Blockchain-Integrated Marine Logistics Applications for Secure Cargo Tracking and Intelligent Port Management

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Abstract

Global maritime transport moves the substantial majority of world trade by volume, yet the industry's underlying documentation and coordination processes remain heavily dependent on fragmented, paper-based, and siloed digital systems that create persistent vulnerabilities to data tampering, cargo misdocumentation, and multi-party coordination failure across shippers, carriers, terminal operators, customs authorities, and freight forwarders. Blockchain technology, offering a distributed, cryptographically verifiable, and tamper-resistant ledger shared across mutually distrusting parties, has been proposed and piloted across the maritime sector as a mechanism for securing cargo tracking, automating multi-party documentation through smart contracts, and improving the operational intelligence of port community systems. This paper reviews blockchain-integrated marine logistics applications, synthesizing systematic literature review evidence on blockchain's role in supply chain and maritime transport management, smart-contract-based shipment and customs automation, and blockchain-enabled port community systems and single-window platforms. The review further examines the documented barriers to industry-wide blockchain adoption in the maritime sector, including interoperability, stakeholder trust, and commercial viability, situating these barriers within the widely discussed case of the Maersk-IBM TradeLens platform, which despite substantial industry participation was discontinued in 2023 due to insufficient commercial viability. A comparative methodology is described using bibliometric and systematic-review-derived classification of blockchain maritime applications by function (cargo tracking, documentation automation, port community integration), alongside barrier-analysis frameworks drawn from the Technology-Organization-Environment model. Reported findings indicate that blockchain pilots consistently demonstrate technical feasibility for reducing document-processing time and improving traceability, but that industry-wide adoption remains constrained less by technical limitation than by the network-effect problem inherent to any shared ledger requiring broad, simultaneous stakeholder participation to deliver value. The paper concludes by identifying persistent challenges in blockchain-IoT integration for real-time cargo condition monitoring, interoperability between competing platforms, and the governance structures required for durable, industry-wide adoption in intelligent port management.

Keywords: Blockchain, Maritime Logistics, Cargo Tracking, Port Management, Smart Contracts, Supply Chain Traceability, Port Community Systems, Distributed Ledger Technology.

I. Introduction

Maritime shipping remains the backbone of global trade, and the documentation and coordination processes underlying it, bills of lading, customs declarations, certificates of origin, and multi-party cargo handoffs between shippers, carriers, freight forwarders, terminal operators, and customs authorities, have historically relied on a combination of paper documents and fragmented, mutually incompatible digital systems maintained independently by each stakeholder [1]. This fragmentation creates well-documented operational costs: manual, paper-based bill-of-lading processing has been estimated in industry practice to account for a substantial share of total shipping transaction costs, while the multiplicity of independently maintained records across supply chain participants creates opportunities for document tampering, cargo

misrepresentation, and disputes over custody and condition that are difficult to resolve without a shared, trusted record accessible to all parties [1], [2].

Blockchain technology, a distributed ledger architecture in which transaction records are cryptographically linked, replicated across a network of participating nodes, and rendered computationally impractical to alter retroactively, has been proposed as a structural solution to this coordination problem because it allows mutually distrusting parties, competing carriers, rival freight forwarders, and government customs authorities, to share a single, tamper-evident record of a shipment's provenance and status without requiring any single party to act as a centralized, trusted intermediary [2]. A substantial body of systematic literature review evidence has examined blockchain's application to supply chain management specifically, identifying traceability, transparency, and reduced transaction costs as the most consistently reported benefits across studied use cases, while noting that the technology's core value proposition in this domain rests specifically on its capacity to establish trust among parties who do not otherwise trust one another, rather than on any single party's ability to secure or verify data independently [1], [3].

Applied to maritime logistics specifically, blockchain has been examined across three broadly distinguishable application categories in the literature: cargo and container tracking, in which shipment location, custody, and condition data are recorded on a shared ledger accessible to all authorized supply chain participants; documentation and customs automation, in which smart contracts, self-executing code deployed on the blockchain, automate the verification and release of shipping documents, payments, or customs clearances upon satisfaction of pre-specified conditions; and port community system integration, in which blockchain infrastructure underlies the broader digital platform coordinating data exchange among the many independent stakeholders operating within a single port [4], [5]. A systematic literature review specifically addressing blockchain implementation in logistics identified sustainability, efficiency, and transparency as recurring evaluative themes across the reviewed case studies, while noting that empirical, large-scale operational deployments remained comparatively rare relative to the volume of conceptual and pilot-stage research [5].

The most extensively documented real-world blockchain application in maritime cargo tracking is TradeLens, a joint venture launched in 2018 by Maersk, the world's largest container shipping line, and IBM, which sought to create a shared, blockchain-based digital platform recording shipment events, bills of lading, and customs documentation across the global container shipping ecosystem [6]. At its height, TradeLens reported participation from more than 175 organizations, including multiple competing ocean carriers, port and terminal operators, and customs authorities in several countries, representing one of the largest attempted industry-wide blockchain deployments in any sector [7]. Despite this scale of participation, Maersk and IBM jointly announced in November 2022 that TradeLens would be discontinued, with the platform going offline by the end of the first quarter of 2023, citing that the platform had not reached the level of commercial viability necessary to continue as an independent business, a decision widely attributed in industry analysis to the difficulty of achieving the full, competitor-inclusive industry collaboration that a shared ledger's value proposition depends upon [6], [7], [8]. This outcome has become a widely cited cautionary case study within the blockchain-maritime literature, illustrating that technical feasibility alone does not guarantee the network-wide adoption a shared-ledger system requires to deliver its intended benefits [8].

Beyond cargo tracking platforms, smart-contract-based approaches have been proposed and prototyped specifically for shipment management automation, in which contractual conditions, such as delivery confirmation, quality inspection, or customs clearance, trigger automatic execution of associated actions, including payment release or document issuance, without requiring manual intermediation by any single party [9]. Complementary research has examined blockchain's integration into port community systems and maritime single-window platforms, the digital infrastructure through which a port's many independent stakeholders, shipping lines, terminal operators, customs, port authorities, and inland transport providers, exchange operational data, with bibliometric and systematic review evidence indicating a marked increase in scholarly attention to this specific application area since 2018, concentrated particularly among researchers in China, Singapore, and other major Asian shipping economies [4], [10].

Despite this substantial and rapidly growing research base, systematic reviews of blockchain adoption specifically within the port sector consistently identify a persistent barrier structure: interoperability between competing and incompatible blockchain platforms, resistance from stakeholders wary of sharing operationally sensitive data with competitors, the absence of clear return-on-investment evidence at the

scale required to justify large infrastructure investment, and unresolved questions of governance and standardization across a fragmented, multi-jurisdictional industry [10], [11]. These barriers have been further examined through the lens of the Technology-Organization-Environment (TOE) framework, which distinguishes barriers rooted in the technology itself from those rooted in organizational readiness and the broader competitive and regulatory environment, providing a structured basis for comparing why some blockchain maritime pilots progress to sustained operational use while others, including TradeLens, do not [4], [11].

This paper synthesizes the growing body of systematic review, case study, and industry evidence on blockchain-integrated marine logistics applications, examining cargo tracking, smart-contract-based documentation automation, and port community system integration, and evaluates the comparative evidence on both the demonstrated technical benefits and the persistent adoption barriers that continue to shape this field's trajectory.

Research Objectives

1. To examine the core technical mechanisms by which blockchain enables secure, multi-party cargo tracking in maritime logistics.
2. To analyze smart-contract-based approaches to shipment documentation and customs automation.
3. To evaluate blockchain integration into port community systems and maritime single-window platforms.
4. To compare reported adoption outcomes, including the TradeLens case, against documented barrier frameworks.
5. To identify persistent technical and organizational challenges constraining industry-wide blockchain adoption in intelligent port management.

II. Literature Review

2.1 Blockchain Fundamentals and Their Relevance to Supply Chain Trust

Blockchain's foundational value proposition for supply chain and logistics applications rests on its capacity to establish a shared, tamper-evident record among parties that do not otherwise trust one another, achieved through cryptographic linkage of transaction blocks and distributed replication across a network of participating nodes rather than reliance on any single centralized authority [2]. Foundational supply chain management research examining blockchain's roles identified traceability, contract automation, and reduced reliance on costly intermediary verification as the technology's primary objectives-meeting mechanisms within supply chain contexts, establishing much of the conceptual vocabulary subsequently applied to maritime-specific research [2]. A widely cited systematic review of blockchain's relationship to sustainable supply chain management similarly emphasized transparency and traceability as the dominant reported benefits across the reviewed literature, while also noting that most studies to that point remained conceptual or small-scale pilot demonstrations rather than mature, large-scale operational deployments [3].

2.2 Blockchain-Enabled Cargo and Container Tracking

Applied specifically to cargo tracking, blockchain systems record shipment location, custody transfer, and condition data at each handoff point along the maritime supply chain, creating a shared, auditable record accessible to all authorized parties, shippers, carriers, terminal operators, and customs authorities, without requiring any single party to serve as the sole custodian of that record [1], [5]. This approach directly targets the coordination failure inherent in traditional maritime documentation, in which each stakeholder maintains an independent record that must be manually reconciled with counterparties' records, a process historically prone to delay, discrepancy, and disputed liability when cargo condition or custody is contested [1]. The most prominent real-world implementation of this cargo-tracking application was TradeLens, which recorded shipment events and associated documentation on a permissioned blockchain accessible to a global network of shipping industry participants [6], [7].

2.3 The TradeLens Case: Technical Feasibility Versus Commercial Viability

TradeLens, launched in 2018 as a joint venture between Maersk and IBM, represents the largest and most extensively documented real-world test of blockchain-based cargo tracking at industry scale, reporting participation from more than 175 organizations at its peak, including competing ocean carriers, terminal operators, and customs authorities across multiple countries [7]. Despite this scale, Maersk and IBM jointly announced the platform's discontinuation in November 2022, with the platform taken fully offline by the end of the first quarter of 2023, explicitly citing that the platform had not achieved the level of commercial viability necessary to continue as an independent business, and that the full industry-wide collaboration the platform's value proposition depended upon had not been achieved [6]. Industry analysis of this outcome has consistently pointed to a network-effect problem specific to shared-ledger platforms in competitive industries: because a blockchain-based tracking platform's value to any single participant scales with the number of other, including directly competing, participants who also join, and because competing carriers and freight forwarders have limited incentive to share operationally sensitive shipment data with rivals on a platform partly owned by one of those same rivals, achieving the critical mass of adoption required for the platform to deliver its intended benefits proved more difficult than achieving the underlying technical implementation [6], [8]. This case has become a central reference point in subsequent systematic reviews of blockchain adoption barriers in the port and maritime sector, illustrating that technical feasibility, which TradeLens is widely credited with having demonstrated, does not by itself guarantee sustained commercial adoption [8], [10].

2.4 Smart-Contract-Based Documentation and Customs Automation

Smart contracts, self-executing code deployed on a blockchain that automatically performs a specified action once pre-defined conditions are verifiably met, have been proposed and prototyped as a mechanism for automating maritime shipment documentation and customs processes without requiring manual intermediation by any single party [9]. A prototype smart-contract-based shipment management framework demonstrated how delivery confirmation, quality inspection outcomes, and payment release could be encoded as automatically triggered contract conditions, reducing the manual coordination burden and associated delay traditionally required to reconcile these steps across independent stakeholder systems [9]. This approach extends the core cargo-tracking value proposition of blockchain, shared, tamper-evident record-keeping, into active process automation, in which the blockchain does not merely record what happened but automatically executes downstream actions contingent on verified events, a capability with particular relevance to customs clearance processes that traditionally require substantial manual document verification across multiple, jurisdictionally distinct authorities [9].

2.5 Blockchain Integration in Port Community Systems and Maritime Single-Window Platforms

Beyond individual cargo shipments, blockchain has been examined as an infrastructure layer for port community systems, the digital platforms through which the many independent stakeholders operating within a single port, shipping lines, terminal operators, customs authorities, port authorities, and inland transport providers, exchange operational data [4]. A systematic literature review with bibliometric analysis covering 51 peer-reviewed articles published between 2013 and 2023 found that scholarly engagement with blockchain applications in maritime single-window and port community systems rose sharply from 2018 onward, with research activity concentrated particularly among institutions in China, Singapore, and other major Asian shipping economies, and identified five major research streams: data security and sharing within ports, behavioral analysis of decentralized technologies in smart ports, factors influencing blockchain adoption success, blockchain's effects on container shipping operations, and integration of blockchain with complementary digital technologies [4]. A case study of blockchain-based port logistics innovation at the Port of Busan similarly demonstrated operational feasibility for integrating blockchain into existing port logistics workflows, contributing to the growing body of case-level evidence supplementing the predominantly conceptual and review-based literature in this area [12].

2.6 Barriers to Industry-Wide Blockchain Adoption in Maritime Logistics

Systematic reviews focused specifically on blockchain adoption within the port sector consistently identify a recurring set of barriers that persist despite continued growth in the underlying research literature: interoperability challenges between competing, mutually incompatible blockchain platforms; institutional and stakeholder resistance rooted in reluctance to share operationally or competitively sensitive data;

unresolved questions of data governance and standardization across a fragmented, multi-jurisdictional regulatory environment; and, most fundamentally, difficulty achieving the scale of adoption required to realize the network effects on which a shared-ledger platform's value depends [10], [11]. A study applying the Technology-Organization-Environment framework specifically to maritime supply chain blockchain diffusion found that organizational readiness and external environmental factors, including regulatory uncertainty and the competitive posture of industry incumbents, contributed as substantially to adoption outcomes as the underlying technology's maturity, reinforcing the broader finding that the primary constraint on blockchain maritime adoption is organizational and economic rather than purely technical [4], [11]. A comparative study examining developing countries' specific concerns regarding blockchain adoption in the maritime sector further identified infrastructure limitations, workforce digital literacy, and disproportionate implementation cost relative to smaller port operators' capital budgets as additional barriers not uniformly shared across all maritime economies [13].

2.7 Research Gap

While blockchain's application to cargo tracking, smart-contract-based documentation, and port community systems have each been extensively reviewed individually, relatively few studies synthesize the specific, well-documented failure of the industry's most prominent large-scale deployment, TradeLens, alongside the broader barrier-analysis literature within a single integrated framework distinguishing technical feasibility from organizational and commercial viability [6], [8], [10]. Furthermore, most existing systematic reviews catalogue conceptual and pilot-stage research without providing a comparative assessment of which specific blockchain maritime application types, tracking, documentation automation, or port community integration, have progressed furthest toward sustained operational deployment relative to which remain predominantly conceptual [4], [5]. This study addresses these gaps by synthesizing evidence across all three application categories and the TradeLens case within an integrated comparative framework centered on the distinction between demonstrated technical feasibility and realized commercial and organizational adoption.

III. Methodology

3.1 Research Design

This study adopts a qualitative, descriptive, and comparative research design based on synthesis of systematic literature reviews, bibliometric analyses, and documented industry case studies addressing blockchain-integrated marine logistics applications. Rather than conducting new primary empirical deployment, the study consolidates reported findings across cargo tracking, smart-contract automation, and port community system integration research to characterize consistent patterns in demonstrated technical benefit and documented adoption barriers.

3.2 Conceptual Framework

The framework applied in this review distinguishes three functional categories of blockchain-integrated marine logistics application, cargo and container tracking, smart-contract-based documentation and customs automation, and port community system integration, and evaluates each along two dimensions: **demonstrated technical feasibility**, encompassing pilot and prototype evidence of the application's core functional capability, and **realized adoption outcome**, encompassing evidence of sustained, scaled, real-world deployment beyond the pilot or conceptual stage. This two-dimensional framework is applied specifically to distinguish cases, such as TradeLens, where technical feasibility was substantially demonstrated but sustained industry-wide adoption was not achieved, from cases where evidence remains predominantly conceptual and neither dimension has been fully tested at scale.

3.3 Data Sources

The literature synthesized in this review draws on foundational and systematic review literature on blockchain's role in supply chain management; systematic literature reviews and bibliometric analyses specifically addressing blockchain applications in maritime freight transport, port operations, and maritime single-window/port community systems; smart-contract shipment management prototype research; documented industry case studies and contemporaneous industry reporting on the TradeLens platform's launch, participation scale, and 2022–2023 discontinuation; and barrier-analysis studies applying the Technology-Organization-Environment framework to maritime blockchain adoption.

3.4 Analytical Framework

Reviewed studies and case evidence were classified according to the three-category, two-dimension framework described in Section 3.2. For each application category, evidence was further classified by barrier type, technical/interoperability, organizational/stakeholder trust, or environmental/regulatory, following the Technology-Organization-Environment structure used in the reviewed adoption-barrier literature, enabling systematic comparison of which barrier types most consistently constrain progression from pilot-stage feasibility to sustained operational deployment.

3.5 Evaluation Criteria

Comparative evaluation in this review uses criteria appropriate to the heterogeneous evidence base spanning conceptual, pilot-stage, and case-study research: **demonstrated functional capability** (whether the reviewed literature or case evidence confirms the application performs its intended tracking, automation, or coordination function), **adoption scale reached** (pilot, multi-organization consortium, or sustained industry-wide deployment), **primary barrier category** (technical, organizational, or environmental, per the TOE framework), and **outcome status** (ongoing, discontinued, or not yet progressed beyond conceptual stage), used to assess the comparative maturity and viability of blockchain applications across the three functional categories reviewed.

IV. Results and Discussion

4.1 Comparative Assessment of Blockchain Maritime Application Categories

Table I summarizes representative evidence on demonstrated technical feasibility and realized adoption outcomes across the three functional categories of blockchain-integrated marine logistics applications reviewed in Section II.

Table I. Comparative technical feasibility and adoption outcomes across blockchain maritime application categories

Application category	Representative case/evidence	Demonstrated technical feasibility	Adoption scale reached	Outcome status	Source
Cargo/container tracking	TradeLens (Maersk/IBM)	Confirmed; platform operated at scale for several years	Industry consortium (175+ organizations)	Discontinued (2023) due to commercial viability, not technical failure	[6], [7], [8]
Smart-contract documentation/customs automation	Prototype shipment management frameworks	Confirmed at prototype/pilot level	Prototype/limited pilot	Not yet progressed to industry-wide deployment	[9]
Port community systems/single-window integration	Port of Busan case study; bibliometric review of 51 studies (2013–2023)	Confirmed at case-study level; growing research volume since 2018	Individual port-level implementation; limited cross-port standardization	Operational at select ports; broader industry standardization not yet achieved	[4], [12]

The comparative pattern evident in Table I indicates that all three application categories have cleared the threshold of demonstrated technical feasibility, meaning that no reviewed evidence suggests blockchain is technically incapable of performing the tracking, automation, or coordination functions proposed for it. What differs sharply across categories is the scale of adoption reached and, in the TradeLens case specifically, the outcome once that scale was reached. TradeLens stands out as the only application in this comparison to have achieved genuine industry-wide, multi-competitor consortium participation, yet it is also the only case among the three to have been formally discontinued, a pairing that directly supports the central finding of this review: the binding constraint on blockchain maritime adoption is not technical maturity but the organizational and commercial challenge of sustaining broad, competitor-inclusive participation once a platform moves beyond its initial pilot phase [6], [8].

4.2 Barrier Analysis Across the Technology-Organization-Environment Framework

Table II compares the barrier types most frequently identified across the systematic review and adoption-analysis literature, organized according to the Technology-Organization-Environment framework applied in Section 2.6.

Table II. Barriers to blockchain adoption in maritime logistics by TOE category

TOE category	Representative barrier	Reported severity/frequency	Illustrative evidence	Source
Technological	Interoperability between competing/incompatible blockchain platforms	Frequently cited across systematic reviews	Fragmented platform landscape limiting cross-carrier data exchange	[10], [11]
Organizational	Stakeholder reluctance to share competitively sensitive shipment data	Consistently identified as a primary barrier	Competing carriers hesitant to join platform partly owned by a rival	[8], [11]
Organizational	Unclear or insufficient return-on-investment justification for large infrastructure spend	Commonly cited, particularly for smaller operators	Disproportionate cost burden for smaller port operators	[13]
Environmental	Regulatory and jurisdictional fragmentation across international maritime trade	Frequently cited	Absence of standardized cross-border data governance	[4], [11]

Environmental	Infrastructure and digital-literacy gaps in developing-country ports	Identified in region-specific studies	Constrained implementation capacity outside major shipping economies	[13]

The barrier pattern in Table II reinforces the interpretation offered in Section 4.1: while technological barriers, particularly interoperability between competing platforms, are consistently reported, the organizational barrier category, especially stakeholder reluctance to share data with competitors on a shared platform, appears with comparable or greater frequency across the reviewed literature and maps directly onto the specific rationale Maersk and IBM cited for discontinuing TradeLens [6], [8], [11]. This suggests that future blockchain maritime initiatives may benefit more from governance innovations addressing competitive trust, such as neutral, non-carrier-owned platform governance structures, than from further technical refinement of the underlying distributed ledger architecture itself, since the reviewed evidence indicates the architecture's technical capability is not the primary factor limiting adoption.

4.3 Discussion

Taken together, the evidence reviewed supports a clear central conclusion: blockchain technology has been repeatedly and consistently demonstrated to be technically capable of securing cargo tracking data, automating multi-party shipment documentation, and integrating into port community coordination systems, but the maritime industry's experience to date, most visibly through the TradeLens case, indicates that realizing these technical capabilities at the industry-wide scale required to deliver their full intended value remains substantially constrained by organizational and commercial factors rather than by any demonstrated technical limitation of the technology itself [6], [8], [9]. This finding carries an important implication for how the field's continued development should be framed: research and investment directed primarily at improving blockchain's technical performance, throughput, latency, or cryptographic security, is unlikely by itself to resolve the adoption barrier most consistently identified in the systematic review literature, namely the reluctance of competing commercial stakeholders to share sensitive operational data on a platform they do not independently control or trust [8], [10], [11]. Applications with narrower, single-organization or single-port scope, such as the Busan case study, or applications automating a specific, bounded documentation task via smart contracts, appear to face a lower version of this same barrier, since they do not require the same breadth of competitor-inclusive participation that a global, cross-carrier tracking platform demands, offering a plausible explanation for why these narrower-scope applications, while individually smaller in ambition, may represent a more tractable near-term pathway toward sustained operational blockchain deployment in the maritime sector [4], [9], [12].

V. Challenges in Blockchain-Integrated Marine Logistics

Several challenges constrain further progress in this field. Interoperability between the multiple, independently developed blockchain platforms that different carriers, ports, and logistics providers have piloted remains a persistent technical barrier, since a cargo shipment routinely passes through the custody of multiple organizations that may each use different, mutually incompatible ledger systems, undermining the shared-record value proposition unless cross-platform data exchange standards are established. The organizational trust barrier illustrated by the TradeLens case remains arguably the most consequential open challenge, since any shared-ledger cargo tracking platform's value scales with the breadth of, including competitor, participation it achieves, and no governance model has yet been widely demonstrated to fully resolve competing carriers' reluctance to share operationally sensitive data on a platform associated with a rival firm. Integration between blockchain and Internet of Things (IoT) sensor technology for real-time cargo condition monitoring, temperature, humidity, shock exposure, remains an active but still maturing research area, since blockchain's tamper-evidence guarantee applies only to data once it is recorded on the ledger and does not itself verify that IoT sensor input was accurate or unmanipulated prior to that recording, an open problem sometimes termed the "oracle problem" in the broader blockchain literature. Regulatory and jurisdictional fragmentation across the many countries any international shipment traverses continue to

complicate standardized, cross-border blockchain-based customs automation. Finally, infrastructure and cost barriers documented in developing-country maritime contexts indicate that blockchain adoption benefits documented in major shipping economies may not translate uniformly to smaller ports or lower-resource maritime administrations without targeted capacity-building investment.

VI. Conclusion

This paper has reviewed blockchain-integrated marine logistics applications spanning secure cargo tracking, smart-contract-based documentation and customs automation, and port community system integration. The evidence gathered across systematic reviews, bibliometric analyses, and the widely documented TradeLens case demonstrates that blockchain technology has repeatedly proven technically capable of performing its proposed functions, establishing tamper-evident, multi-party shipment records, automating conditional document and payment processes, and coordinating data exchange among a port's many independent stakeholders. At the same time, the industry's most prominent large-scale deployment was discontinued not because the underlying technology failed, but because the breadth of competitor-inclusive industry participation required for a shared cargo-tracking ledger to deliver its intended value was not achieved at sustainable commercial scale. This distinction between demonstrated technical feasibility and realized organizational adoption emerges as the central lesson of the current evidence base, and it suggests that narrower-scope applications, single-port community systems and bounded smart-contract automation tasks, may represent a more immediately tractable path toward sustained operational deployment than global, cross-carrier tracking platforms of the kind TradeLens attempted. As the maritime industry continues to digitalize, the future trajectory of blockchain-integrated marine logistics will likely depend less on further technical refinement of distributed ledger architecture and more on the development of governance models capable of resolving the competitive trust barrier that has repeatedly constrained industry-wide adoption to date.

VII. Future Work

Future research should prioritize comparative, empirically grounded studies of governance models capable of resolving the competitive trust barrier that constrained TradeLens, potentially examining neutral, non-carrier-owned consortium structures or public-sector-anchored platforms as alternatives to the carrier-co-owned model that may have contributed to competitor reluctance in that case. Further work is needed to develop and test interoperability standards enabling data exchange across the multiple, independently piloted blockchain platforms currently fragmenting the maritime sector, since a shipment's value from tracking is undermined whenever it must cross between incompatible ledger systems during transit. Continued research on blockchain-IoT integration should address the oracle problem directly, developing verification mechanisms that extend blockchain's tamper-evidence guarantee back to the point of physical sensor data capture rather than only to the point of ledger recording. Research should also examine the comparative cost-effectiveness and adoption pathway for narrower-scope, single-port or single-task blockchain applications relative to global tracking platforms, testing directly whether the lower-barrier hypothesis proposed in this review's discussion holds across a broader sample of port-level case studies. Finally, future work should extend blockchain maritime adoption research beyond the major shipping economies currently dominating the literature to lower-resource ports and developing-country maritime administrations, addressing the infrastructure and capacity gaps identified as a distinct barrier category in the existing evidence base.

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