



WHICH BARRIERS DRIVE THE OTHERS? MODELLING THE INTERDEPENDENCIES OF INTEGRATED IOT-BLOCKCHAIN-BIG DATA ANALYTICS ADOPTION IN EMERGING-ECONOMY MARITIME LOGISTICS

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DOI: <https://doi.org/10.63544/jbii.v5i10.242>

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Article History:

Received: 01.09.2026

Accepted: 22.09.2026

Published: 04.10.2026

Abstract

Integrated Internet of Things (IoT), blockchain, and Big Data Analytics (BDA) offer substantial potential to improve visibility, trust, coordination, and decision-making in maritime logistics. However, their combined adoption remains constrained by interdependent technological, organisational, and environmental barriers, particularly in emerging economies. This study identifies these barriers, examines their causal relationships, and develops a sequenced implementation framework for integrated digital transformation. A systematic literature review of 32 studies produced 12 barriers, which were subsequently evaluated through Fuzzy-DEMATEL using judgments from 18 maritime experts. The analysis classified seven barriers as causal drivers and five as dependent outcomes. Lack of management commitment and organisational capability emerged as the strongest driver, followed by limited stakeholder participation and weak ecosystem coordination. The dependent barriers comprised interoperability limitations, inadequate connectivity, resistance to change, scalability constraints, and cybersecurity-related risks. These findings indicate that many visible technical difficulties are consequences of deeper governance, capability, and coordination weaknesses. Accordingly, maritime organisations should first strengthen leadership commitment, internal capabilities, stakeholder engagement, and ecosystem collaboration before prioritising downstream technological integration and risk controls. The study contributes a causal, system-oriented understanding of adoption barriers rather than treating them as isolated constraints. It also offers policymakers, port authorities, logistics firms, and technology partners a practical pathway for allocating resources, coordinating implementation, and reducing failure risks when deploying integrated IoT-blockchain-BDA solutions in emerging-economy maritime logistics settings. By distinguishing root causes from resultant obstacles, the framework helps decision-makers sequence interventions more effectively and supports a more resilient, scalable, secure, and coordinated transformation of maritime operations.

Keywords: IoT; Blockchain; Big Data Analytics; Maritime Logistics; Fuzzy-DEMATEL; Technology Adoption; Emerging Economies

1. Introduction

Maritime logistics is in the midst of a significant transformation to digital, with a surge in adoption of digital technologies by the maritime sector's actors, including ports, shipping companies, terminal operators, and others in the maritime supply chain, to enhance operational efficiency, visibility, coordination, and resilience. This transition has been accelerating towards interconnected smart-port ecosystems (Rizwan & Ahmed, 2026). According to the authors of Jovic et al. (2022), the technologies linked to digitalization have gained more and more significance in the areas of maritime transport and seaport studies.



These technologies work together, such as Internet of Things (IoT), blockchain, and Big Data Analytics (BDA). The Internet of Things (IoT) helps to continuously gather data, thereby enabling real-time surveillance of maritime and port activities (Nguyen et al., 2023). Blockchain offers secure, transparent, traceable, and decentralized records (Alahmadi et al., 2021) and BDA brings operational data into the realm of analytical insights. Therefore, these technologies should be considered a digital system as a whole and not as standalone technological applications (Heikkilä et al., 2022).

Although the benefits of digital integration are there, the adoption of technology in maritime logistics is still inconsistent. Port digitalization can be impeded by interoperability deficiencies, stakeholder coordination problems, technological incompatibility, regulatory requirements, and organizational readiness (Brunila et al., 2021). Importantly, these barriers can work together, and may not be separate barriers. Guan et al. (2023) provide significant correlations between the blockchain adoption barriers, and economic barriers also can have causal effect on other maritime digitalization barriers (Koca & Erdogan, 2024). Existing literature largely identifies barriers, categorizes barriers, or ranks barriers, but offers limited explanation of which barriers cause which other barriers.

Three gaps are thus worthy of investigation, each of which relates to the others. First, there has been a lack of attention to the barriers for IoT, blockchain and BDA as a technological architecture. Second, there have been few studies that investigate the direction of cause-effect relationships; Surucu-Balci et al. (2024) point to a lack of theoretically based causal empirical studies. Thirdly, digital transformation evidence continues to be restricted in emerging economy maritime contexts, where digital transformation is influenced by interconnected institutional, governance, stakeholder, resource and organisational constraints (Sakita et al., 2024). Therefore, research should clarify the interactions between barriers and differentiate between the upstream barriers and downstream consequences.

1.1 Research Objectives

Against this background, this study seeks to develop a systematic understanding of the interdependencies among barriers to integrated IoT-blockchain-BDA adoption in emerging-economy maritime logistics. Specifically, the study aims to:

1. Identify the principal barriers to adopting integrated IoT-blockchain-BDA systems in maritime logistics;
2. Examine the cause-effect structure of these barriers and determine which barriers function as drivers and which emerge as dependent outcomes; and
3. Develop a sequenced implementation strategy for maritime stakeholders based on the identified cause-effect structure of integrated IoT-blockchain-BDA adoption barriers.

1.2 Research Questions

Consistent with these objectives, the study addresses the following research questions:

1. What are the principal barriers to adopting integrated IoT-blockchain-BDA systems in maritime logistics?
2. What is the cause-effect structure of these barriers, and which barriers function as drivers and which as dependent outcomes?
3. How should the identified cause-effect structure guide a sequenced implementation strategy for maritime stakeholders?

The study is a contribution to maritime digitalization research by moving the focus of analysis from identifying and ranking adoption barriers to explaining the causal interdependencies of barriers. This separation is of theoretical and practical significance as it affects the adoption of innovation in the port, which for instance is shaped by organizational capabilities, financial capacity, technological characteristics, network relations as well as external pressures (Sooprayen et al., 2024). The separation of driving barriers from dependent outcomes provides a foundation on which to focus limited resources and prioritize interventions over all barriers. It therefore provides practical advice to maritime managers, port authorities, technology suppliers and policy makers and adds to the empirical body of knowledge on digitalisation in emerging economy maritime logistics.



2. Literature Review and Theoretical Background

2.1 Digital Transformation in Maritime Logistics

Digital transformation is increasingly transforming maritime logistics, changing the way the business is operated from asset-centred and fragmented systems to connected and data-driven systems. The smart ports, as one of the key expressions of this shift towards smart ports, combine intelligent infrastructure, automation, information platforms and advanced analytics to enhance the coordination of operations and sustainability (Dağıstan et al., 2025). This is becoming a trend that is growing beyond a single technological application to digitally integrated environments for port and shipping. For instance, Lee et al. (2024) link emerging port configurations with the presence of IoT, blockchain, AI and associated technologies. It is a process that calls for cooperation between shipping lines, terminals, customs authorities, logistic companies, and port authorities (Liao et al., 2023). However, there is a lack of digital maturity, especially in less developed maritime contexts, due to constraints in the infrastructure and institutional capacity to modernize (Burmambet, 2025).

2.2 IoT in Maritime Logistics

IoT is the underlying mechanism that makes physical maritime operations digitally observable, within this transformation. Information is continuously being generated through sensors, RFID, connected equipment and smart containers regarding the location of cargo, its environment, and the condition of the vessel. This continuous flow of data enables real-time monitoring, predictive maintenance, and enhanced operational visibility across the maritime supply chain. However, the deployment of IoT in maritime logistics faces challenges related to connectivity, data standardization, cybersecurity, and the integration of heterogeneous devices and systems (Nguyen et al., 2023; Farah et al., 2022).

2.3 Blockchain in Maritime Logistics

Blockchain technology offers secure, transparent, traceable, and decentralized records that can enhance trust and coordination among maritime supply chain partners. It enables the secure sharing of documentation, smart contract automation, and tamper-proof record-keeping, which are critical for maritime operations involving multiple stakeholders across different jurisdictions. However, blockchain adoption in maritime logistics is hindered by challenges such as scalability limitations, interoperability issues, high implementation costs, regulatory uncertainty, and lack of common standards (Alahmadi et al., 2021; Muñoz-Sánchez et al., 2025).

2.4 Big Data Analytics in Maritime Logistics

Big Data Analytics (BDA) transforms the vast amounts of data generated by IoT devices and other sources into actionable insights for decision-making. In maritime logistics, BDA can support demand forecasting, route optimization, risk assessment, and performance monitoring. However, the effective use of BDA requires reliable data, analytical skills, and integration with existing systems, which are often lacking in emerging economy contexts (Munim et al., 2020).

2.5 Integrated IoT-Blockchain-BDA Systems

The literature highlights the IoT, Blockchain, and Big Data Analytics (BDA) technologies as interrelated ones, not as autonomous ones, in maritime logistics. In this comprehensive system, the operational and logistics data generated by IoT devices are constantly stored, verified, and protected using blockchain technologies. This trustworthy and traceable data can then be analyzed using BDA to derive valuable insights and aid in informed decision-making (Rizwan & Nikko, 2026). Therefore, the technological stream moves from the generation of data using IoT, to the validation and security of data through blockchain, and finally to analysing and making decisions based on the data, using BDA. For this holistic approach, the use of blockchain-based maritime systems continues to focus on the coordination of information, documentation and operational processes throughout the maritime supply chain (Shin et al., 2023). Similarly, Surucu-Balci et al. (2024) show that digital information-sharing capabilities are linked to other technological enablers, barriers and performance outcomes. As a consequence, incomplete data due to unreliable IoT connectivity can limit the ability to rely on data; blockchain interoperability issues can hinder trusted exchanges; and lack of analytical power can hinder the ability to leverage validated data for actionable intelligence. The overall



architecture is thus subject to various interactive technological, economic, institutional and collaborative factors (Alavi-Borazjani et al., 2025).

2.6 Barriers to Integrated Digital Technology Adoption

The interdependencies can be arranged in an expanded technology-organization-environment (TOE) model. From a technological perspective, connected adoption is limited by the lack of interoperability and standards, connectivity and latency issues, blockchain scalability and energy consumption, and IoT cybersecurity and data-integrity risks. The issue of cross-system standardization is still a challenge for intelligent maritime systems (Zou et al., 2025), and the application of blockchain technology introduces further interoperability and scalability challenges (Muñoz-Sánchez et al., 2025).

There are organizational level barriers that can hinder organizations from implementing and using technology when available: digital-skills shortages, resistance to change, capability and leadership gaps, and financial constraints. Adopting digital technologies in the sea industry depends on the organizational capabilities and institutionalization (Janmethakulwat & Thanasopon, 2025), the perceived investment cost strongly affects blockchain adoption for maritime freight businesses (Singh et al., 2024).

From an environmental perspective, regulatory fragmentation, legal uncertainty, immaturity of standards and infrastructure fragmentation, and network-externality issues limit the ability to adopt the ecosystem scale. Lin (2023) indicates that there is a need to recognize the influence of environmental factors on maritime blockchain adoption, in addition to organizational and technical factors. The constraints are particularly relevant to integrated systems since their value is dependent on participation across organizational lines. The twelve barriers should instead be thought of as likely to reinforce each other rather than independent determinants.

2.7 Theoretical Foundation

The TOE framework offers the main theoretical support for the search for these barriers in technological, organizational and environmental environments. But recognizing contextual barriers is not sufficient to determine how organizations become capable of tackling these contextual barriers. The dynamic capabilities perspective is an add-on to TOE, which emphasises skills of the organisation in sensing opportunities and constraints in technology, capturing them with strategic investments and mobilisation of resources, and reconfigure the routines, skills, and assets. There have been some observations from shipping SMEs showing that the lack of such capabilities can hinder digital transformation (Nguyen & Le, 2025). Digital adoption, in turn, can be better theoretically explained by combining dynamic capabilities with TOE (Abdurrahman et al., 2024). TOE identifies barriers to adoption while dynamic capabilities explain how organisations deal with them. This integrated view then underpins the theoretical foundation of the modelling of barriers as dependent consequences and the modelling of barriers as fundamental drivers.

2.8 Conceptual Framework

Building upon literature and theoretical foundations, this study creates a conceptual framework to explore the barriers of integrated IoT-blockchain-BDA in the emerging-economy maritime logistics. The framework starts with the integrated adoption and then categorizes the barriers identified into the three dimensions of the extended TOE framework (technological, organizational and environmental). The framework does not take these constraints as barriers in isolation, but rather considers that they could reinforce each other. It is therefore decided to use Fuzzy-DEMATEL for identifying the direction and intensity of these inter-dependencies and differentiating between cause/barriers and effect/dependent barriers. This causal structure then allows for the identification of important barriers based on their systemic impact, not just on the basis of their perceived importance. This prioritization is then used during implementation to create a sequence: where influential driving barriers are dealt with first, before dependent barriers. This framework then links barrier identification, interdependency analysis, prioritization and implementation into a cohesive path towards integrated adoption.



Figure 1

Conceptual framework for analysing the interdependencies of barriers to integrated IoT-blockchain-BDA adoption in emerging-economy maritime logistics.



3. Methodology

3.1 Research Design

The research design used in this study was a sequential two-stage research design consisting of a systematic literature review (SLR) and Fuzzy-DEMATEL analysis. Stage 1 involved conducting a systematic literature review to identify and collate barriers to the adoption of IoT, blockchain and BDA in the maritime logistics industry, yielding a final list of 32 studies. For Stage 2, Fuzzy-DEMATEL was applied with the judgments collected from 18 experts to establish the direction and intensity of relationships between the barriers identified and to identify driving barriers and dependent barriers. The combination was suitable since the DEMATEL-based approaches allowed the consideration of the adoption barriers as a complex causal system of elements, instead of being considered as separate barriers (Özbek et al., 2024).

3.2 Stage 1: Systematic Literature Review

3.2.1 Review Protocol. The review was carried out in accordance with the PRISMA 2020 reporting guidelines, to guarantee transparency and methodological repeatability. Page et al. (2021) created the updated PRISMA 2020 for systemically reporting the study identification, screening, eligibility and inclusion (PRISMA). Thus, the review protocol detailed the information sources, search strategy, the eligibility criteria, screening process and the data-extraction process.

3.2.2 Databases. The Scopus and Web of Science Core Collection databases were used to obtain relevant literature. The databases were chosen for being multidisciplinary in nature since they had the widest



scope of coverage in peer-reviewed research in maritime logistics, maritime transportation, information systems and technology management.

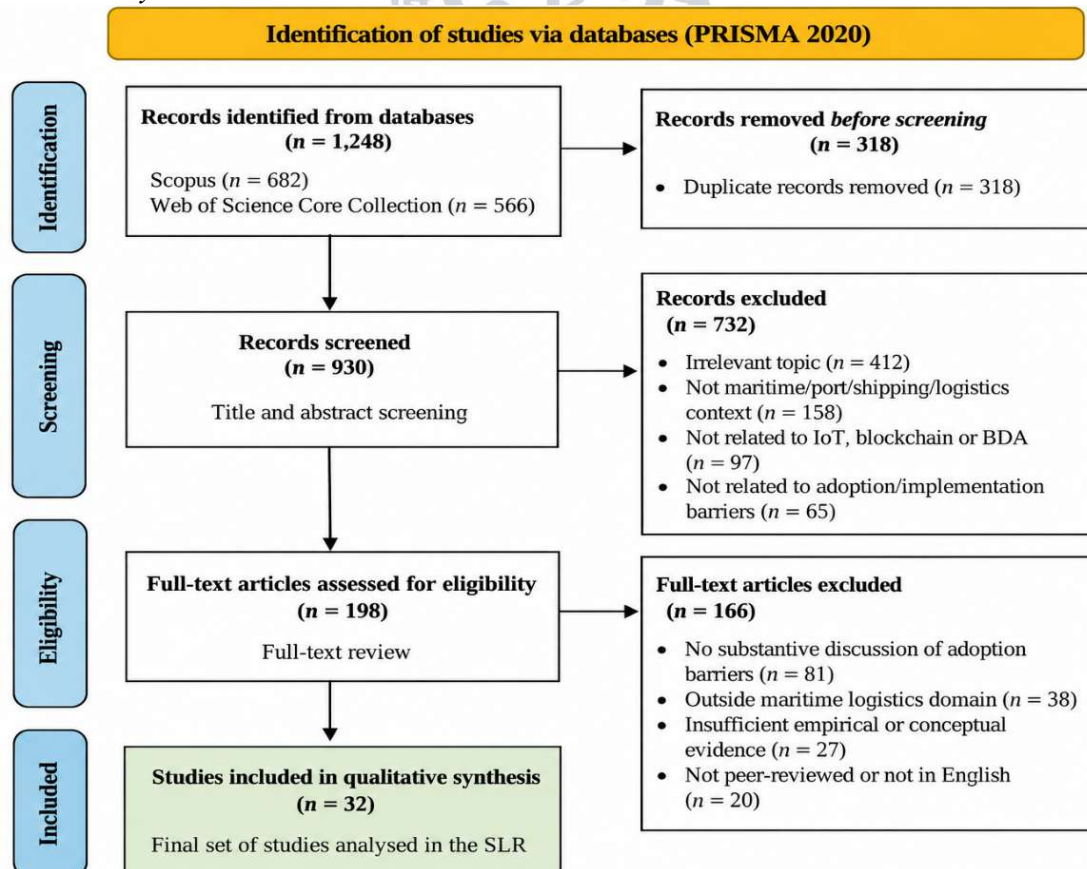
3.2.3 Search Strategy. Maritime-context terms such as maritime, shipping, port and logistics were used as a search strategy along with technology-related terms such as Internet of Things, IoT, blockchain, big data and BDA. The terms were, additionally, paired with adoption, implementation, digitalization, barrier and challenge. Extensive search strings were formulated using boolean operators (AND/OR), and database specific syntax. Search procedures and dates were recorded to improve reproducibility, similar to systematic review (Kolaski et al., 2023).

3.2.4 Eligibility Criteria. Studies were considered if they were peer-reviewed; published in English during the set timeframe; located in maritime, port, shipping or logistics; included at least one of the key terms of IoT, blockchain and/or BDA; and included a meaningful discussion on the barriers to adoption/implementation. In studies outside the field of maritime logistics, studies not related to technology adoption, irrelevant technology studies and publications that gave inadequate evidence about barriers for technology adoption were not included.

3.2.5 Study Selection. The selection of studies was done by identifying the studies, removing the duplicate studies, screening the title and abstract, screening the full text of articles, and deciding which studies would be included. Documentation of reasons for not including in full-text assessment. After applying the eligibility criteria, 32 peer-reviewed studies were retained in the final SLR sample which was then subjected to the data-extraction and barrier-consolidating phases. Details of the entire screening process were detailed in a "PRISMA flow diagram" (Figure 2) which allows for transparent and clear tracking of the evidence base.

Figure 2

PRISMA 2020 flow diagram showing the identification, screening, eligibility assessment, and final inclusion of 32 studies in the systematic literature review.





3.2.6 Data Extraction and Barrier Consolidation. For each of the 32 studies included in this study, the following data were recorded using a structured extraction template: authors and publication year, geographical or empirical context, technology investigated, barriers to reported adoption, and dimension of the barriers. Similar or conceptually similar barriers were compared and combined in order to avoid duplication and to arrive at a parsimonious and final set of barriers. This consolidation was needed because the meaning of the barrier may vary in the technological and empirical contexts, but has a similar conceptual meaning as constraints (Salman et al., 2025).

3.2.7 Reliability of Barrier Coding. The barriers were extracted by two independent researchers who coded them based on the TOE dimensions of the technological, organizational and environmental dimensions. After independent coding the classifications were systematically compared for the areas of agreement and disagreement. Barrier interpretations, terminologies and TOE classifications were discussed between the researchers until they reached a consensus if there were any discrepancies. This allowed for a more consistent and transparent barrier consolidation and classification (Neethling et al., 2024) and helped to minimise interpretation bias in individual interpretations.

3.3 Stage 2: Fuzzy-DEMATEL Analysis

3.3.1 Expert Panel. After the barriers have been consolidated, Fuzzy-DEMATEL assessments were gained from a panel of 18 experts (purposive sampling with snowball sampling). Participants included port operators, maritime logistics and shipping/carrier organisations, maritime digitalisation transformation functions, and regulatory/policy institutions in the emerging economy (South Asia) maritime context. The panel's make-up allowed judgments to be gained from experts who have first-hand experience of maritime digitalisation and challenges with technology adoption. The number of samples was comparable to similar maritime Fuzzy-DEMATEL studies conducted by other researchers, such as Guan et al. (2023) who used 18 experts to analyze the influence among the barriers of interdependency in the seaport industry related to blockchain adoption.

3.3.2 Expert Selection Criteria. Experts were chosen for their professional experience in maritime logistics, awareness of digital technologies and their professional experience in ports, carriers, logistics or shipping and regulatory activities. These criteria ensured that the pairwise evaluations were not based on general perceptions, but rather were informed judgements made by professionals.

3.3.3 Data Collection Instrument. The structured pairwise influence-assessment matrix was administered to the 18 experts, and data was gathered. The research tasks for the participants were to rate each barrier pair in relation to the extent to which one barrier impacts on another barrier for the pair. Five language levels were used for responses: no influence, very low influence, low influence, high influence and very high influence. The linguistic scale was used because it allowed to represent mathematically uncertainty and ambiguity that exists in expert judgments, using fuzzy methods (Smidovnik & Groselj, 2021).

3.3.4 Fuzzy-DEMATEL Procedure. The Fuzzy-DEMATEL analysis was carried out in a step-by-step fashion. Firstly, the expert linguistic evaluations were transformed into triangular fuzzy numbers, and then aggregated over the 18 participants. The aggregated fuzzy values were then defuzzified to get crisp values and finally initial direct relation matrix was built and normalized. The normalized matrix was then multiplied to get the total-relation matrix that reflects both direct and indirect relationships between the barriers (Markosyan et al., 2024).

For each barrier, D was the total influence that the barrier had on other barriers, while R was the total influence that other barriers had on the barrier. Consequently, $D + R$ was a measure of the overall salience of a barrier in the system, and $D - R$ was a measure of the causal significance of the barrier. Barriers with $D - R > 0$ were considered as cause/driving barriers - these barriers had more influence than they received. However, barriers with $D - R < 0$ were considered to be effect/dependent barriers as they were most affected by other barriers. This process helped the study go beyond the traditional barrier ranking and find the barriers that serve as "drivers" throughout the system and would thus be considered leverage points for a "sequenced" intervention.



3.4 Ethical Considerations

The experts were informed of the purpose and procedure of the study before they participated and informed consent was obtained from all the experts. It was a voluntary participation and anonymous/confidential responses were used. There was no penalty for a participant that chose to withdraw. The data collected were securely saved, used only for research and reported only in aggregated form to ensure anonymity for the participant(s).

4. Results

4.1 Results of Systematic Literature Review

4.1.1 PRISMA Search Results. The systematic literature search was carried out according to the PRISMA 2020 framework, including identification, elimination of duplicate papers, screening of the title and abstract, screening of the full-text, and inclusion in the final selection. Combinations of maritime, shipping, port, logistics, IoT, blockchain, Big Data Analytics, adoption, implementation, barrier, and challenge were used in Scopus and Web of Science Core Collection databases to conduct the searches.

A total of 286 records were identified in the selected databases in the systematic review. After 64 duplicate records were removed, 222 records went to the title and abstract screening. Of these, 161 records were removed because they did not meet the pre-defined criteria for eligibility. Then, 61 full-text articles were reviewed for relevance, with 29 being deemed irrelevant due to limited maritime-logistics focus, lack of a maritime-logistics context, or the absence of substantive evidence. Therefore, the final evidence base consisted of 32 peer-reviewed studies, which are included in the systematic literature review.

Table 1

PRISMA 2020 Search and Selection Results

Selection Stage	Number
Records identified	286
Duplicates removed	64
Records screened	222
Records excluded during title/abstract screening	161
Full-text articles assessed	61
Full-text articles excluded	29
Studies included in qualitative synthesis	32

4.1.2 Identified Adoption Barriers. The literature analysis led to the identification of 12 main barriers to the adoption of the integrated solution between IoT, blockchain and BDA in maritime logistics. To prevent duplication of effort, some conceptual overlap barriers were grouped together and termed by the Technology-Organization-Environment (TOE) framework.

Table 2

Identified Barriers to Integrated IoT-Blockchain-BDA Adoption

Code	Barrier	TOE Dimension	Supporting Literature
T1	Interoperability and system-integration limitations	Technological	Brunila et al. (2021); Liu et al. (2021); Muñoz-Sánchez et al. (2025)
T2	Connectivity and communication-infrastructure limitations	Technological	Farah et al. (2022); Nguyen et al. (2023); Zou et al. (2025)
T3	Scalability and computational/energy requirements	Technological	Li and Sun (2025); Muñoz-Sánchez et al. (2025)
T4	Cybersecurity, privacy, and data-integrity risks	Technological	Farah et al. (2022); Li and Sun (2025)
O1	Digital-skills and technical-expertise shortages	Organizational	Janmethakulwat and Thanasopon (2025); Nguyen and Le (2025)



Code	Barrier	TOE Dimension	Supporting Literature
O2	Resistance to organizational and technological change	Organizational	Brunila et al. (2021); Nguyen and Le (2025)
O3	Inadequate management commitment and organizational capabilities	Organizational	Guan et al. (2023); Janmethakulwat and Thanasopon (2025)
O4	High investment and implementation costs	Organizational	Guan et al. (2023); Singh et al. (2024); Koca and Erdoğan (2024)
E1	Regulatory fragmentation and legal uncertainty	Environmental	Lin (2023); Li and Sun (2025)
E2	Lack of common standards and standards maturity	Environmental	Brunila et al. (2021); Zou et al. (2025)
E3	Inadequate external digital infrastructure	Environmental	Sakita et al. (2024); Alavi-Borazjani et al. (2025)
E4	Limited stakeholder participation and ecosystem coordination	Environmental	Guan et al. (2023); Surucu-Balci et al. (2024); Sooprayen et al. (2024)

4.1.3 Classification of Barriers. The 12 barriers were spread over all three areas of the TOE framework. There were four technological barriers, four organizational barriers, and four environmental barriers.

The technological barriers identified were interoperability and system-integration limitations (T1); connectivity and communication-infrastructure limitations (T2); scalability and computational/energy requirements (T3); and cybersecurity, privacy and data-integrity risks (T4). Together these barriers show that the technical complexity is involved in the integration of information generated by the IoT, validation mechanisms based on blockchains, and analytical systems enabled by BDA.

The digital-skills and technical-expertise shortages (O1), resistance to organizational and technological changes (O2), insufficient management commitment and organizational capabilities (O3), and high investment and implementation costs (O4) were the organizational barriers. The results show that adoption of the technology is merely a component of a larger process that requires the organizational capability, managerial support, financial resources and willingness to change.

The environmental barriers were regulatory fragmentation and legal uncertainty (E1), lack of common standards and maturity (E2), insufficient external digital infrastructure (E3) and limited stakeholder involvement and ecosystem coordination (E4). These barriers highlight the need for institutional and ecosystem factors, since connected maritime technologies rely on cooperation and knowledge sharing across organizational and institutional boundaries.

4.2 Fuzzy-DEMATEL Results

Finally, the relationships between the 12 barriers identified were explored using Fuzzy-DEMATEL. In line with the analytical procedure specified, pairwise influence values were converted to a direct-relation structure, normalized and converted to a total-relation matrix. A matrix was created to analyze the influence exerted (D), influence received (R), prominence (D + R), and net causal influence (D - R) of each barrier.

4.2.1 Direct-Relation Matrix. The direct-relation matrix is a matrix in which the direct influence of each barrier with respect to each other barrier is expressed as relative values. The diagonal was set to zero, as barriers were not thought to directly impact themselves.



Table 3

Direct-Relation Matrix

	T1	T2	T3	T4	O1	O2	O3	O4	E1	E2	E3	E4
T1	0	1.51	1.37	1.69	1.50	1.30	0.94	1.31	1.15	1.30	1.24	1.39
T2	1.56	0	1.40	1.59	1.25	1.33	1.07	0.91	1.19	1.12	1.19	0.95
T3	1.51	1.14	0	1.18	0.97	1.45	0.94	1.10	0.99	1.39	1.03	0.85
T4	1.11	1.23	1.42	0	0.98	1.16	0.69	1.11	1.00	1.06	0.94	0.94
O1	1.82	1.71	1.92	1.81	0	1.98	1.39	1.51	1.53	1.25	1.55	1.36
O2	1.22	1.16	1.57	1.15	1.25	0	0.62	1.00	0.98	1.15	1.27	1.13
O3	1.95	1.91	1.84	1.97	1.55	1.92	0	1.32	1.72	1.65	1.57	1.44
O4	2.09	1.96	2.10	1.96	1.68	2.06	1.29	0	1.48	1.64	1.73	1.49
E1	1.80	1.77	2.17	1.87	1.84	1.86	1.51	1.52	0	1.93	1.30	1.54
E2	1.96	1.80	1.74	1.59	1.64	1.85	1.51	1.63	1.79	0	1.35	1.53
E3	2.08	1.96	2.26	2.17	1.86	2.38	1.42	1.68	1.50	1.69	0	1.61
E4	2.08	1.96	2.26	2.17	1.86	2.38	1.42	1.68	1.50	1.69	1.61	0

There is significant cross dimensional interaction between technological, organizational, and environmental barriers. O3, E1 and E4 have relatively high direct impacts on some technological and organizational obstacles.

4.2.2 Normalized Direct-Relation Matrix. The direct-relation matrix was normalized so that the influence coefficients are within the mathematical requirements of the DEMATEL.

Table 4

Normalized Direct-Relation Matrix

	T1	T2	T3	T4	O1	O2	O3	O4	E1	E2	E3	E4
T1	0.000	0.073	0.066	0.082	0.072	0.063	0.045	0.063	0.056	0.063	0.060	0.067
T2	0.075	0.000	0.068	0.077	0.060	0.064	0.052	0.044	0.058	0.054	0.058	0.046
T3	0.073	0.055	0.000	0.057	0.047	0.070	0.045	0.053	0.048	0.067	0.050	0.041
T4	0.054	0.059	0.069	0.000	0.047	0.056	0.033	0.054	0.048	0.051	0.045	0.045
O1	0.088	0.083	0.093	0.087	0.000	0.096	0.067	0.073	0.074	0.060	0.075	0.066
O2	0.059	0.056	0.076	0.056	0.060	0.000	0.030	0.048	0.047	0.056	0.061	0.055
O3	0.098	0.091	0.107	0.098	0.078	0.094	0.000	0.081	0.087	0.088	0.098	0.080
O4	0.094	0.092	0.089	0.095	0.075	0.093	0.070	0.000	0.064	0.083	0.080	0.076
E1	0.101	0.095	0.101	0.095	0.081	0.100	0.062	0.072	0.000	0.072	0.079	0.084
E2	0.087	0.086	0.105	0.090	0.089	0.090	0.073	0.074	0.073	0.000	0.093	0.063
E3	0.095	0.087	0.084	0.077	0.079	0.089	0.073	0.079	0.087	0.075	0.000	0.065
E4	0.101	0.095	0.109	0.105	0.090	0.115	0.069	0.081	0.072	0.082	0.078	0.000

The normalized values preserve the direction of the original relationships while providing a standardized basis for determining the direct and indirect effects within the barrier system.

4.2.3 Total-Relation Matrix. The total-relation matrix incorporates both direct and indirect influences and therefore provides a more complete representation of the interdependent barrier system.

Table 5

Total-Relation Matrix

	T1	T2	T3	T4	O1	O2	O3	O4	E1	E2	E3	E4
T1	0.259	0.313	0.332	0.333	0.288	0.337	0.222	0.271	0.255	0.273	0.275	0.259
T2	0.308	0.225	0.312	0.309	0.260	0.310	0.201	0.234	0.241	0.248	0.256	0.225
T3	0.289	0.262	0.231	0.274	0.234	0.285	0.199	0.231	0.219	0.246	0.235	0.208
T4	0.256	0.250	0.278	0.204	0.221	0.264	0.169	0.214	0.207	0.218	0.217	0.199
O1	0.389	0.367	0.406	0.387	0.263	0.410	0.290	0.322	0.310	0.312	0.330	0.295
O2	0.277	0.262	0.301	0.272	0.245	0.213	0.191	0.222	0.218	0.235	0.244	0.219



O3	0.445	0.419	0.468	0.443	0.375	0.455	0.231	0.365	0.359	0.375	0.390	0.344
O4	0.410	0.391	0.419	0.409	0.346	0.415	0.272	0.265	0.314	0.344	0.348	0.316
E1	0.425	0.401	0.439	0.418	0.359	0.431	0.281	0.334	0.260	0.341	0.354	0.329
E2	0.409	0.389	0.438	0.409	0.362	0.416	0.279	0.332	0.326	0.271	0.363	0.308
E3	0.407	0.382	0.411	0.389	0.346	0.404	0.275	0.331	0.330	0.334	0.271	0.304
E4	0.441	0.417	0.463	0.443	0.380	0.464	0.294	0.354	0.341	0.364	0.367	0.264

The total-relation results reveal a strong linkage between the barriers. Organizational and environmental constraints also show significant impact throughout the system, suggesting technological challenges could be a downstream effect of other organizational and ecosystem constraints.

4.2.4 Prominence Analysis (D + R)

The prominence index (D + R) is the overall importance of each barrier in the interconnected system, as measured by both influence exerted and influence received.

Table 6

Prominence and Cause-Effect Analysis

Code	Barrier	D	R	D + R	D - R	Group
E2	Lack of common standards and standards maturity	4.316	3.561	7.878	+0.755	Cause
E4	Limited stakeholder participation and ecosystem coordination	4.595	3.269	7.865	+1.326	Cause
E3	Inadequate external digital infrastructure	4.194	3.651	7.846	+0.543	Cause
E1	Regulatory fragmentation and legal uncertainty	4.373	3.382	7.755	+0.991	Cause
O4	High investment and implementation costs	4.255	3.481	7.736	+0.773	Cause
O1	Digital-skills and technical-expertise shortages	4.049	3.680	7.729	+0.369	Cause
T1	Interoperability and system-integration limitations	3.397	4.314	7.711	-0.917	Effect
O3	Inadequate management commitment and organizational capabilities	4.666	2.955	7.621	+1.711	Cause
T3	Scalability and computational/energy requirements	2.912	4.499	7.411	-1.587	Effect
O2	Resistance to organizational and technological change	2.902	4.332	7.234	-1.430	Effect
T2	Connectivity and communication-infrastructure limitations	3.133	4.079	7.212	-0.945	Effect
T4	Cybersecurity, privacy, and data-integrity risks	2.701	4.291	6.992	-1.590	Effect

This suggests that standards, stakeholder coordination and infrastructure are critical, well connected players within the adoption system.

But there are times when prominence means nothing, or that a barrier is a cause or a consequence. For instance, T1 was one of the most prominent trees (7.711) and had a negative D - R value, meaning that systemic importance for T1 was mainly caused by the influence from other barriers.

4.2.5 Cause-Effect Analysis (D - R). The D - R index divided the barriers into cause/driver and effect/dependent categories.

Cause/Driver Group

The following seven barriers had positive D - R values:

O3 (+1.711) > E4 (+1.326) > E1 (+0.991) > O4 (+0.773) > E2 (+0.755) > E3 (+0.543) > O1 (+0.369).

Of those, O3 (management commitment and organisational capabilities) was the most powerful net causal barrier. D value of 4.666 and relatively low R value (2.955) yielded the highest positive D - R score (+1.711) but this was not the highest in terms of prominence. This suggests that factors such as management commitment and organizational ability have a much greater impact on other barriers than they are given credit for.

The second strongest driver was E4 - limited stakeholder involvement and ecosystem coordination (D - R = +1.326). It demonstrates the network-dependency of integrated maritime digitalization, where the successful implementation of digitalization demands coordinated participation of ports, shipping companies, logistics providers, regulators, technology providers and other ecosystem actors.



The regulatory fragmentation and legal uncertainty (+0.991) was also found as having strong causal influence, followed by high investment, implementation costs ($O4 = +0.773$), immaturity of standards ($E2 = +0.755$), inadequate external digital infrastructure ($E3 = +0.543$), and digital-skills shortages ($O1 = +0.369$).

As a whole, the cause group dominates with organizational and environmental factors, and many of the potential technical adoption barriers may be exacerbated by upstream managerial, financial, institutional, infrastructure, and ecosystem issues.

Effect/Dependent Group

Five barriers had negative D - R:

T1 (-0.917), T2 (-0.945), O2 (-1.430), T3 (-1.587), and T4 (-1.590).

The biggest negative value (-1.590) was for cybersecurity, privacy and data-integrity risks, closely followed by scalability and computational/energy requirements ($T3 = -1.587$). The dependent barrier of resistance to organisational and technological change ($O2 = -1.430$) also proved to be a significant barrier.

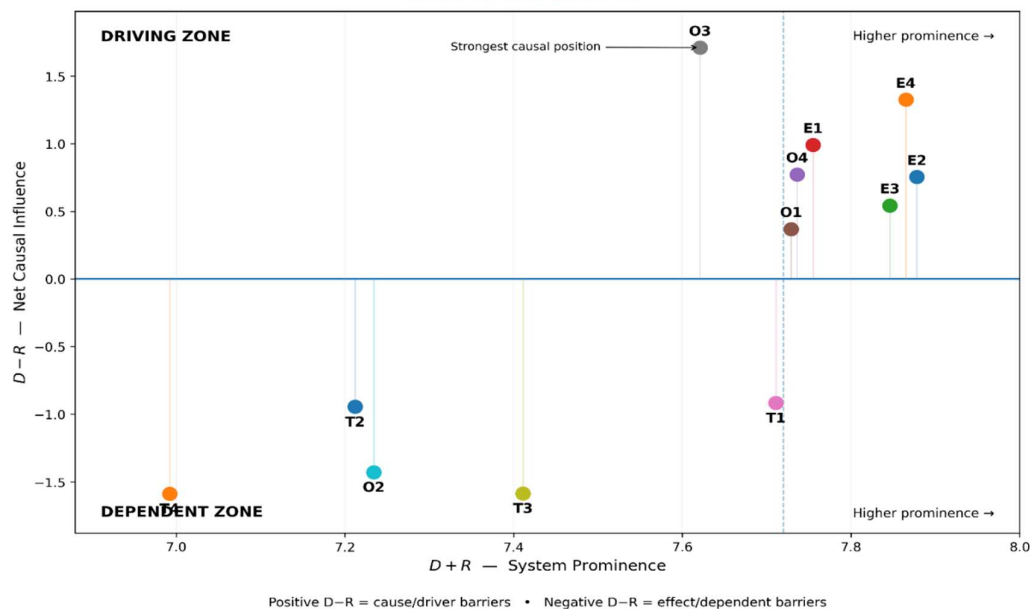
Limiting factors of interoperability and system-integration ($T1 = -0.917$) and connectivity and communication-infrastructure ($T2 = -0.945$) were also placed in the effect group.

These technological and behavioral constraints are not necessarily independent causes, therefore, the results suggest. Rather, they can be amplified due to management skills weakness, investment capacity, regulatory processes, common standards, infrastructure, skills, ecosystem coordination, etc.

4.2.6 Impact-Relation Map. The Impact-Relation Map was built with $D + R$ as the horizontal axis and $D - R$ as the vertical axis. Things above the horizontal zero line are the cause group; below the horizontal zero line are the effect group.

Figure 3

Impact-Relation Map of Integrated IoT-Blockchain-BDA Adoption Barriers



5. Discussion

5.1 Principal Barriers to Integrated Adoption

The results show that the implementation of integrated IoT-blockchain-BDA in maritime logistics is limited by technological, organizational, and environmental obstacles, and not purely technological. The 12 main barriers identified in the systematic review spread across the three dimensions of TOE span interoperability, connectivity, scaling, cyber security, skills, managerial capability, investment costs, regulation, standards, infrastructure and stakeholder coordination and are interrelated. This multi-dimensional pattern aligns with earlier maritime digitalization studies that underscore the importance of the technological



readiness in addition to organizational and ecosystem factors for the successful implementation of technological transformation (Brunila et al., 2021; Sooprayen et al., 2024).

5.2 Cause/Driving Barriers

The Fuzzy-DEMATEL results give a more detailed interpretation by pinpointing seven barriers, which are causal drivers. Limited participation and coordination of stakeholders and the ecosystem (E4) and regulatory fragmentation and legal uncertainty (E1) accounted for the remaining high levels of driver, with inadequate management commitment and organizational capabilities (O3) being the strongest driver ($D - R = +1.711$). This implies that managerial capacity influences the ability of organizations to mobilize financial resources, build capacities, coordinate the technological implementation, and meet the institutional needs of the outside world. The study results align with the conclusions of Guan et al. (2023), Janmethakulwat and Thanasopon (2025) that highlight critical factors for maritime technology adoption—management commitment and organizational capabilities. The coordination of stakeholders is also essential as it is necessary to exchange information among ports, shipping companies, regulators, logistics providers, and technology vendors to maintain integrated maritime systems (Surucu-Balci et al., 2024).

Additionally, organizational drivers are also very significant, further strengthening the dynamic capabilities perspective underlying this study. Lacking management commitment and organizational capabilities, in particular, can limit an organization's capacity to sense new digital opportunities, strategically invest in them and mobilize resources, and reconfigure current skills and routines. Likewise, a lack of digital skills and financial resources might limit the capacity to build digital skills needed for an integrated technological transformation. The findings thus support the TOE explanation by showing that barriers to adoption and the organizational capacity to react to them are very closely interrelated.

5.3 Effect/Dependent Barriers

On the other hand, cyber security/privacy/data-integrity risks (T4), scalability and computational needs (T3), resistance to change (O2), connectivity constraints (T2) and interoperability hurdles (T1) were found to be interdependent barriers. These negative causal values mean that these constraints are subjected to more systemic influence than they have. So technical problems could be part of a range of other issues of management, finance, infrastructure, regulations, standardization etc. that might not have a technical cause. This interpretation builds on findings by Farah et al. (2022) and Li and Sun (2025) that cybersecurity, interoperability and scalability are significant maritime technology problems.

5.4 Interdependencies Among Barriers

The total-relation structure shows the considerable inter-dimensional relationships. The impact of technological barriers is compounded with unreliable connectivity, which makes it more difficult to acquire data from IoT devices, interoperability issues, which hinder exchange through blockchain, and the lack of scalability, which compromises further processing of BDA. The same is true for organizational and technological barriers: Lack of leadership, skills, and investment make it harder to adopt secure and interoperable architectures. Other factors influencing readiness include regulation, infrastructure, standards, and ecosystem participation. Thus, the findings provide confirmation for the idea that adopting IoT-blockchain-BDA is a systemic change rather than three discrete technology-adoption decisions.

5.5 Comparisons to the Work of Others

The results are synthesized from patterns found in technology-specific literatures. The research on IoT focuses on connectivity, heterogeneous devices, interoperability and cyber security (Nguyen et al., 2023; Farah et al., 2022), while blockchain research highlights investment costs, regulations, scalability, organizational readiness, and the participation of the ecosystem (Lin, 2023; Guan et al., 2024; Singh et al., 2024). BDA research has focussed on the reliability of information and analytical skills (Munim et al., 2020). For maritime digitalisation, institutional capacity, coordination, and organisation readiness are also key conditions for transformation (Brunila et al., 2021; Sakita et al., 2024). The present findings build on this literature by bringing to light the operation of these barriers in a common causal system.



5.6 Emerging-Economy Context

For emerging economies, these relationships are especially significant because external digital infrastructure can be limited, investment may not be readily available, a lack of specialized skills can make regulatory uncertainty appear more likely and immature standards can make the lack of external digital infrastructure more of a challenge. Limited infrastructure, constrained finances, and organizations' lack of analytical capabilities. Another issue with cross-organizational data exchange is the lack of standards and regulatory fragmentation. Thus, without building foundations in institutions, organizations and ecosystems, integrated adoption from technological symptoms is unlikely to lead to sustainable adoption.

5.7 Sequenced Implementation Framework

The cause-effect structure is the basis for a framework of implementation in four layers, wherein upstream institutional and organizational constraints are tackled first, followed by technological difficulties in the downstream. The framework addresses the 12 barriers but prioritizes intervention based on the systemic scope of the barrier.

5.7.1 Layer 1: Policy and Institutional Alignment. The implementation should start by providing regulatory clarity and harmonization, data-governance arrangements, and common standards. Institutional uncertainty was identified as a causal barrier in the adoption system, as regulatory fragmentation (E1) and standards immaturity (E2) can be observed as areas of institutional uncertainty. Maritime authorities and regulators should, therefore, develop harmonised rules on data ownership, privacy, cyber security, blockchain transactions and cross-organisational data sharing. Common technical and data standards are especially crucial for minimizing uncertainty in terms of interoperability and system integration (Lin, 2023; Zou et al., 2025).

5.7.2 Layer 2: Organizational Preparedness and Capability Development. The second level deals with the commitment of management, financial preparedness, digital skills and organizational competence. This is particularly significant as the commitment to manage and organizational abilities (O3) was the strongest causal barrier. Organizations should, therefore, create digital-transformation leadership, invest financial resources, build digital-transformation skills and enhance their ability to manage technological changes. This capability development will lay the groundwork for an organization to effectively implement external changes in policy (Janmethakulwat & Thanasopon, 2025; Nguyen & Le, 2025).

5.7.3 Layer 3: Technological Integration and Standardization. When the institutional/organizational structure is reinforced, implementation will begin to concentrate more on interoperability, connectivity, cyber security, scalability, and integrated system architecture. The infrastructure of IoT is responsible for generating reliable data, Blockchain mechanisms are designed to facilitate trusted exchanges and BDA systems are able to convert verified data to actionable intelligence. Several technological barriers were identified as dependent outcomes, so investments at this layer should be tied to the investments in Layers 1 and 2, not made on their own.

5.7.4 Layer 4: Collaborative Ecosystem Development. The last layer formalizes the cooperation of the stakeholders and the involvement of the ecosystems between ports, carriers, logistics operators, regulators, customs services, technology companies and other actors involved in shipping. Additionally, although limited stakeholder involvement and ecosystem coordination (E4) was the second strongest causal driver, collaboration should extend to the previous layers of the system and should not be considered only a last step in the process. Participation of the ecosystem can be enhanced by shared platforms, interoperable data arrangements, pilot projects, port networks, and long-term technology-provider relationships, which can lead to integrated technologies generating value for the entire ecosystem (Surucu-Balci et al., 2024; Sooprayen et al., 2024).

Overall, it is proposed that the framework be implemented in a sequence of policy and institutional alignment, organisation preparedness, technology integration and development of a collaborative ecosystem. The order of the steps shows the study's main conclusion that sustainable adoption of IoT-blockchain-BDA demands to deal with the upstream structural drivers before the downstream technological consequences can be adequately mitigated.



5.8 Implications

5.8.1 Theoretical Implications. This study advances the discussion in technology-adoption literature by considering IoT, blockchain, and BDA as a unified digital architecture instead of stand-alone technologies. It extends the TOE framework by adding causal interdependencies and the concept of dynamic barriers between technologies, upstream and downstream, which brings a more dynamic view of technology adoption.

5.8.2 Managerial Implications. The findings offer a systematic approach for prioritizing interventions and using limited resources. Maritime organisations need not focus on all barriers at once, but can prioritise those that are influential by focusing on managerial, financial, institutional and ecosystem challenges before dependent technological challenges.

5.8.3 Policy Implications. The findings highlight to policymakers a need for coordinated regulatory frameworks, common standards, investment in digital infrastructure, financial support, and capability development. This is especially relevant in the emerging economies where the combination of institutional and resource restrictions may negatively impact integrated maritime digitalization.

6. Conclusion

This research identified barriers to the adoption of integrated IoT-blockchain-BDA systems at emerging-economy maritime logistics and importantly advanced the field of barrier identification by uncovering causal interdependencies of barriers. A systematic literature review revealed 12 main barriers in the technological, organizational and environmental aspects of the TOE framework. These barriers were then analyzed using fuzzy-DEMATEL analysis, which showed that these are not equally systemic. Seven barriers were identified as causal drivers and five were considered dependent outcomes. The most salient causal drivers were inadequate management commitment and organizational capabilities, followed by limited participation of stakeholders and ecosystem co-ordination, regulatory fragmentation and legal uncertainty. On the other hand, the barriers of cybersecurity, scalability, resistance to change, connectivity and interoperability were mainly dependent barriers.

The results indicate that a focus on visible technological challenges could be insufficient for digital transformation to be sustainable. Upstream constraints in management, institutions, finance, infrastructure, standardization, skills, and ecosystem can be targeted for greater strategic value, as they can create or exacerbate downstream technological issues. This causal approach aligns with research in the maritime sector that underscores the interdependent nature of digitalization barriers and the importance of understanding the underlying drivers of digitalization barriers instead of considering digitalization barriers in isolation (Guan et al., 2023).

Therefore, the proposed sequential implementation framework builds up from Policy and institutional alignment to building organizational capacities and integrating technologies to creating a collaborative ecosystem. This sequence offers a framework for prioritising interventions by maritime stakeholders and making the best use of limited resources. Overall, the study enriches the literature on digital-transformation in maritime contexts by combining three technologies (IoT, blockchain, BDA) in one coherent causal framework and by providing insights into barrier interdependencies as a basis for more systematic approaches to digitalization in emerging-economy maritime contexts.

6.1 Limitations and Future Research

The results for further research are given below, and there are some limitations. The Fuzzy-DEMATEL analysis relies on expert opinions and the expert panel of 18 experts might not represent the entire maritime stakeholder base. Furthermore, the transferability of the emerging-economy/South Asian context could be constrained as barrier relationships might differ between institutional and technological settings. The cross-sectional assessment also represents perceived causal relationships at one moment in time. Future studies should use larger panels of experts, compare cross-nationally and compare developed and emerging economies, and test the causal structure with ISM-MICMAC or other MCDM techniques. Further research is needed using longitudinal data to investigate if barrier relationships change over time and if efforts to address identified causal barriers lead to measurable decreases in dependent barriers.



Author's Contributions

All authors participated in ideation, development, and writing the manuscript. All authors read and approved the final manuscript.

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this article.

Funding Statement

The authors did not receive financial support from any funding agency or external organization for the research, authorship, or publication of this article.

Informed Consent

Informed consent was obtained from all participants prior to data collection. Participants were informed about the purpose of the study, the voluntary nature of their participation, and their right to withdraw at any time without any consequences. The confidentiality and anonymity of respondents were guaranteed throughout the research process.

Data Availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request. The authors are committed to transparency and will provide detailed methodological information and analysis protocols upon request.

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