

Smart Port Technologies: A Scoping Review

Tran Xuan The*, Thomas Do, and Hoang Quoc Dong

Abstract: Port digitalization has accelerated rapidly, and the body of literature on the technologies that enable smart ports has grown with it. This paper presents a scoping review of recent research on these enabling technologies: digital twins, blockchain, artificial intelligence (AI), the Internet of Things (IoT), computer vision, unmanned aerial vehicles (UAVs), automation, and cybersecurity. Following a PRISMA-guided search of IEEE Xplore and Web of Science and the screening of 322 records, 67 studies were retained and coded. For each technology we examine the current state of deployment, documented applications, reported maturity, and known limitations. The literature organises around six core domains: digital twin; blockchain and distributed ledger; AI and data analytics; IoT and 5G connectivity infrastructure; computer vision and UAV-based sensing; and automation, robotics, and autonomous systems. We map these pillars against cross-cutting themes (interoperability, governance, human factors, and cybersecurity) in a coverage matrix that exposes where research is concentrated and where it is thin. Three gaps recur: interdisciplinary approaches are underused, human-centred research is scarce, and empirical deployment studies lag behind conceptual work. The review is intended as a resource for researchers, practitioners, and policymakers working on port automation and efficiency.

Keywords: Artificial intelligence, blockchain, cybersecurity, digital twin, industry 4.0, IoT, maritime logistics, smart port, sustainability, port automation.

1. INTRODUCTION

Seaports increasingly need to operate as intelligent, data-driven facilities that optimise throughput, safety, resilience, and environmental performance. This shift is commonly framed as the smart port, or Port 4.0, transformation, enabled by ICT, advanced analytics, and cyber-physical integration [1], [2], [3]. Research activity in this area has grown rapidly, and the literature now covers a wide range of technology pathways [4], [5], [6]. A practical gap remains, however: it is not always clear which digitalization approaches have been deployed operationally and which remain conceptual.

Dedicated conference tracks and journal special issues reflect the field's volume [7]. A persistent problem is that "smart port" applies to a broad range of strategies, from basic network upgrades to full autonomy, with no common architectural framework to distinguish between them. Earlier work focused on ICT's role in improving port visibility and coordination [1], whereas more recent contributions propose structured architectures drawing on Industry 4.0 principles: interoperability, data governance, and convergence across operational levels

[8]. Enterprise-architecture methods have also been used to translate the smart port vision into operational roadmaps, mapping the business, information, and technology layers needed for automation and digital twin implementation [9]. There is also the question of investment timing: when to commit, and how much, in an environment where technology options change faster than capital cycles. Thus, digital strategies need to be driven by operational objectives rather than technology availability alone [10].

The digital twin (DT) is a virtual, data-connected representation of port assets and processes that supports monitoring, prediction, and optimization [11], [12]. DT applications have been demonstrated in automated container terminals for real-time monitoring and resource allocation, showing that simulation and analytics can directly inform operational decisions [13]. DT-based methods have also been used in decarbonization work, where improved arrival prediction enables more coordinated ship-port scheduling [14]. Combining DT frameworks with machine learning has shown feasibility for improving terminal production efficiency [15]. Beyond productivity, DT-based safety

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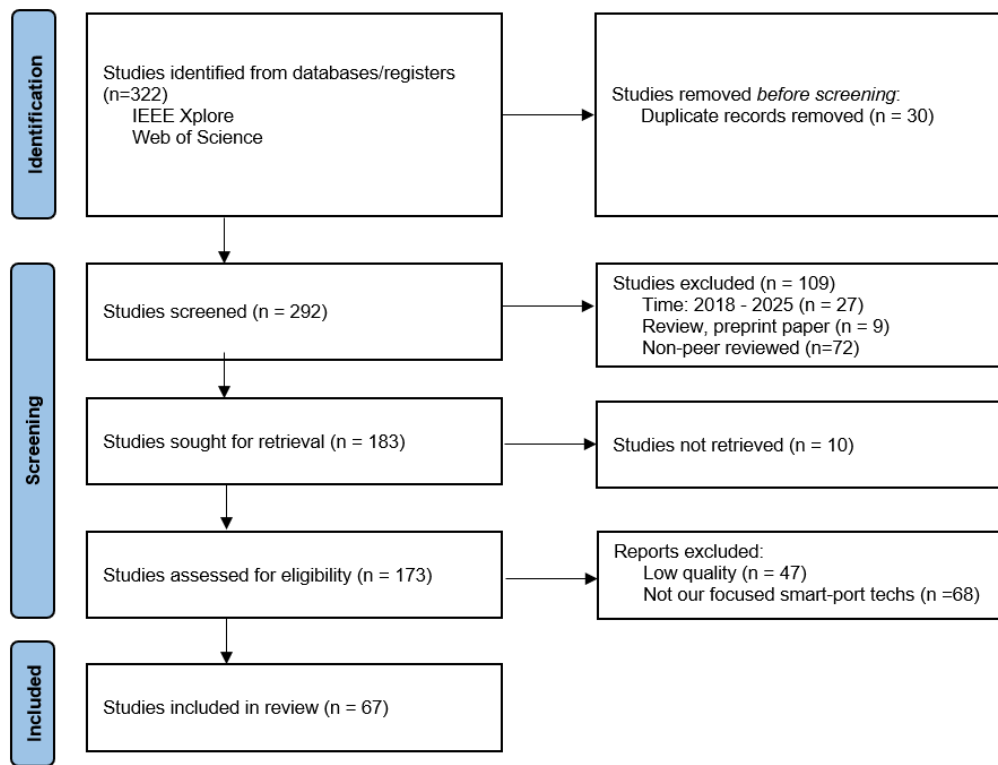


Fig. 1. PRISMA-style flow diagram.

management has been proposed for hazardous cargo handling, using predictive analytics to support risk prevention decisions [16]. Further, event-driven, real-time frameworks show how DT-ready architectures can support decentralized, autonomous decision making [17].

In addition to DTs, smart port architectures typically include connectivity infrastructure (e.g., IoT), AI and analytics, cybersecurity, and energy management. IoT sensor deployments are being evaluated for performance monitoring and operational visualization [18]. Quantitative, IoT-enabled performance indices for environmental monitoring are becoming common and allow near-real-time comparison and benchmarking [19].

Computer vision and deep learning have been used for traffic and yard management, including parking, lane control, and drayage efficiency, with documented prospects for AI-enabled port mobility [20]. AI adoption is also shaped by organizational readiness and the socio-technical context of individual facilities, not by technical capability alone [21], [22]. For environmental operations, AI has been used to connect terminal optimization directly to emissions outcomes [23], [24].

As ports incorporate more IoT devices and shared digital platforms, trust, security, and data integrity become harder to treat as secondary concerns. Blockchain has been studied for coordination, traceability, and decision support in port logistics [25], [26]. Smart-contract-based approaches have also been proposed to automate shipping-port processes, reflecting broader interest in decentralized trust for operational workflows [27]. Digitalization also enlarges the attack surface. Risk management frameworks for port IoT devices stress the need for systematic vulnerability identification and mitigation to ensure continued

operation [28]. Hence, the cyber governance requirements grow with the digital ambitions.

Sustainability is no longer treated as separate from operational goals. Reviews and conceptual models have examined how ecological, social, and economic factors, along with the indicators and management practices used to track them, shape smart port performance [29], [30]. Port operations are further shaped by organizational factors such as management capacity, stakeholder involvement, and institutional capacity to integrate technology with existing practices [31].

Smart port initiatives are also converging with the push for autonomous maritime transport. Research on maritime autonomous surface ships examines the port operational adaptations required [32], [33], while broader discussions address the regulatory, economic, and cybersecurity aspects of AI-enabled and autonomous solutions in maritime contexts [34]. These developments carry workforce implications, as new technologies are reshaping maritime work faster than retraining strategies can respond [35].

Several recent reviews have surveyed parts of this landscape: bibliometric and thematic mappings of maritime digitalization [4], [5], innovation-focused reviews of container-port digitalization [36], and technology-specific surveys of digital twins [54] or blockchain [46]. These contributions are valuable, but they tend to stay within a single technology silo or adopt a purely bibliometric lens, offering limited cross-technology synthesis and little assessment of deployment maturity. This review differs in three respects. First, it organises the field into six technology pillars and maps each pillar to concrete port operational objectives rather than treating technologies in isolation. Second, it

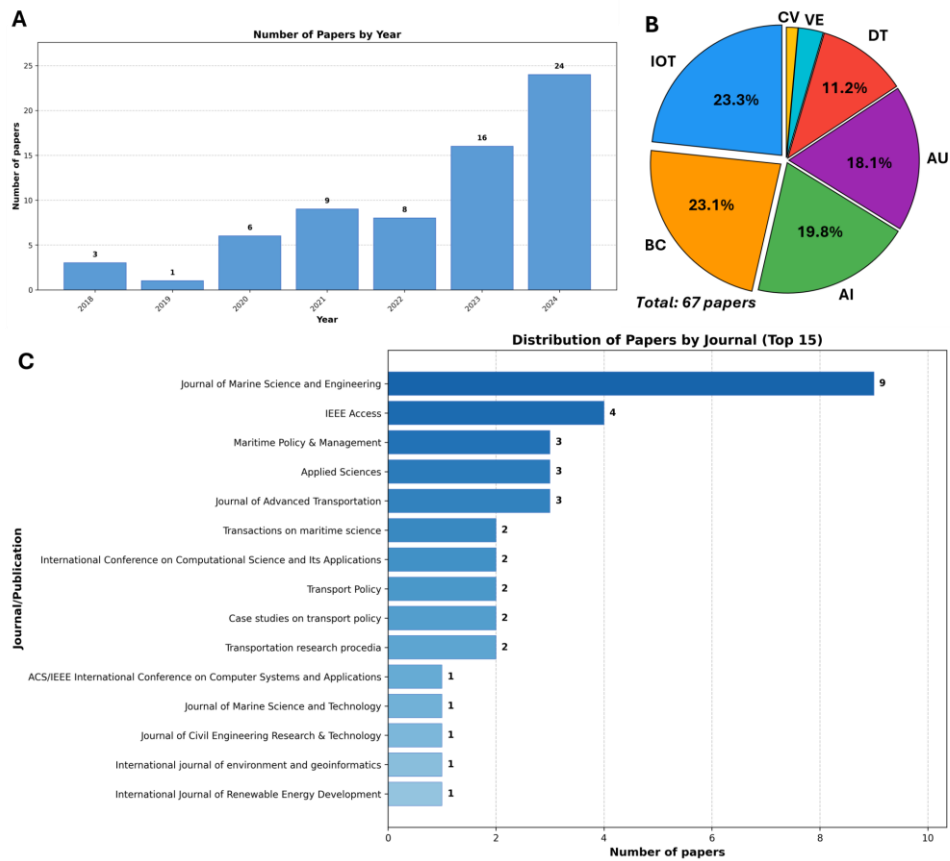


Fig 2. Publication trends and thematic coverage in the screened smart-port subset (N = 67). (A) Number of papers by year (2018–2024). (B) Technology-domain distribution across the subset: IoT (IoT and data infrastructure) - 23.3%, BC (Blockchain and cybersecurity) - 23.1%, AI (Artificial intelligence and machine learning) - 19.8%, AU (Automation and robotics) - 18.1%, DT (Digital twin) - 11.2%, CV (Computer vision) - 1.4%, and VE (Vehicles- UAV and Drone) - 3.1%. (C) Top 15 publication venues by paper count.

introduces a cross-cutting coverage matrix (Fig. 6) that positions the six pillars against four integration themes (interoperability, governance, human factors, and cybersecurity), making explicit where research is mature and where it is sparse. Third, it foregrounds practical deployment barriers and technology maturity (summarised in Table 1) rather than describing capabilities alone.

The literature reflects rapid progress but remains fragmented across technology silos, with limited synthesis connecting operations, security, sustainability, and human factors into integrated architectures [36], [37]. This paper addresses that gap. We provide an overview of the main technology pillars mapped to operational objectives; we synthesise enabling architectures and decision-support approaches, with a focus on digital twin-driven planning and operations; we treat trust, security, and sustainability as design requirements rather than afterthoughts; and we identify cross-cutting issues including interoperability, standards, and socio-technical readiness. Section 2 outlines the review methodology; Section 3 reviews the enabling technologies and the cross-cutting integration themes; Section 4 discusses research gaps and future directions; and Section 5 concludes with implications for research and practice.

2. METHODOLOGY

2.1. Literature search strategy

Fig 1. PRISMA-style flow diagram summarizing the study identification, screening, eligibility assessment, and inclusion process for the smart port technology literature review. Records were retrieved from IEEE Xplore and Web of Science (n=322), duplicates were removed (n=30), and the remaining studies were screened (n=292). After full-text retrieval and eligibility assessment, a final set of studies was included in the review (n=67), with exclusions at each stage documented by the main reasons shown in the diagram.

A systematic, PRISMA-guided search was carried out to identify peer-reviewed research on smart port technologies, architectures, and applications. Two indexing databases with strong coverage of engineering and maritime venues, IEEE Xplore and Web of Science, were searched for the period January 2018 to March 2025, reflecting the years in which maritime digitalization initiatives accelerated. The search combined port-domain terms with technology terms using the Boolean query: (“smart port” OR “digital port” OR “port digitalization” OR “port automation”) AND (“digital twin” OR “blockchain” OR “artificial intelligence” OR “machine learning” OR “Internet of

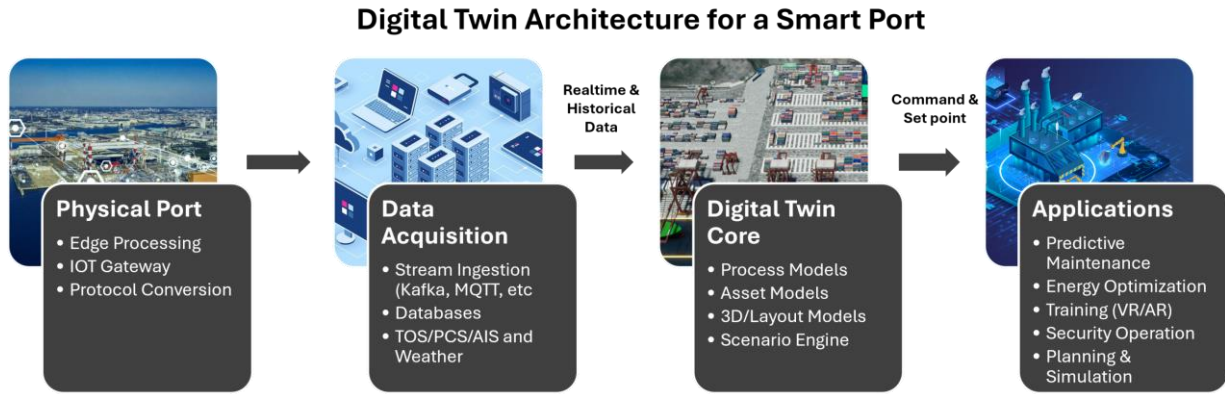


Fig 3. High-level smart port digital twin architecture. Data from the physical port (edge processing, IoT gateways, and protocol conversion) is collected via a data acquisition layer (stream ingestion such as Kafka/MQTT, databases, and external operational feeds including TOS/PCS/AIS and weather). These inputs power a digital twin core comprising process, asset, and 3D/layout models with a scenario engine, enabling downstream applications such as predictive maintenance, energy optimization, VR/AR training, security operations, and planning/simulation.

Things” OR “IoT” OR “5G” OR “computer vision” OR “UAV” OR “automation” OR “cybersecurity”). Queries were restricted to the title, abstract, and keyword fields and to English-language journal articles, conference proceedings, and selected book chapters. The initial search returned 322 records.

As summarized in Fig. 1, the following inclusion criteria were applied:

- (i) The report mentions ports or maritime terminals and refers to digital or smart technologies in this context.
- (ii) The manuscript highlights one or more enabling technologies relevant to smart ports (for instance IoT, digital twin, blockchain, AI, automation, etc.)
- (iii) The contribution may involve theoretical frameworks, system architectures, case studies, simulations or empirical studies.
- (iv) The publication of the work is in English and it is available from the recognised databases.

Studies were excluded if they:

- (i) Concentrating on maritime transport or shipping only with no port-related factor.
- (ii) Share only top-level policy-making conversations, omitting technicalities or architectural detail.
- (iii) Are exclusively descriptive news articles, short editorials or non-scholarly opinion pieces.

Following full-text retrieval, each remaining study was appraised for methodological quality against four criteria: (i) clarity of aim and stated contribution; (ii) adequacy of methodological description; (iii) presence of empirical, simulation, or case-study evidence rather than opinion alone; and (iv) relevance to one or more of the targeted smart-port technologies. Studies that failed two or more criteria were recorded as low quality and excluded ($n = 47$); a further 68 records that did not address the targeted technologies were also excluded, leaving 67 studies for synthesis (Fig. 1).

2.2. Screening and classification process

The screening and coding process was conducted in three stages (Fig. 1). First, the titles and abstracts of all records were screened to remove items clearly outside scope. Second, the full texts of the remaining records

were assessed against the inclusion, exclusion, and quality criteria. To limit selection bias, screening decisions were made independently by two of the authors, and disagreements were resolved through discussion with the third author. Third, the retained studies were coded against a classification framework capturing technology type, application domain, methodological approach (conceptual, simulation, case study, or empirical), and reported outcomes. The framework groups the literature into six pillars: digital twin; blockchain and distributed ledger; artificial intelligence and data analytics; IoT and 5G connectivity infrastructure; computer vision and UAV-based sensing; and automation, robotics, and autonomous systems. These pillars structure the technology synthesis in Section 3. Fig. 2 summarises the publication trend and the distribution of the screened studies across the six pillars.

3. TECHNOLOGY REVIEW

3.1. Digital twin technology

(a) *Overview and concept*: Technology Digital Twin (DT) technology is one of the most important capabilities for smart ports, enabling an iteratively refreshed virtual image of port assets, systems, and processes representing the dynamic physical state of operations [11], [12]. DTs came initially from manufacturing and complex engineering systems but are adopted for port operations to facilitate the intercomputation of highly coupled socio-technical activities (berth-yard-gate), automate equipment-dependent terminals, and enhance resilience and sustainability in case of operational uncertainty [1], [8]. A port DT in real-world examples, is not one model, but a stack that connects (i) data infrastructure (Internet of Things / Operational Technology (IoT/OT) telemetry; Port Community System / Terminal Operating System databases (PCS/TOS) databases; logistics events), (ii) digital models (discrete-event simulation, optimization and in recent years ML-based predictors) and (iii) decision interfaces (dashboards, APIs, alerts and sometimes closed-loop operational control) [12], [38].

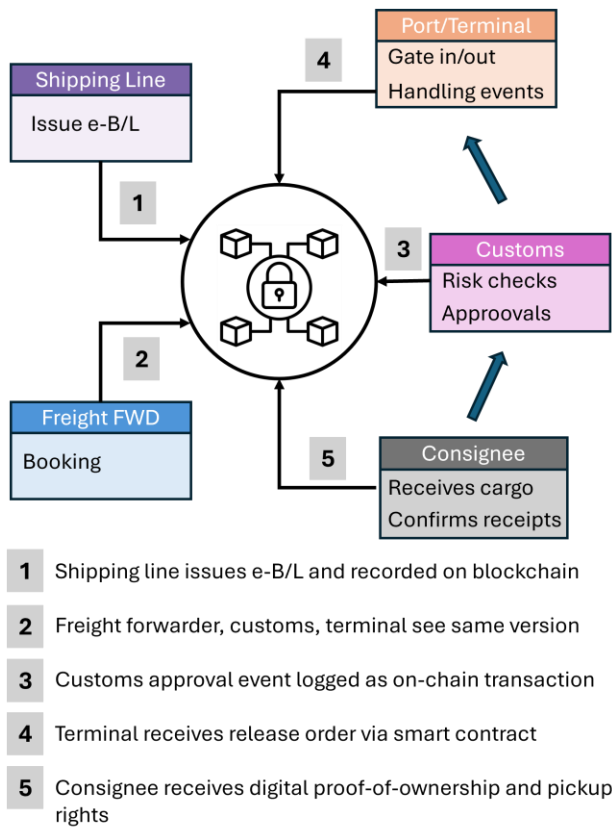


Fig. 4. Blockchain-enabled port documentation and clearance workflow.

Key element is bidirectional coupling: real-time data inputs calibrate and synchronize the twin, producing forecasts, “what-if” analysis and operational recommendations that guide planning and execution [13], [17]. This architecture allows ports to progress from descriptive visibility to predicting and prescriptive decision support as long as consistent data governance and model validity are present with all parties [4], [39]. Fig. 3 illustrates this layered, data-connected digital twin architecture for a smart port.

(b) *Applications and use cases*: Digital twins deployment in the ports include different areas and focus mainly on operational performance, safety, and sustainability [16], [36]: Live Monitoring and Operational Decision Making – DT-based platforms can integrate equipment telemetry with ongoing operational activities to monitor terminal state and take data driven decisions (e.g., congestion detection, yard re-planning, vessel service performance review) [13]. Moreover, event-driven DT designs facilitate tactical-operational optimization, where coordinated models act in parallel and modify decisions with emerging events [17]. Automatic Terminal Optimization and Predictive Asset Administration: DT frameworks are emerging for container terminals driven by automated processes that enhance production methods and resource allocation with the help of predictive models and learning components, minimizing delays and improving throughput [13], [15]. DTs play an invaluable role in bridging the gap between asset condition estimates,

operating plans, and active maintenance, thus enabling proactive scheduling and optimal use of cranes, vehicles and yard resources [15]. Safety and Risk-Aware Port Operations: DT-driven approaches can also help safety management and decision support of hazardous cargo or disruption scenarios by integrating monitoring with predictive models that predict unsafe states [16]. In these DT-enabled operations, risk management for IoT devices and connected infrastructure are being addressed by DT as the cyber-physical attack surface expands [28]. Decarbonising energy and environmental performance: port DTs can reduce emissions by modelling operating policies that decrease ship waiting time and improve scheduling [14]. DT components concentrated on energy can embed measurements and control strategies for port energy systems (e.g., microgrids, electrified infrastructure) and enable a holistic perspective in complement to sensor-driven environmental performance monitoring approaches [19], [40], [41]. Connected Mobility and System-Wide Coordination: An increasing number of DTs are being integrated with connected and intelligent automation components in port mobility (e.g. vehicle coordination and infrastructure-aware automation) [42], further enabling DT to be used for transport and interfaces at ports other than terminals.

(c) *Benefits and challenges*: Digital Twins present clear advantages for smart ports in terms of: increased situational awareness, faster identification of bottlenecks and risks, and the evaluation of policies and investments through scenario testing without compromising operational performance [10], [13]. DTs might serve as an integration layer that lessens information silos by integrating operational systems, environmental monitoring and energy management into a single decision processing workflow [19], [38]. Nevertheless, a number of challenges limit DT deployment and scalability. The first is data interoperability and quality issues that persist (due to heterogeneous legacy systems, different sensor areas, and inconsistent data semantics), resulting in model reliability and trust problems [4], [37]. Secondly, model development and validation are resource-intensive: since operating conditions, equipment and policies change, ports need to continuously calibrate simulations and predictive models [17], [39]. Third, due to the incorporation of IoT devices and decision pathways, DT stacks also rise to prominence in terms of cybersecurity and operational risk, where DT stacks help define structured risk management and governance for real operations [16], [28]. Finally, organizational readiness and investment uncertainty (knowledge, change management, and prioritization based on incomplete information) can inhibit adoption despite the demonstration of technical feasibility [10], [37]. To overcome these challenges, the approach adopted is generally with the use of phased implementation, transparent data sharing contracts, and cooperation between DT goals in line with sustainability and operational KPIs [31], [43].

3.2. Blockchain and distributed ledger technologies

(a) *Overview of blockchain in ports*: Blockchain and distributed ledger technologies (DLTs) have been suggested as the bedrock enablers of transparent,

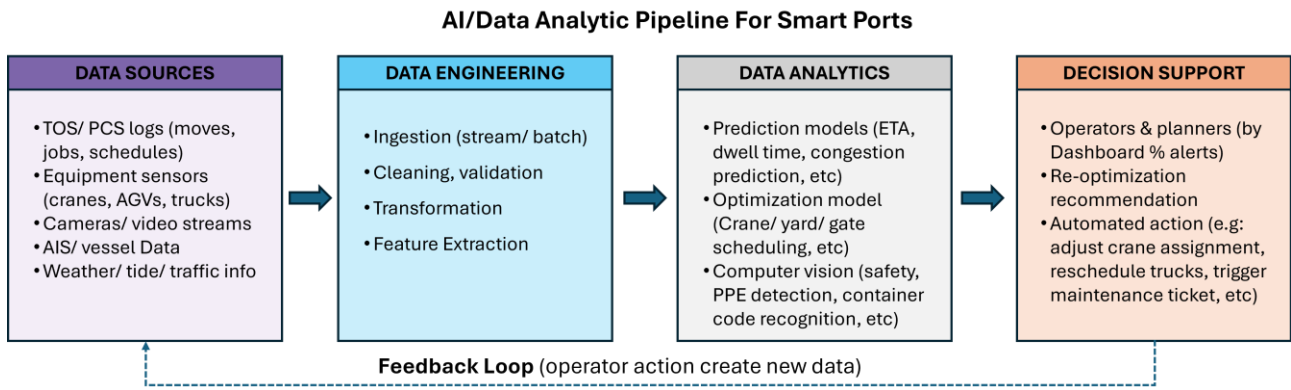


Fig 5. End-to-end AI/analytics pipeline for smart port decision support. Operational and contextual data sources (e.g., TOS/PCS logs, equipment sensors, camera streams, AIS/vessel data, and weather/tide/traffic information) are ingested and engineered (cleaning, validation, transformation, and feature extraction) to power analytics modules (prediction, optimization, and computer vision), which feed decision-support services for operators and planners, including dashboards/alerts, re-optimization recommendations, and automated operational actions.

Cross-Cutting Themes versus Technologies Map

Themes	Technologies					
	DT	Blockchain	AI	IoT/5G	CV/UAV	Automation
Inter-operability	High	Very-high	Medium	High	Medium	High
Governance	High	High	Medium	Medium	Medium	Medium
Human Factors	High	Medium	Medium	Medium	High	Medium
Cybersecurity	High	High	Medium	Medium	High	Medium

Strong research coverage
Gaps/ Emerging topics

Fig 6. Cross-technology coverage matrix of the smart port literature, highlighting the relative strength of research attention across intersections of key technology domains. Cell colors indicate areas of strong research coverage (blue) versus gaps/emerging topics (peach), with qualitative intensity levels reported as Medium, High, and Very-high.

tamper-evident data sharing for port communities [44], [45], [46]. There are multiple actors involved in ports—shipping lines, terminal operators, freight forwarders, customs agencies, inland transport providers—each with separate information systems [47], [48]. Classical data exchange processes, that rely on user interfaces, point-to-point exchanges or central platforms, suffer from inconsistencies, latency and distrust issues [45], [46]. Blockchain offers a decentralized alternative where transactions are documented in a collective record by a network of users [46], [47]. Smart contracts, self-executing code residing on the blockchain, can automate business rules and operations, to include process approval for documents or payments, and compliance checks [44], [46]. In the port context, blockchain has been studied for various applications like digital bills of lading, cargo tracking, customs clearance, and trade finance [44], [45], [47], as shown in Fig. 4.

(b) *Use cases and pilot projects*: Several notable blockchain initiatives have been launched in the

maritime and port sectors [46], [47]. Shipping alliances, technology firms, and port authorities have collaborated on platforms to digitize bills of lading, streamline customs processes, and improve cargo visibility [44], [45]. These initiatives aim to replace paper-based documentation and manual reconciliation with shared digital records, reducing delays and administrative overhead [46], [47].

(i) In the ports industry blockchain has been used for [44], [45],

(ii) Document Management: Digital bills of lading, certificates of origin, and inspection reports can be issued, transferred, and checked on the blockchain such that fraud and inaccuracy are minimised [46], [47].

(iii) Cargo Tracking: End-to-end cargo tracking systems can log entries for loading, unloading, gate in/out, or for customs inspections on the common ledger to be the sole truth [44], [45].

(iv) Customs and Regulatory Compliance: Platforms with built-in blockchain functionality can help traders and customs authorities facilitate data sharing, risk-based inspections and fast clearance [44], [46].

(v) Port Community systems: DLTs can add capability to standard port community systems, such as by providing verifiable audit trails and automatically settling transactions [45], [48].

3.3 Limitations and barriers to adoption

The commercialization of blockchain technology in ports has had limited applications, despite the possibility of successful pilots [44], [47]. Potential barriers include [44], [45]:

(i) Interoperability and Standardization: Multiple blockchain platforms and standards exist, making it hard for stakeholders to interconnect and avoid vendor lock-in [44], [46].

(ii) Governance and Consortium Management: Setting up governance models governing permissioned blockchains such as participation guidelines, data access policy, and resolution mechanisms is very complex [45], [47].

(iii) Integration Into Legacy Systems: Blockchain

Table 1. Comparative port use cases, deployment maturity, and key adoption barriers of the six smart-port technology pillars.

Technology pillar	Representative port use cases	Deployment maturity	Key deployment barriers	Key refs
Digital twin	Real-time terminal monitoring, predictive asset management, decarbonization scheduling	Pilot to early operational (leading automated terminals)	Data interoperability and quality, cost of model validation, expanded cyber attack surface	[11]-[17]
Blockchain & distributed ledger	Electronic bills of lading, cargo tracking, customs clearance, port community systems	Pilots; limited commercial roll-out	Platform standardization, consortium governance, legal status of e-documents	[25]-[27], [44]-[48]
AI & data analytics	Berth/ETA prediction, yard and gate optimization, predictive maintenance, video analytics	Operational in narrow tasks; broader use emerging	Data quality and governance, explainability, integration with legacy systems	[15], [20]-[24], [49]-[52]
IoT & 5G connectivity	Asset and environmental sensing, URLLC for remote cranes, edge video analytics	Sensing operational; private 5G at pilot stage	Infrastructure cost, protocol heterogeneity, spectrum and QoS management	[18], [19], [48]-[50], [55], [56]
Computer vision & UAV sensing	ALPR, container-code and damage detection, infrastructure inspection, surveillance	Computer vision operational; UAV piloting	Robustness to weather/lighting, airspace regulation, data volume	[20], [22], [52], [58]
Automation, robotics & autonomous systems	Automated quay/yard cranes, AGVs and straddle carriers, autonomous trucks	Operational at greenfield terminals; mixed-fleet emerging	Capital cost, human-machine coexistence, safety certification and liability	[49]-[51], [58]

platforms have to integrate with existing enterprise systems, which takes considerable technical effort and change management [44], [48].

(iv) Legal & Regulatory Issues: The legal landscape for digital documents like electronic bills of lading is also multi-faceted, affecting the effectiveness of blockchain [46], [47].

Furthermore, not all of the port processes need immutable and decentralized aspects that blockchain provides, and centralized solutions may be more convenient and cheap in some cases [44], [47]. Accordingly, blockchain remains the most appropriate among a plurality of technologies for use in smart port technology stack especially for multi-party workflows, which entail high trust and auditability requirements [44], [45].

3.3. Artificial intelligence and data analytics

AI and data analytics are playing a central role in deriving value from the large data which smart port infrastructures generate [49], [50], [51]. Machine learning (ML), deep learning (DL), and optimization algorithms have been employed in various port activities, such as equipment maintenance, traffic forecasting, berth allocation, and security monitoring [15], [49], [52]. As summarized in Fig. 5, successful smart-port AI usually comprises an end-to-end pipeline that connects disparate operational and contextual data sources, cleanses and augments data, and utilizes features, and then deploys

predictive, optimization and computer-vision algorithms that provide action-aware decision support in several ways e.g., dashboards, alerts and automated control behaviours. Some AI in the port industry are:

(i) Supervised Learning: Classification, estimation models used for forecasting container dwell times, truck arrival habits, and equipment malfunctions.

(i) Unsupervised Learning: Extracting the cluster data from model training for the visual identification of unusual vessel or vehicle behavior, security threats, or process bottlenecks.

(iii) Reinforcement learning: dynamic optimization of berth allocation, crane scheduling, and yard management policies through time, under uncertain conditions.

(iv) Computer Vision: deep neural networks for image and video analysis in container inspection, damage detection, traffic monitoring.

There are several fundamental domains into which AI uses in smart ports can be aggregated:

(a) *Vessel and berth management*: Predictive models predict arrival times of vessels, service times and departure hours to optimize berth scheduling and quay crane allocation. In port-based call optimization frameworks, real-time predictions can be provided and incorporated into the existing systems to reduce waiting times and fuel consumption [49]. Operation of yard and gate applications AI based decision support service is supported for yard crane scheduling, stacking of containers, gate appointment system, etc. Using prior

data to identify where congestion needs to be monitored and act to avoid congestion (e.g., rescheduling truck movements and reallocating resources), these systems could be designed to identify congestion patterns [50].

(b) *Maintenance of equipment*: Predictive maintenance schemes are based on sensor measurements (vibration, temperature) and logs of operation that can predict failures of cranes, AGVs, and other very important assets [15]. Machine learning-based system can initiate maintenance interventions at the best times, minimizing downtime and avoidable inspection [49].

(c) *Safety and security*: Video-based AI-enabled analytics can identify unauthorized use and unauthorized access in addition to unusual events [22], [52]. Computer vision models could detect personnel without protective equipment, vehicles in restricted zones, and suspicious activities in cargo areas, for instance [22], [52].

(d) *Environmental monitoring*: Data-driven models allow predictions on emissions, noise, spread of pollutants and supports environmental compliance initiatives and green port operations [49], [53]. AI can assist with the optimization of equipment operations and vessel scheduling to reduce emissions during peak periods [51], [53].

(e) *Data quality, governance, and ethics*: AI in smart ports relies on data quality, availability, and governance [50]. Many port environments suffer from fragmented data sources, missing values, and inconsistent formats [48]. Data cleaning, integration, and feature engineering often consume more resources than model development [49]. Governance frameworks are essential to establish data ownership, access rights, and usage policies. Ports must balance the benefits of data sharing against privacy, competitive, and security concerns. Furthermore, the use of AI raises ethical questions, particularly when algorithms influence operational decisions affecting safety or employment [50]. Transparency, explainability, and human oversight are essential considerations in designing AI-enabled port systems.

3.4. IoT, 5G, and connectivity infrastructure

(a) *Sensor networks and IoT platforms*: The Internet of Things sensors give the sensing and connectivity backbone to smart ports [49], [50], [54]. Internet of Things (IoT) technologies [48], [50] IoT sensor networks record information on equipment status, conditions of cargo, environmental data and human activities. Examples are RFID tags and readers for tracking containers, GPS devices placed in trucks and vehicles, environmental sensors that indicate air and water quality, and condition sensors in cranes and conveyor belts [48], [49], [55]. For applications sensitive to latency, IoT-based systems integrate cloud-based platforms with edge computing devices to aggregate, store, and use sensor data [49], [50], [56]. These platforms allow for device management and data streaming, as well as analytics, as well as the use of application programming interfaces (APIs) to be integrated with high-level port management systems and with Digital Twins [49], [50], [57].

(b) *5G and edge computing*: Using 5G networks at port areas would greatly improve connection performance while facilitating ultra-reliable low-latency communication (URLLC) and massive machine-type

communication (mMTC) [49], [50], [56]. These capabilities are indispensable for demanding applications like remote crane operation, autonomous vehicles and real-time video analytics [49], [56], [58]. Edge computing works in parallel with 5G by bringing computation and storage closer to the data source [50], [56]. The processing and filtering of data about the sensors can be done at edge nodes [49], [50] and thus the bandwidth consumption can be minimized and reaction times can be faster. Edge-based video analytics, for instance, can detect anomalies on an edge and will send the relevant alerts or metadata only to central systems [22], [52], [56]. The use of 5G and edge computing relies on significant investment in infrastructure and planning for coverage, reliability, and integration with wired and wireless networks [50], [56]. Ports should also address the necessity of multi-operator environments, the spectrum allocation and the risk of compromising other industrial wireless systems [50], [56].

(c) *Interoperability and network management*: It is challenging to maintain heterogeneous IoT and communication networks in ports [48], [50]. Devices may also have various communication protocols ranging from Wi-Fi and LTE, to 5G, to LoRaWAN and Zigbee, to data formats, as well as various security protocols to protect the data [48], [50]. Thus, interoperability standards, middleware solutions, as well as uniform data models are required to bring data flows together and to facilitate the integration between systems [48], [50], [59]. QoS on a network management needs to cover the QoS requirements required by various applications [50], [56]. A practical example would be that remote control of cranes required high reliability and low latency, while batch data transfer in the form of reporting would bear delays [49], [56]. Software-defined networking (SDN) and network slicing in 5G networks provides dynamic resources allocation and prioritization schemes that cater traffic prioritization at application level [50], [56]. In maturity terms, IoT sensing is operationally mature in many ports, whereas private-5G and network-slicing deployments remain largely at the pilot stage, constrained by spectrum access, multi-operator coordination, and the cost of port-wide coverage [49], [50], [56].

3.5. Computer vision, UAVS, and sensing for smart ports

(a) *Image- and video-based monitoring*: Automated perception and monitoring tasks in ports are increasingly being performed with the help of computer vision technologies, as previously emphasized [22], [49], [52]. Cameras deployed at gates, terminals, berths and yards [50], [52] are used to capture video feeds to ensure security, safety and process monitoring. Image recognition and object detection algorithms that are driven by deep learning can identify containers, vehicles, staff and detect collisions, spills or unauthorized access [22], [52]. Some popular computer vision applications include automatic license plate recognition (ALPR) for gates, container code recognition, damage detection on containers and equipment, and traffic flow monitoring [22], [49], [52]. These technologies reduce the number of manual inspection operations, accelerate processing and

offer more extensive data for analyses and decision support [49], [52].

(b) *Unmanned Aerial Vehicles*: UAVs, or drones, have been used increasingly frequently for inspection, surveillance, and monitoring for difficult, dangerous, or otherwise unsafe tasks in ports [49], [58]. Unmanned aerial vehicles with optical, thermal and multispectral cameras would check structures such as the quay walls, cranes, roofs and pipelines and monitor for structural damage, corrosion or leaks [52], [58]. Besides survey of infrastructure, UAVs may be used for inventory management, security protection, and environmental surveillance [49], [58]. For instance, drones can rapidly survey large storage yards to evaluate container distributions and detect misplaced units or check open storage locations for hazardous substances [50], [58]. Autonomous or semi-autonomous UAV operations need to integrate with airspace management systems, and to comply with aviation rules, which may differ between jurisdictions [58].

(c) *Sensor fusion and real-time monitoring*: Beyond technical feasibility, routine UAV use in ports is still constrained by fragmented airspace regulation and beyond-visual-line-of-sight restrictions, so most reported deployments remain pilot trials rather than continuous operations [58].

These techniques can significantly improve situational awareness in ports particularly when data from various sensors are combined; including cameras and LiDAR, radar, and environmental sensors [13], [49], [60]. In other studies, sensor fusion algorithms combine data streams using these data streams to obtain holistic views [13], [60] about areas such as traffic flows, equipment locations, and environmental conditions. Thus, a blend of camera and radar data may improve robustness of target detection and tracking for both target and traffic detection under adverse weather or lighting conditions [13], [60]. Improved decision-making in vessel traffic control, collision avoidance, emergency response and security operations, in line with such considerations is made possible by enhanced situational awareness [49], [60]. Visualisation tools (eg, 3D maps and dashboards) are very useful to visually show interlaced data from the model in a user-friendly style for both the operator and the manager [51], [57].

3.6. Automation, robotics, and autonomous systems

(a) *Terminal automation*: Terminal operations automation has been a key focus of port modernization [49], [50], [51]. Automated container terminals are equipped with unmanned or semi-automated quay cranes, yard cranes, and horizontal transport systems including AGVs or automated straddle carriers [49], [50], [58]. Automation enhances throughput and safety while limiting human interaction with dangerous environments and offering predictability in performance [50], [51]. Digital control tools, advanced planning and scheduling algorithms, and real-time monitoring are the major components of automated terminals [49], [50]. They also need robust safety systems with collision avoidance sensors, geofencing, emergency stop mechanisms [49], [58], and more systems to avoid accidents. Integration to the terminal operating system (TOS) makes the

automated system interoperable with the upstream and downstream processes, including vessel planning and gate operation [50], [57].

(b) *Autonomous vehicles and equipment*: Aside from AGVs, autonomous or remotely operated vehicles (ARVs) and drones, which are forecast to become more common for port logistics [49], [58]. Automated trucks on road-side robots and autonomous trucks working within the wall of the ports, autonomous trucks at port, robotic stackers in warehouses, remote cranes on the warehouse floors, automated cranes driven from centralized control rooms, for example [50], [58]. For these systems, a dependence on reliable connectivity, exact position (e.g., GNSS, RTK), and advanced perception and control algorithms all depend on the design [56], [58]. The transformation to a more self-sufficient technology both raises technical and organizational questions [51], [58]. Ports must make certain that autonomous systems and regular human-operating equipment are able to live side by side, given the coexistence of these two sets for the long-term [50], [58]. Safety certification, liability frameworks and workforce reskilling are critical considerations as autonomy increases [51], [58]. Compared with digital twins and AI, the evidence on full terminal automation is concentrated in a small number of greenfield, well-capitalised terminals; whether these results transfer to brownfield ports with mixed human-machine fleets remains largely untested [50], [51], [58].

(c) *Human factors and organizational change*: While automation and robotics appear promising and more efficient than ever, they are no substitute for human factors [51], [59]. Automation redefines a job, a skill, and an organization [51], [59]. Operators may move from manual management of discrete assets to supervisory responsibilities for the automated systems from control centers and beyond [50], [51]. This needs new knowledge in data interpretation, system monitoring, and incident management [51], [59]. The process of change management must be linked to the workforce's fear for job losses, and to developing reskill and upskill policies [51], [59]. Engaging employees in the planning and implementation of automation project processes can positively influence commitment and highlight constraints that may not be evident through a purely technical lens [51], [59]. Human operators should be alert and prepared to deal with high automation scenarios for safety and resilience [51], [59].

(d) *Cybersecurity and resilience considerations*: Smart port technologies provide new attack surfaces and vulnerabilities [50], [61], [62]. The further integration of IT and operational technology (OT), the wide usage of IoT devices, and the dependence of IT solutions on the cloud and edge platforms has increased the complexity of the cybersecurity management [61], [62]. Cyber incidents at ports can result in operational disruption, safety hazards, and financial losses [61], [62]. From such a set of cybersecurity issues for smart ports we can say that the smart ports cybersecurity should also take into account device security, network security, application security, and human behavior [61], [62]. This comprises secure device provisioning, encryption of data in transit and at rest, access control and authentication

mechanisms, intrusion detection systems, and routine security checks [61], [62]. Ports, and ports need to go defense-in-depth in nature, and align with international data standards and best practices for protecting the critical infrastructure [61], [62]. Resilience is more than cybersecurity; it has to do with the ability to absorb and recover from a range of disturbances (such as natural disaster, an equipment failure or a shock for the supply chain) [51], [63]. Digital Twins and AI-driven tools for risk assessment can aid resilience planning by simulating disturbances and considering how to respond [51], [63]. But excessive use of digital can cause single point of failure if not properly constructed with redundancy and backups in place [62], [63]. Practical governance increasingly references established frameworks such as the ISPS Code, IMO Resolution MSC.428(98) on maritime cyber risk management, and IEC 62443 for industrial control systems; however, empirical evidence on their effectiveness in port settings remains scarce [61], [62].

3.7. Cross-cutting themes and integration

(a) *Interoperability and standardization*: A perennial problem in smart port development is how to maintain interoperability in heterogeneous systems and with a variety of stakeholders [9], [16], [64]. Ports generally consist of a variety of legacy and recent systems such as terminal operating systems, port community systems, customs platforms, equipment proprietary control systems [16], [63], [64]. The diverse data models, messaging protocols, and interfaces used in many of these systems may lead to data silos and integration problems [9], [64], [65]. Some initiatives that aim to combat this are the standardization initiatives to promote standard data formats, APIs, etc. [9], [16], [64]. Examples are standards [16], [64], and [66], for electronic data interchange in shipping, data models for port call optimization [16], and reference architectures for industrial IoT [64]. These standards ensure harmonization between smart port projects, promote integration of systems [9], reduce the risk of entering into vendor lock-in [16], and promote cross-port collaboration [9], [63], [65]. Nevertheless, this standardization landscape is quite fragmented. Different industry bodies, as well as different technology groups or suppliers and regulatory agencies, give different and overlapping incentives for standardization projects which must now be passed through their various authorities [9], [64], [65]. Ports must steer through this complexity, then make strategic decisions as to what standards to adopt [63], [65]. Since technologies and standards will only improve further and change over time, flexibility and adaptability are essential to succeed [16], [64].

(b) *Governance, stakeholder co-operation, business models and collaboration*: Smart port technologies include various relevant players with different interests and capacities [16], [63], [64]. Effective governance models are required to help in directing technology adoption, data sharing, and cost-benefit allocation [16], [63], [65]. There are governance structures such as port authorities, terminal operators, shipping lines, logistics providers, and public groups [16], [63], [67]. They need to balance competitive relations with collaboration in

common infrastructures and platforms [63], [67]. Stakeholder involvement is of particular relevance for cross-organizational initiatives (e.g., port community systems, blockchain platforms, digital twins) where there is an overlap and cross-organizational approach to implementation [16], [45]. These are also seen as some important considerations in participation including: trust, transparency, and value distribution equity [45], [63]. We may need new business models which involve platform-type ecosystems where third-party developers can provide support on top of the shared data infrastructure [16], [64]. Investments in smart port projects should consider the operational benefits as well as strategic objectives of sustainability, resilience, and regional competitiveness [51], [53], [63]. Public-private partnerships might be required to fund large-scale infrastructure improvements, especially in ports that are significant national assets [63], [67].

(c) *From human to technology interaction and skills development*: Smart port technologies disrupt the very interaction between port workers with systems, data, and with one another [51], [59], [63]. The usability of interfaces, cognitive load, confidence in automated recommendations, and control of humans-on-machine interaction (HTI), including human-to-machine [51], [59] considerations, are human-technology interaction (HTI) considerations. Inappropriate interfaces, poorly constructed algorithms, or other non-conformist software can expose operators to mistakes, lack of situational awareness, and resistance to use and deployment [51], [59]. Thus, building of skills is very important for smart port tactics [51], [63]. In an extensive ecosystem of global economies, all ports require professionals proficient in data analytics, cybersecurity, software engineering, and system integration in addition to traditional maritime and logistics skills [51], [61]. Such capabilities can be built with training programs and partnerships with educational institutions [51], [63]. The pace at which technology can evolve on an accelerated basis [51], [64], calls for constant learning. On a societal level, the design of smart port projects should be done in conjunction with the use of the technology by the end-users in order to enable, as opposed to obstruct, operational workflows [51], [59]. Participatory design methods could unveil practical limitations and opportunities to enhance both efficiency and work conditions [51], [59].

(d) *Sustainability, green ports and social impact*: There is interdependence with the sustainable and green port initiatives with such smart port technologies [51], [53]. Digital tools can help with emissions monitoring for ships, with energy optimisation or use optimization and resource efficiency in support of the ports meeting environmental compliance and social needs of environmental performance [53], [56]. These encompass system design for controlling vessel speed and port calls which will reduce fuel consumption, control of lighting that dynamically uses to enhance fuel efficiency, intelligent energy management at port terminals [49], [53]. In addition to environmental sustainability, social and economic aspects must also be taken into account [51], [63]. Automation and digitalisation affect employment dynamics, possibly displacing some (but at

the same time creating new) job types in high-skilled fields [51], [59]. Ports are significant for local and regional economies, with smart port strategies that should align with development goals for employment, innovation ecosystems, and community development [34], [63]. Interdisciplinary perspectives and involvement of stakeholders outside of the core maritime sectors are needed to assess the social impact of smart port initiatives [51], [63]. Designing and evaluating the approaches needs to consider factors such as ethical perspectives on data usage, surveillance, and equity [51], [61]. Taken together, the literature reviewed is poorly distributed along technology frontiers, as most studies build for single-domain solutions and a narrow range only address tightly coupled, end-to-end integration issues. A cross-technology coverage matrix (Figure 6) summarises this landscape and shows us where research interest is concentrated (e.g., high operational maturity well-studied pairings) and where the gaps remain (e.g., new combinations that need new approaches towards interoperability, governance, and system-engineering). In this sense, the synthesis encourages an integration of reference architectures and evaluation frameworks that explicitly account for multi-technology dependencies, and doesn't conceptualize IoT, AI, automation, blockchain, and digital twins as standalone capabilities.

4. RESEARCH GAP AND FUTURE DIRECTION

Integration of multiple technologies: Much of the existing literature examines individual technologies — Digital Twins, blockchain, AI — in isolation; fewer studies address how these work together within a unified smart port architecture [51], [54], [57]. Reference architectures and integration frameworks that combine sensing, connectivity, analytics, automation, and human interfaces into coherent systems are largely absent from the literature [55]. Digital Twins are increasingly positioned as platforms that coordinate data flows from IoT devices, AI systems, and blockchain infrastructure [16]. For example, smart contracts could trigger actions within Digital Twin simulations or physical port operations based on sensor data and predictive analytics [44], [45]. Building such integrated systems raises open questions around interoperability, performance, and security [61].

Scalable and transferable solutions: Most prior work focuses on specific ports or terminals in well-resourced, advanced economies [16], [51]. How smart port approaches can be adapted for smaller ports and emerging markets, where resources, digital infrastructure, and regulatory environments differ substantially — is not well understood [34], [63], [65]. Modular, standards-based frameworks and open-source tools could lower the barrier to entry, and their feasibility across different port contexts warrants investigation [59], [67]. Comparative studies across ports with different characteristics could identify contextual factors that shape successful adoption [51], [63]. Maturity models and performance measurement frameworks could also help ports assess where they stand and plan realistic roadmaps [51], [59].

Cybersecurity, privacy, and risk management: Cybersecurity and privacy are frequently mentioned in

the smart port literature but receive little systematic empirical attention [51]. As ports become more interconnected, the potential impact of cyber incidents grows [61]. Threat modeling, risk assessment, and resilient architecture suited to port contexts are underexplored areas [61], [62]. Further work is needed on the effectiveness of different security measures, incident response systems, and governance arrangements, including the trade-offs between security and operational performance [61]. Mechanisms for sharing threat intelligence among ports and related parties also need development [61], [63]. Privacy-preserving analytics and federated learning could enable data sharing between organizations without exposing sensitive information; their applicability to port contexts has not been thoroughly examined [51], [61].

Human factors, organizational change, and policy: Technical research on smart ports needs to be paired with more systematic investigation of human and organizational factors [51], [63]. Studies on technology acceptance, trust in AI-driven systems, workforce retraining, and organizational culture in adoption are underdeveloped [51], [59]. Longitudinal work tracking how port organizations change in response to digital initiatives would also be informative [51], [63]. Policy frameworks at national and international levels shape what smart port development is possible [63], [67]. How regulations covering data governance, competition, labor, and environmental standards enable or constrain innovation, and where harmonization across jurisdictions may be needed, remain underexplored [53], [63], [67].

Evaluation, benchmarking, and impact assessment: Much of the smart port literature reports qualitative outcomes, with limited quantitative measurement of operational, economic, environmental, or social effects [51], [59]. Evaluation frameworks covering all four dimensions, and accounting for context-dependent variables and uncertainty in future demand and technology development, still need to be developed [34], [53], [59], [63]. Standardized performance indicators would enable cross-case comparisons and support evidence-based investment decisions [51], [59]. Experimental and quasi-experimental designs, simulation, and scenario analysis can complement conventional before-after studies and provide better evidence on causal relationships and unintended effects [59].

5. CONCLUSION

Smart ports have moved from a high-level digital vision to a connected set of technologies spanning digital twins, AI, IoT, blockchain, computer vision, and automation. This paper has presented a scoping review of these enabling technologies and their architectures, mapping each to port operational objectives and to a roadmap for digital transformation in modern maritime hubs. Across the six pillars, the synthesis shows that convergence, interoperability, governance, and human-technology interaction matter as much as the individual technologies. A workable and sustainable smart port cannot rest on technical solutions alone; it depends on an effective, evolving, multi-stakeholder ecosystem that

balances operational efficiency with broader goals of environmental sustainability and economic equity. The review identifies persistent research gaps, particularly in holistic system integration and in the social and organisational dimensions of automation, and offers a structured basis for future interdisciplinary work. On this basis, the findings can help researchers, policymakers, and practitioners develop port futures that are not only technologically advanced but also secure, inclusive, and adaptable to the changing demands of global trade.

REFERENCES

- [1] K.-L. A. Yau et al., "Towards smart port infrastructures: enhancing port activities using information and communications technology," *IEEE Access*, vol. 8, pp. 83387–83404, 2020.
- [2] A. Karas, "Smart port as a key to the future development of modern ports," *The International Journal on Marine Navigation and Safety of Sea Transportation*, vol. 14, no. 1, pp. 27–31, 2020.
- [3] H. A. Al-Fatlawi and H. Jassim Motlak, "Smart ports: Towards a high performance, increased productivity, and a better environment," *International Journal of Electrical and Computer Engineering*, vol. 13, no. 2, pp. 1472, 2023.
- [4] M. Jovic et al., "Digitalization in maritime transport and seaports: bibliometric, content and thematic analysis," *Journal of Marine Science and Engineering*, vol. 10, no. 4, pp. 486, 2022.
- [5] N. Kastelan et al., "Digital horizon: assessing current status of digitalization in maritime industry," *Transactions on Maritime Science*, vol. 13, no. 1, 2024.
- [6] G. Aerts and G. Mathys, "Discovering trends in the digitalization of shipping: an exploratory study into trends using natural language processing," *Journal of Marine Science and Engineering*, vol. 12, no. 4, pp. 618, 2024.
- [7] Y. Du et al., "Special issue on 'Smart port and shipping operations,'" *Maritime Policy & Management*, vol. 50, no. 4, pp. 413–414, 2023.
- [8] H. Min, "Developing a smart port architecture and essential elements in the era of Industry 4.0," *Maritime Economics & Logistics*, vol. 24, no. 2, pp. 189–207, 2022.
- [9] A. Nurrosyidah and A. F. Rachmannullah, "A TOGAF-based framework for the enterprise architecture development of smart digital port: a case of container port in indonesia," *Journal of Manufacturing and Enterprise Information System*, vol. 2, no. 2, pp. 1–7, 2024.
- [10] B. Lu and X. Xu, "Digital transformation and port operations: Optimal investment under incomplete information," *Transport Policy*, vol. 151, pp. 134–146, 2024.
- [11] R. Klar, A. Fredriksson, and V. Angelakis, "Digital twins for ports: derived from smart city and supply chain twinning experience," *IEEE Access*, vol. 11, pp. 71777–71799, 2023.
- [12] K. Wang et al., "Multi-aspect applications and development challenges of digital twin-driven management in global smart ports," *Case Studies on Transport Policy*, vol. 9, no. 3, pp. 1298–1312, 2021.
- [13] Y. Ding et al., "Real-time monitoring and optimal resource allocation for automated container terminals: a digital twin application at the Yangshan port," *Journal of Advanced Transportation*, vol. 2023, pp. 1–12, 2023.
- [14] J.-O. Eom et al., "Port digital twin development for decarbonization: a case study using the Pusan newport international terminal," *Journal of Marine Science and Engineering*, vol. 11, no. 9, pp. 1777, 2023.
- [15] Y. Li, et al. "Automated container terminal production operation and optimization via an adaboost-based digital twin framework," *Journal of Advanced Transportation*, vol. 2021, pp. 1–16, 2021.
- [16] K. Wang et al., "Digital twin-driven safety management and decision support approach for port operations and logistics," *Frontiers in Marine Science*, vol. 11, pp. 1455522, 2024.
- [17] D. Abril, C. D. Paternina-Arboleda, and J. Velasquez-Bermudez, "An integrated event-driven real-time tactical-operational optimization framework for smart port operations planning," *Logistics*, vol. 8, no. 3, pp. 65, 2024.
- [18] G.-Y. Gan, H.-S. Lee, and J.-Y. Liu, "A DEA approach towards to the evaluation of iot applications in intelligent ports," *Journal of Marine Science and Technology*, vol. 29, no. 3, pp. 257–267, 2021.
- [19] T. Milosevic et al., "The port environmental index: a quantitative IoT-based tool for assessing the environmental performance of ports," *Journal of Marine Science and Engineering*, vol. 11, no. 10, pp. 1969, 2023.
- [20] H. Lee, I. Chatterjee, and G. Cho, "AI-powered intelligent seaport mobility: enhancing container drayage efficiency through computer vision and deep learning," *Applied Sciences*, vol. 13, no. 22, pp. 12214, 2023.
- [21] M. Abu Ghazaleh, "Smartening up ports digitalization with artificial intelligence: a study of artificial intelligence business drivers of smart port digitalization," *Management and Economics Review*, vol. 8, no. 1, pp. 78–97, 2023.
- [22] Safuan and A. Syafira, "Artificial intelligence in indonesian ports: opportunities and challenges," *Transactions on Maritime Science*, vol. 13, no. 2, 2024.
- [23] N. Tsolakis et al., "Towards AI driven environmental sustainability: An application of automated logistics in container port terminals," *International Journal of Production Research*, vol. 60, no. 14, pp. 4508–4528, 2022.
- [24] I. Durlik et al., "Harnessing AI for sustainable shipping and green ports: challenges and opportunities," *Applied Sciences*, vol. 14, no. 14, pp. 5994, 2024.
- [25] R. W. Ahmad et al., "Blockchain applications and architectures for port operations and logistics management," *Research in Transportation Business & Management*, vol. 41, pp. 100620, 2021.
- [26] C. A. Duran et al., "Boosting the decision-making in smart ports by using blockchain," *IEEE Access*, vol. 9, pp. 128055–128068, 2021.
- [27] P. S. Sangeerth and K. V. Lakshmy, "Blockchain based smart contracts in automation of shipping ports," *Proc. of 2021 6th IEEE International Conference on Inventive Computation Technologies (ICICT)*, pp. 1248–1253, 2021.
- [28] I. Argyriou and T. Tsoutsos, "Assessing critical entities: risk management for IoT devices in ports," *Journal of Marine Science and Engineering*, vol. 12, no. 9, pp. 1593, 2024.

- [29] W. Sankla and T. Muangpan, "Smart and sustainable port performance in Thailand: a conceptual model," *Journal of Sustainable Development*, vol. 15, no. 4, pp. 1, 2022.
- [30] O. B. Inal and C. Dere, "An approach to green ports in terms of low-carbon energy and sustainability," *International Journal of Environment and Geoinformatics*, vol. 11, no. 1, pp. 43–49, 2024.
- [31] E. Valioniene, E. Zuperkiene, and B. Placiene, "Acceleration of green transitions on the base of port organizational ecosystem," *Applied Sciences*, vol. 14, no. 21, pp. 9948, 2024.
- [32] I. Kurt and M. Aymelek, "Operational adaptation of ports with maritime autonomous surface ships," *Transport Policy*, vol. 145, pp. 1–10, 2024.
- [33] M. Riyadh, "Transforming the shipping industry with autonomous ships and artificial intelligence," *Journal of Maritime Technology and Society*, pp. 16–21, 2024.
- [34] T. Olamide Ogundare et al., "The economic and regulatory challenges of implementing digital twins and autonomous vessels in U.S. maritime fleet modernization," *International Journal of Innovative Science and Research Technology*, pp. 5–32, 2024.
- [35] A. Kiritsi, V. Adamantidis, and T. Stamatellos, "Analysis of evolving technologies and impact of smart shipping on the future workforce in the maritime industry," *International Journal of Management, Knowledge and Learning*, vol. 13, 2024.
- [36] M. Heikkilä, J. Saarni, and A. Saurama, "Innovation in smart ports: future directions of digitalization in container ports," *Journal of Marine Science and Engineering*, vol. 10, no. 12, pp. 1925, 2022.
- [37] Y. Autsadee et al., "NON-digital factors as a prerequisite for the implementation of seaport digitalization through bibliometric analysis," *Journal of Maritime Logistics*, vol. 3, no. 2, pp. 59–73, 2023.
- [38] N. Kapkaeva et al., "Digital platform for maritime port ecosystem: port of hamburg case," *Transportation Research Procedia*, vol. 54, pp. 909–917, 2021.
- [39] P. S. A. Ferreira, "Developing a roadmap for implementing digital transformation to improve the resilience of port operations," *International Journal of Scientific Management and Tourism*, vol. 10, no. 3, pp. e888, 2024.
- [40] M. Sadiq et al., "Toward next-generation smart ports: a case study on seaport microgrids customized for islands," *IEEE Transactions on Industry Applications*, vol. 60, no. 5, pp. 7681–7692, 2024.
- [41] H. P. Nguyen, N. D. K. Pham, and V. D. Bui, "Technical-environmental assessment of energy management systems in smart ports," *International Journal of Renewable Energy Development*, vol. 11, no. 4, pp. 889–901, 2022.
- [42] M. E. Vaca-Recalde et al., "Connected and intelligent framework for vehicle automation in smart-ports," *IEEE Access*, vol. 12, pp. 120347–120361, 2024.
- [43] Z. Su et al., "Critical success factors for green port transformation using digital technology," *Journal of Marine Science and Engineering*, vol. 12, no. 12, pp. 2128, 2024.
- [44] S. Nasih, S. A. Sara Arezki, and T. Gadi, "Blockchain Technology for tracking and tracing containers: Model and conception," *Data and Metadata*, vol. 3, pp. 373, 2024.
- [45] S. Nguyen et al., "Blockchain-powered incentive system for jit arrival operations and decarbonization in maritime shipping," *Sustainability*, vol. 15, no. 22, pp. 15686, 2023.
- [46] S. Tsiulin et al., "Blockchain-based applications in shipping and port management: A literature review towards defining key conceptual frameworks," *Review of International Business and Strategy*, vol. 30, no. 2, pp. 201–224, 2020.
- [47] D. K. Boison and A. Antwi-Boampong, "Blockchain ready port supply chain using distributed ledger," *Nordic and Baltic Journal of Information & Communications Technologies*, 2020.
- [48] J. L. Cacho et al., "Port data integration: opportunities for optimization and value creation," *Advances in Business Information Systems and Analytics*, 2021, pp. 1–22.
- [49] W. Wang et al., "Smart container port development: Recent technologies and research advances," *Intelligent Transportation Infrastructure*, vol. 3, pp. 22, 2024.
- [50] M. R. N. Abdillah and M. Wahyulahi, "Digital twin technology in logistics: a narrative review of implementation, impact, and challenges," *Sinergi International Journal of Logistics*, vol. 2, no. 4, pp. 225–238, 2024.
- [51] M. Karlsson et al., "Digital twins for resource optimization in multi-purpose ports: A design approach for data-driven decision making," *Journal of Physics: Conference Series*, vol. 2867, no. 1, pp. 012055, 2024.
- [52] P. Wang et al., "Intelligent port logistics: A spatiotemporal knowledge graph and AI-agent framework for berth allocation," *Advanced Engineering Informatics*, vol. 68, pp. 103633, 2025.
- [53] A. Toygar, "Sustainability in the maritime industry: integration of digital twin and autonomous control," *Advances in Logistics, Operations, and Management Science*, 2024, pp. 31–49.
- [54] J. Neugebauer, L. Heilig, and S. Voß, "Digital twins in the context of seaports and terminal facilities," *Flexible Services and Manufacturing Journal*, vol. 36, no. 3, pp. 821–917, 2024.
- [55] G. Marinova and M. Zeneli, "Implementation of IoT for green transformation of a port," *NATO Science for Peace and Security Series - D: Information and Communication Security*, P. Daponte, M. Klósak, and A. Bendarma, Eds., IOS Press, 2024.
- [56] Z. Huang and B. Li, "Synergistic development of port economy and smart logistics," *Journal of Statistics and Economics*, vol. 1, no. 6, pp. 15–19, 2024.
- [57] R. Klar, A. Fredriksson, and V. Angelakis, "Assessing the maturity of digital twinning solutions for ports," *Proc. of 2023 IEEE International Conference on Pervasive Computing and Communications Workshops*, pp. 552–557.
- [58] R. Abudu and R. Bridgelall, "Autonomous ships: a thematic review," *World*, vol. 5, no. 2, pp. 276–292, 2024.
- [59] R. Klar, A. Fredriksson, and V. Angelakis, "Assessing the maturity of digital twinning solutions for ports," *Proc. of 2023 IEEE International Conference on Pervasive Computing and Communications*, pp. 552–557.
- [60] D. Galar and U. Kumar, "Seas of change: steering maritime innovation with digital twins, the metaverse, and robotics," *NATO Science for Peace and Security Series - D: Information and Communication Security*, P. Daponte, M. Kłosak, and A. Bendarma, Eds., IOS Press,

2024.

- [61] M. V. Clavijo Mesa, C. E. Patino-Rodriguez, and F. J. Guevara Carazas, "Cybersecurity at sea: a literature review of cyber-attack impacts and defenses in maritime supply chains," *Information*, vol. 15, no. 11, pp. 710, 2024.
- [62] A. Haidine et al., "Mapping the applications of vehicular communications in the context of smart maritime ports," *Vehicular Networks - Principles, Enabling Technologies and Modern Applications*, 2024.
- [63] M. Heikkilä et al., "Navigating the future: developing smart fairways for enhanced maritime safety and efficiency," *Journal of Marine Science and Engineering*, vol. 12, no. 2, pp. 324, 2024.
- [64] H.-T. Liao, T.-M. Lo, and C.-L. Pan, "Knowledge mapping analysis of intelligent ports: research facing global value chain challenges," *Systems*, vol. 11, no. 2, pp. 88, 2023.
- [65] F. Almeida, "Challenges in the digital transformation of ports," *Businesses*, vol. 3, no. 4, pp. 548–568, 2023.
- [66] A. Othman, S. El-gazzar, and M. Knez, "A Framework for adopting a sustainable smart sea port index," *Sustainability*, vol. 14, no. 8, pp. 4551, 2022.
- [67] E. Haezendonck, "Port strategy for sustainable development: circularization and value creation—introduction to a special issue," *Sustainability*, vol. 12, no. 23, pp. 9914, 2020.