To overcome workforce and operational challenges, ports need continuous staff training, strong cybersecurity measures, and systems that are interoperable across technologies. Predictive maintenance tools can reduce downtime, while clear communication and change management help reduce resistance from workers. Collaboration with educational institutions and technology providers further supports customized, sustainable automation solutions, enabling ports to improve efficiency and remain competitive.

METHODOLOGY

AUTOCAD

AutoCAD is a commonly used computer-aided design (CAD) software in port planning and coastal infrastructure development. It allows engineers and planners to produce accurate 2D and 3D drawings of port layouts and structural elements. In this study, AutoCAD was used to design key port components such as the harbor layout, approach and entrance channels, turning basin, berthing facilities, breakwaters, groynes, quays, storage areas, and associated road and rail networks. The software supports precise scaling, alignment, and dimensioning in accordance with navigational and engineering standards.

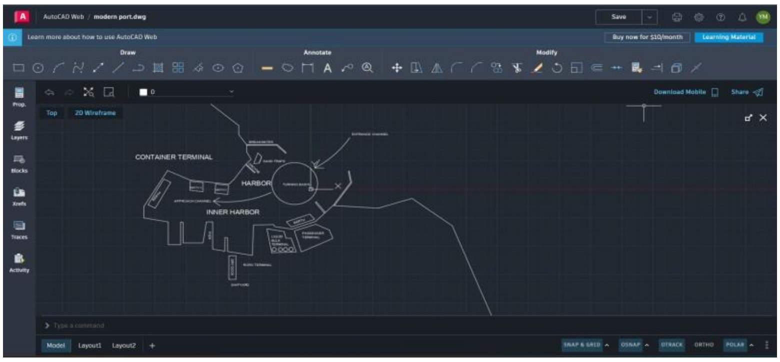

Fig 1: Shows plan of port drafted in Auto CAD

The design process started with importing base site data and setting up appropriate layers, line types, and scales to ensure clarity and accuracy. Drafting tools such as polyline, offset, trim, extend, and dimension commands were used to develop each structure systematically. Repetitive features like breakwaters, groynes, and berths were created as blocks to maintain uniformity and reduce drafting time. The plan mainly focuses on the entrance and approach channels, turning basin, and berthing areas, with design parameters such as a 460 m turning basin radius, breakwater lengths of 1750 m on the seaward side and 600 m on the leeward side, and a berth length of 520 m. The final drawings include clear annotations, dimensions, and technical notes to improve understanding and support further analysis. Based on existing port guidelines and reference plans, the proposed layout was prepared using the AutoCAD web browser, providing a strong foundation for subsequent simulations and studies.

ANYLOGIC:

AnyLogic is a multi-method simulation software widely used for modeling complex systems involving logistics, transportation, and infrastructure operations. In the context of port planning, AnyLogic enables dynamic simulation of port activities such as cargo handling, vessel movements, berth allocation, storage operations, and intermodal transportation. The software combines discrete-event, agent-based, and system dynamics modeling approaches, allowing users to analyze both physical processes and decision-making behaviors within the port system.

AnyLogic offers a visual, interactive platform for port planners to import CAD layouts and simulate real-time operations, helping evaluate performance metrics such as waiting times, throughput, congestion, and resource utilization. It enables identification of bottlenecks, optimization of terminal layouts, and assessment of design or policy impacts before implementation. GIS integration and 3D visualization enhance spatial analysis and support efficient, sustainable port development.

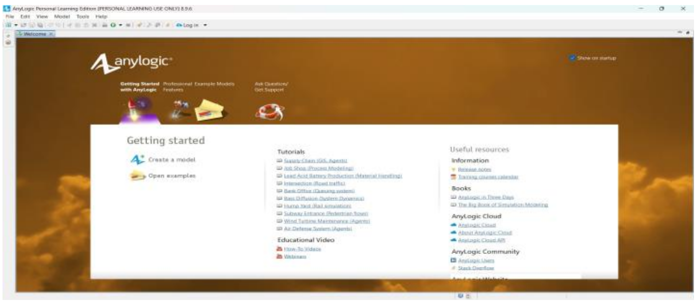

Fig 2: Shows Interface of Anylogic Software.

In this study, the simulation model was developed using AnyLogic Personal Learning Edition 8.9.6 with an agent-based modelling approach. Custom agents representing moving entities were created with defined behaviors, parameters, and state logic to reflect port operations. The main environment was built using the Presentation view, incorporating visual components and schematic diagrams via Image elements for alignment with real-world layouts. Core process components like Source, Queue, Conveyor, and Sink from the material and process modelling libraries were arranged to represent cargo or vessel movement through sequential operations. Conveyors were calibrated for realistic transport speeds, and Queues modeled waiting under capacity constraints. A 3D Window provided three-dimensional visualization of cargo flow, equipment positioning, and system dynamics, enhancing model interpretability and validation. Components were linked and parameterized, and multiple test runs ensured logical consistency, smooth agent movement, and accurate representation of operational workflows.

DESIGN CONSIDERATIONS IN GENERAL

The design of modern ports is a multidisciplinary process that combines engineering, logistics, environmental science, and economics to meet the growing demands of global maritime trade. Unlike traditional ports, which focused mainly on basic cargo handling, modern ports must accommodate larger vessels, diverse cargo types, advanced technologies, and sustainability goals. Effective port design balances technical feasibility, operational efficiency, and environmental responsibility.

Navigational requirements are a primary consideration, with ultra-large container vessels, tankers, and bulk carriers demanding sufficient depth, width, and turning basins. Channel alignment, dredging, tidal variations, and sedimentation patterns are analyzed using hydraulic and coastal engineering principles to ensure safe maneuvering, efficient berthing, and long-term maintenance. Structural and functional planning integrates berths, docks, cargo yards, and repair facilities to optimize space and cargo flow. Specialized equipment is designed for different cargo types, from high-capacity cranes for container terminals to pipelines and storage tanks for oil and LNG terminals. Intermodal connectivity ensures smooth transfers between sea, road, rail, and inland waterways, reducing congestion and improving efficiency.

Technological integration is essential, with digital twins, automation, smart monitoring systems, AGVs, and real-time tracking enhancing resource allocation, operational flow, and decision-making, while cybersecurity safeguards digital infrastructure. Environmental considerations are equally critical, with sustainable practices such as eco-friendly dredging, renewable energy, shoreline protection, waste management, and climate resilience measures helping minimize ecological impact. Socio-economic factors are also incorporated, ensuring ports support regional development, align with trade strategies, and allow modular expansion for future technologies.

In essence, modern port design adopts a holistic systems approach that integrates navigational safety, structural efficiency, technological innovation, environmental stewardship, and socio-economic adaptability. This comprehensive perspective transforms ports into smart, sustainable, and resilient hubs capable of handling global trade demands and future uncertainties.

DESIGN CRITERIA:

Design criteria are the quantitative and qualitative parameters that guide engineers and planners in the detailed design of port facilities. These criteria ensure the port is safe, efficient, durable, and environmentally sustainable.

Below are the key design criteria commonly considered in port planning:

Design vessel dimensions:

The largest ship ever built was an oil tanker, Sea-wise Giant, which is 458.45m (1,504ft) built in 1979. Dead weight tonnage is 564,763 tons and width is 69m (225ft). Taking this into consideration, I've taken the length of the vessel as 460m and beam as 70m. Draft as 16m and design depth as 23m refined with site-specific squat calculations and UKC policy. Static UKC 1.0-1.5m, squat allowance of 1.5-3.0m and siltation of 0.5-1.0m considered.

Approach channel width:

Generally, 3–5 times the beam of the design vessel for one-way traffic and 5-7 times beam for two-way traffic.

W= N*B* +2C

= 2 *70+2* (0.3*70)*

= 182m

W= Total width

N= No. Of ships arrest

B= Beam width

C= Clearence on each side 0.3B to 1.0B

*As beam of the vessel considered is 70m, for two-way traffic the width of channel ranges as 5*70 to 7*70 i.e. 350 to 490. So, considered channel width as 450m.

Entrance channel width:

1.2* Approach channel width

1.2*450 = 540m

Turning basin diameter:

Usually, 1.5 to 2.5 times the length of the design vessel.

Overall length (LOA)= 2*460m

= 920m.

Berth length and spacing:

Length= vessel LOA + 10–15% clearance; spacing for mooring operations.

=30m+460m+30m

= 520m.

RESULTS AND DISCUSSION

The study produced key results that closely align with its objectives and methodologies. The review of modern port planning principles clarified essential components such as 520 m berths, 460 m turning basins, operational zones, and cargo-handling areas which guided the port layout design. Using AutoCAD, a detailed functional layout was developed with accurate geometric dimensions and realistic spatial arrangements, effectively representing structural elements like berths, storage yards, approach channels, and internal transport corridors. The drawings ensured clarity, technical consistency, and suitability for further operational analysis.

AnyLogic simulations provided deeper insights into the dynamic functioning of the designed layout. By modeling cargo movement, truck and equipment operations, and vessel navigation along defined paths, the study captured realistic port behavior. Results highlighted travel times, queue lengths, resource utilization, and loading/unloading cycles, while pinpointing critical areas such as storage–berth interfaces, navigational turns, and entry–exit zones under high-demand scenarios. Quantitative outputs showed improved system performance when modern planning features like optimized yard allocation, streamlined truck routes, controlled queues, and realistic vessel trajectories were applied.

Comparison with conventional planning methods revealed that modern approaches significantly enhance efficiency, reduce delays, and improve capacity utilization. Modern systems also demonstrated greater adaptability to fluctuations in cargo volumes, vessel arrivals, and equipment availability. Integration of smart planning concepts, including automated flow control and optimized resource deployment, further promoted sustainable and resilient operations. Overall, the combination of precise AutoCAD design and dynamic AnyLogic simulation proved to be a reliable method for evaluating and improving port layouts, identifying operational strengths and weaknesses, and supporting technology-driven modern port planning strategies.

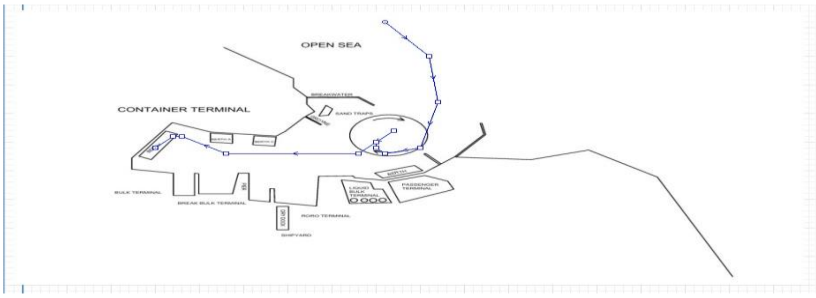

Fig 3: Path of the vessel into Berth 1.

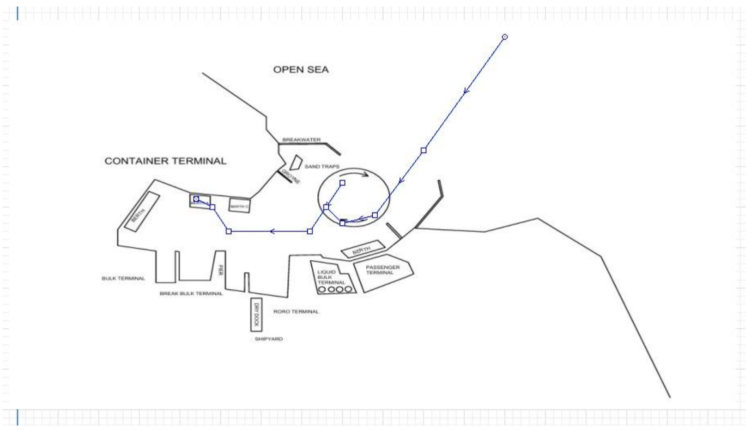

Fig 4: Path of the vessel into Berth 2.

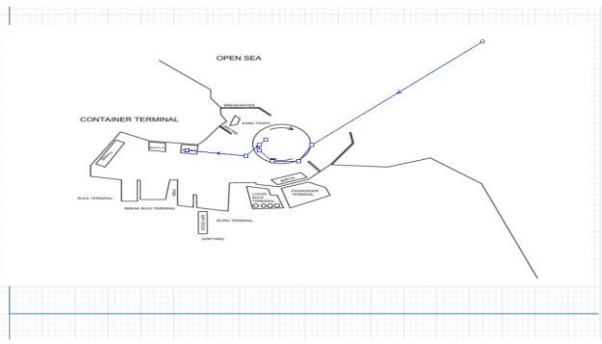

Fig 5: Path of the vessel into Berth 3.

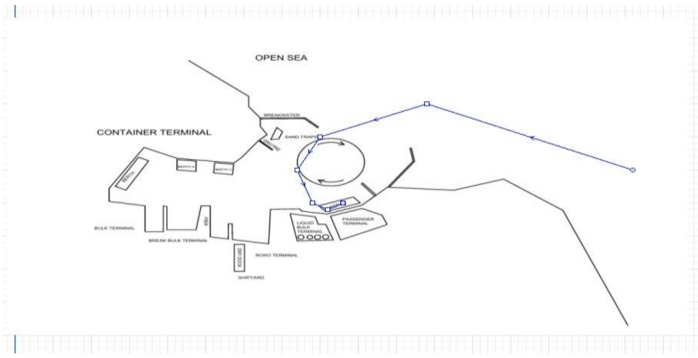

Fig 6: Path of the vessel into Berth 4.

The discussion highlights how combining AutoCAD design with AnyLogic simulation enhances port planning, operational assessment, and decision-making. With global trade surpassing 11 billion tons in 2024, ports face growing cargo volumes and require precise planning tools. AutoCAD provides accurate, detailed layouts of ports, including channels, berths, and turning basins, ensuring compliance with international standards for navigation and operational efficiency. Proper berth spacing, channel widths, and turning basin dimensions help prevent collisions, reduce delays, and allow cranes and vessels to operate smoothly.

Once the AutoCAD design is completed, it is imported into AnyLogic, a dynamic simulation tool that models real-world port operations under varying conditions, such as peak traffic or adverse weather. The simulations track vessel arrivals and departures, queue lengths, berth occupancy, truck movements, and cargo handling, revealing bottlenecks that static plans cannot capture. For example, congestion at busy docks or delays in cargo transfer under multiple simultaneous arrivals becomes evident. By integrating AutoCAD's precise visual layout with AnyLogic's dynamic operational modeling, planners gain a complete understanding of daily operational stresses, enabling ports to optimize traffic flow, reduce redesign costs, and improve resilience. This combined approach supports more efficient, adaptable, and future-ready port systems capable of handling increasing trade demands.

CONCLUSIONS

The study successfully met all the stated objectives related to understanding and advancing modern port planning. A detailed review of port principles, components, and operational requirements established a strong foundation for evaluating contemporary planning approaches. The assessment of emerging technologies such as automation, IoT, smart systems, and digital twins highlighted their significant role in improving port development, efficiency, and decision-making. An accurate and functional port layout was developed using AutoCAD, reflecting modern design standards and realistic spatial requirements, and serving as a reliable base for further analysis.

Using AnyLogic, vessel movement paths and operational behavior were effectively simulated, providing insights into logistics, waiting times, handling efficiency, and overall system flow. The study also evaluated approach channel conditions, emphasizing the need for economical dredging and silt-control measures to maintain adequate depth and ensure safe navigation. Comparisons between conventional and modern planning methods showed clear advantages of technology-driven approaches in efficiency, adaptability, and sustainability. While challenges such as high initial costs, data management, and skill requirements were identified, the findings also underscored opportunities for optimization through automation, real-time monitoring, and predictive operations.

Overall, the integration of precise geometric design with dynamic simulation proved to be a robust framework for modern port planning. The results support the development of resilient, sustainable, and technology-enabled ports, reinforcing the importance of smart tools and data-driven strategies for long-term adaptability and performance.

LIMITATIONS OF THE STUDY:

The study effectively demonstrates the combined use of AutoCAD and AnyLogic to evaluate innovative port design concepts; however, several limitations influence the depth and applicability of the results.

In AutoCAD, the port layout remains at a conceptual level and does not include detailed structural, geotechnical, or hydrodynamic analyses. Critical aspects such as soil bearing capacity, foundation stability, wave forces, and long-term settlement are not assessed, which limits the design’s readiness for real-world implementation. As a result, the layout functions more as a preliminary planning model than a fully validated engineering design.

Similarly, the AnyLogic simulation is based on simplified assumptions. Vessel arrivals, service times, and cargo movements rely on estimated or fixed values rather than real operational data. In reality, port operations are highly variable due to peak traffic periods, weather conditions, and equipment availability, which are not fully captured in the model. The use of the AnyLogic Personal Learning Edition further restricts model scale and complexity, limiting its ability to represent large, high-traffic ports.

Environmental factors such as tides, waves, sedimentation, and extreme weather events are also excluded, despite their significant influence on port efficiency and maintenance requirements. Additionally, the study focuses mainly on operational flow, without incorporating economic analysis, environmental impacts, or risk and safety assessments, all of which are essential for comprehensive port planning.

Overall, these limitations indicate that the model serves as a strong conceptual and exploratory tool rather than a complete decision-making system. Incorporating real operational data, advanced software capabilities, environmental processes, and multidisciplinary inputs would enhance accuracy and transform the framework into a more robust and practical solution for real-world port planning.

SCOPE FOR FURTHER STUDY:

This study provides a strong foundation for modern port planning, but several opportunities exist for future improvement. The simulation model can be enhanced by incorporating realistic vessel arrival patterns, such as peak-season traffic surges, along with environmental influences including wind, fog, and tidal variations that affect navigation and berthing. Integrating these factors would improve the realism and reliability of the results.Further development could include advanced cargo-handling technologies, such as automated cranes, smart conveyors, and AI-based systems that predict congestion and optimize operations in real time. These additions would help reduce delays and improve overall port efficiency.

While the AutoCAD layouts offer an effective starting point, future work could extend them by incorporating structural strength assessments, geotechnical considerations, and cost estimation tools. This would allow the transition from conceptual layouts to more comprehensive, construction-ready designs. Environmental studies also present scope for expansion. Hydrodynamic modelling, wave analysis, and sediment transport studies can help assess erosion risks, storm impacts, and channel maintenance needs, thereby improving safety and long-term resilience.

The AnyLogic model can be broadened to represent complete port ecosystems, including trucks, cranes, storage yards, workforce movement, and hinterland transport connections. Linking this with a digital twin framework—supported by real-time sensor data—would enable continuous monitoring, predictive maintenance, and adaptive decision-making. Overall, these advancements can transform the current framework into an intelligent, data-driven system capable of supporting autonomous, efficient, and resilient port operations.

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