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Research article

Barriers to blockchain adoption in the seaport industry: A fuzzy DEMATEL analysis

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Abstract: Blockchain technology, marked as a disruptive force across various sectors, including seaport logistics, faces challenges and obstacles that impede its effective adoption. We aim to empirically identify the significant barriers impeding blockchain adoption in the seaport industry and elucidate the interconnected relationships between these impediments. Utilizing the Fuzzy Decision-Making Trial and Evaluation Laboratory Analysis (Fuzzy DEMATEL) technique, we quantify the cause-and-effect relationships between various barriers to blockchain adoption. Structured interviews involving 18 experts were conducted, collecting both qualitative interview data and quantitative data. The nature of ports and the maritime industry did not seem to be accurately reflected in the literature about blockchain adoption, presenting several new findings in this study. Four primary obstacles were identified: 1) Lack of management support and commitment. 2) Issues in supply chain collaboration, communication and coordination. 3) Resistance from and lack of involvement of external stakeholders. 4) The high cost. Furthermore, cost was reaffirmed as a significant factor influencing blockchain adoption. We enhance existing literature by revealing the interdependencies among identified barriers and offers insights for policymakers and industry practitioners. We aim to foster successful blockchain integration in the seaport industry, improving its sustainability performance. During this research, it has been acknowledged by the business sector that the effective employment of business process re-engineering (BPR) and the strategic implementation of blockchain technology are crucial strategies to surmount the obstacles that have impeded the extensive integration of blockchain within port operations.

Keywords: blockchain technology; seaport industry; adoption barriers; fuzzy-DEMATEL; cause-and-effect relationship

1. Introduction

Constituting roughly 80% of global trade and serving as the bedrock of the world economy, maritime trade faces sustainability challenges necessitating the integration of multi-faceted practices [1]. Its challenges include complex ecosystem interactions and paper-based documentation systems that lead to delays, lack of transparency and fraud vulnerability [2]. Amidst these complexities, the port industry plays a pivotal role as a linchpin within the broader maritime sector, facilitating international trade by coordinating the exchange of goods among ships, land-based transport and warehouses [3]. Shipping companies constitute the primary clientele of the port, establishing a strong interconnection between the port industry and the shipping sector [4]. These bustling hubs are logistical nuclei, coordinating cargo movement, customs procedures and distribution. However, the industry grapples with issues like ecosystem intricacies and outdated paper-based systems, resulting in delays, opacity and fraud susceptibility [5]. Several preceding investigations have demonstrated the noteworthy impact of blockchain on enhancing the functionality of diverse maritime sectors [6]. Nevertheless, the integration of blockchain technology within the maritime domain has exhibited a gradual pace. In this study, we examine blockchain's implementation in maritime activities, with a specific emphasis on utilizing ports as illustrative instances to delve into the obstacles hindering the widespread adoption of blockchain technology [7].

Integrating digitalization and emerging technologies enhances corporate competitiveness, establishing a positive relationship between economic expansion and sustainable returns, particularly in the interaction between ships and ports [8]. Empirical research highlights the significant potential of digitalization in improving port efficiency, productivity, security and sustainability. Initiatives centered around digitalization and data exchange open new avenues by connecting carriers, ports, personnel and infrastructure through emerging technologies [9]. Amid various technological advancements in digitalization, blockchain stands out as a pivotal force reshaping port logistics and digitization by meticulously recording, validating and safeguarding each transaction in a secure chain, bolstering security, transparency and data traceability [10]. This potential for transformative impact extends to revolutionizing port processes, addressing trust, traceability, data integrity and transparency issues, and promoting sustainability and operational efficiency within the industry [11]. It streamlines decision-making across all levels of the supply chain. Although not fully integrated into the Port industry, blockchain technology is progressively finding its place in discussions and potential applications [12]. The adoption of blockchain in port operations not only optimizes resource utilization, enhances contract automation and reduces waste and fraud risks but also aligns with the shift towards a more efficient and environmentally responsible future for global trade through the amalgamation of Industry 4.0 principles [13–15].

Undoubtedly, global port managers have recognized the potential of blockchain to enhance the security, integrity and efficiency of port logistics. Consequently, they have proactively adopted measures to harness the capabilities of this technology. However, despite the touted advantages of blockchain technology, its tangible application within the port industry has not progressed as desired [6]. The current body of literature emphasizes blockchain technology's limited or gradual incorporation within the maritime sector, encompassing both the port and shipping industries. This gradual pace can be attributed to a range of factors. Due to the special status of the port, blockchain emerges as a pivotal solution to address these challenges within port operations, drawing scholarly attention [16]. Potential reasons for this slow adoption include a lack of management commitment and support—an obstacle rooted in the industry's hesitancy to embrace profound technological innovation, particularly at authoritative levels [17]. A notable impediment is the limited endorsement from key stakeholders [6]. They underscore that, except for a handful of container lines, influential entities capable of driving change are not adequately advocating for or endorsing the implementation of blockchain technology in maritime supply chains. Practitioners hesitate to trust blockchain technology [6]. Many stakeholders lack a clear understanding of blockchain technology, including its operational mechanisms and the distinctions between public and private blockchains [6]. Furthermore, the absence of new organizational policies concerning utilizing blockchain for cargo information transfer complicates adoption, exacerbated by the intricate operational and legal aspects associated with information transfer [18].

Additionally, apprehensions about sharing proprietary business data within a platform and the perceived costs of blockchain implementation contribute to the sluggish pace of adoption. Notably, the scarcity of guidance from existing practices exacerbates port administrators' challenges in surmounting barriers to blockchain adoption [19]. What adds an element of intrigue is the disparity between the findings presented in this paper and those from previous works, such as Balci et al. (2021), within the extant literature. For instance, the research in this paper has determined that the presence of experts is not as crucial for the adoption of blockchain technology within ports. Furthermore, the stakeholders impeding the adoption of blockchain are not necessarily the primary stakeholders of the port, yet they wield significant influence.

This project combines the Technology-Organization-Environment (TOE) and Technology Acceptance Model (TAM) to identify blockchain adoption barriers. TAM helps explain innovation reception, while TOE effectively explains technology adoption [20]. By merging these models, the study examines the broader organizational and environmental influences and delves into ports' perceptions and attitudes toward blockchain technology [21]. This integrated perspective promises to unveil intricate relationships between technological, organizational and human factors, providing a nuanced understanding that can guide strategies to overcome adoption challenges and facilitate successful implementation [22]. This research addresses the gaps in understanding the cause-and-effect relationships between these barriers within the maritime port domain. The complex relationships between challenges surrounding the adoption of blockchain in ports are illuminated by tapping into expert insights using the fuzzy-DEMATEL (Decision-Making Trial and Evaluation Laboratory) technique [23]. The objective is to gauge the varying significance of these barriers in hindering or propelling blockchain integration within ports. Our examination relies on data from 18 interview participants, including senior academics and practitioners. This endeavor aims to uncover the subtle links of causation that shape this intricate landscape, thereby enhancing the understanding of obstacles in decision-making related to incorporating blockchain technology in the port sector. This methodological approach promises to enhance decision-making in this intricate realm, offering valuable insights to address fundamental questions "What are the key barriers that influence the decision-making process for adopting blockchain technology within the maritime port sector?" and "How do the critical barriers to blockchain adoption within ports interact and mutually influence each other?" This study primarily seeks to uncover the central barriers impeding the integration of blockchain technology within the port industry, focusing specifically on port sustainability.

Addressing crucial issues within the port industry is paramount because of their role as linchpins in global maritime trade, particularly for developing economies and their connection to organizational challenges, government relationships and information transparency obstacles [24]. Blockchain adoption is a potential solution to enhance trade efficiency and information flow. Harmonizing ports with Industry 4.0 innovations is imperative to prevent trade disruptions while recognizing blockchain's multi-faceted potential for sustainable supply chains and social improvements [4]. This study highlights the transformative potential of blockchain within port operations, emphasizing the need for a thorough grasp of the obstacles involved. This understanding is crucial for devising successful approaches to leverage blockchain's advantages to enhance global trade fully. Instances of such practices encompass the implementation of business process re-engineering (BPR) and adopting decision-making strategies centered around blockchain principles.

The rest of the article is structured as follows. Section 2 reviews the literature on blockchain adoption in ports, covering benefits and barriers. Section 3 outlines the research methodology for investigating blockchain challenges in this sector. Section 4 presents research results and the analysis of internal and external adoption obstacles and their connections. Section 5 compares findings with previous studies, drawing relevant links for a comprehensive view. Last, Section 6 concludes the study, offering recommendations to overcome barriers and promote blockchain use in ports.

2. Literature review

We first provide a comprehensive review of the existing literature on the barriers to blockchain adoption in the port industry. Blockchain technology can revolutionize ports' operations by providing secure and transparent transactions between parties. However, several barriers exist to adopting blockchain technology in the port industry. The initial pool of 316 articles on blockchain from Web of Science, Science Direct and Scopus databases was narrowed to 104 relevant articles after reviewing their titles and abstracts and excluding non-blockchain-focused papers.

In Figure 1, we delineate the methodology for amalgamating the Technology Acceptance Model (TAM) and the Technology-Organization-Environment (TOE) framework to identify and classify barriers to blockchain adoption in the port industry. Initiated by a systematic literature review to accumulate a comprehensive list of potential barriers, the process integrates insights from TAM regarding user acceptance and TOE's multifaceted organizational and environmental dimensions. A detailed explanation of TOE and TAM can be found in Section 2.4. Figure 1 visually illustrates the methodology utilized in this study for research synthesis and categorization. The procedure initiates with a Systematic Literature Review (SLR), entailing a comprehensive compilation of barriers by examining existing literature. This initial compilation of barriers then undergoes a thorough categorization process guided by three fundamental theoretical frameworks: The Technology Acceptance Model (TAM), the Technology-Organization-Environment (TOE) framework and an additional concept referred to as 'Port Context,' which represents the specific contextual factors related to ports integrated into the study. For instance, we delve into questions such as the timing of blockchain technology implementation, the potential applications of blockchain technology in ports and the stakeholders whose interests would be impacted by its adoption in ports. These inquiries are elucidated in Sections 2.1–2.3, and the details can be located in Section 2.5. The combination of insights from various sources facilitates a multifaceted categorization of barriers. The culmination of this process yields the creation of Tables 1–3, which classify the barriers into distinct groups. This structured taxonomy of barriers is the groundwork for subsequent analyses and discussions on technology adoption and organizational change management.

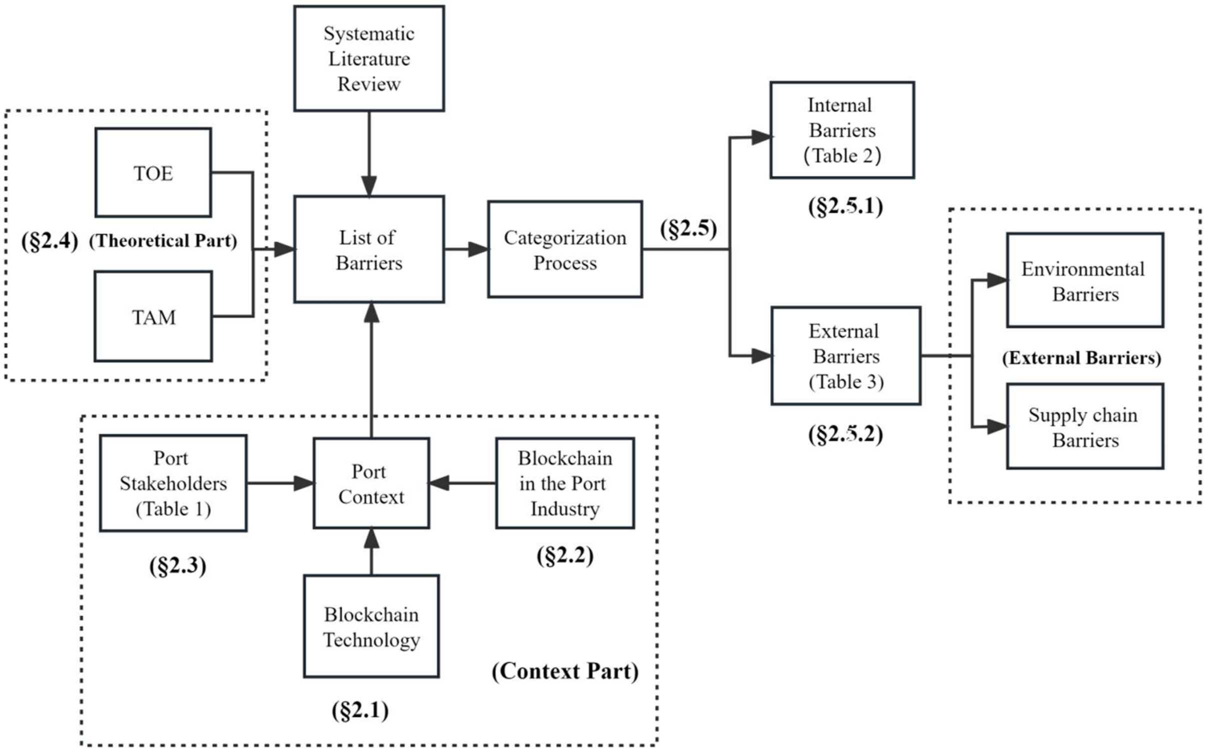

Figure 1. Integrating TOE and TAM.

2.1. Blockchain technology

Blockchain is a revolutionary technology that combines distributed data storage, peer-to-peer communication, consensus mechanisms and encryption algorithms [25]. It emerged as a disruptive force following the trajectory of mainframes, personal computers and the Internet [26]. Blockchain is a sequential chain of data blocks secured through cryptography for immutability and authenticity [27]. Beyond this, it presents an entirely novel distributed infrastructure and computing paradigm. It employs distributed node consensus algorithms and smart contracts to establish trust for multi-party collaborations, addressing business challenges and fostering innovation [25]. Blockchain operates as a trust mechanism built on asymmetric information, obviating the need for intermediaries or mutual assurances [28].

Blockchain technology is categorized into three major types: Public Blockchain, where read and write privileges are open; Consortium Blockchain (or Permissioned Blockchain), granting writing rights to a consortium of entities; and Private Blockchain, controlled by a single entity with authorized write access [29]. Each type has specific attributes and applications, with the consortium model being well-suited for container transportation and documentation chains due to its balance of efficiency and confidentiality [27].

The evolution of blockchain can be divided into three distinct stages [30]. Blockchain 1.0 initially focused on digital currency exchange and payments, notably exemplified by Bitcoin. Blockchain 2.0 expanded its reach to financial products such as stocks and bonds, with Ethereum as a prominent example. Blockchain 3.0 marked a transition towards the 'value internet', extending its applications to various sectors, including government, logistics and healthcare, illustrating its potential to transform various industries beyond finance.

2.2. Blockchain in the port industry

The relationship between the port and shipping industries is rooted in a fundamental customer-supplier dynamic. The port industry's primary customer base comprises shipping companies, forming a symbiotic partnership that fuels the global supply chain. Ports supply critical infrastructure and services for shipping companies to handle cargo efficiently by loading and unloading. This infrastructure includes berths, quays, cranes, storage facilities and customs clearance services [31]. Hence, even though general ports and shipping companies employ distinct management and operational approaches, they frequently utilize a shared system [3].

The application of blockchain addresses pressing challenges in the port industry, including cumbersome paperwork, complex procedures and data transparency issues [6]. In the global trade landscape, the intricate network of documents, including the "bill of lading", plays a crucial role in import and export operations [10]. This network involves stakeholders like sellers, buyers, carriers and port authorities and has often faced delays and inaccuracies due to paper-based processes [7]. The advent of blockchain technology presents a transformative solution that effectively mitigates fraud, leading to a revolutionized port industry [6].

Blockchain's security and transparency are harnessed by the port supply chain through immutable, distributed storage, eliminating the need for traditional paperwork and enabling secure peer-to-peer communication [32]. Cryptography techniques record Ownership transfers immutably [7]. Customs clearance benefits from blockchain's ledger recording cargo details, enhancing operational efficiency by eliminating redundant submissions [7].

In maritime insurance, blockchain's distributed nature streamlines data exchange and retrieval in complex scenarios, simplifying accountability and claims processing [17]. Furthermore, blockchain is reshaping port financing by offering transparent alternatives like Initial Coin Offerings (ICOs) and reducing cross-border payment costs through intermediary cryptocurrencies [33]. Smart contracts integrated into blockchain enhance trust in container bookings and dispute resolution, revolutionizing the port sector [7]. Overall, blockchain's advent heralds a pivotal transformation in the port industry's operational landscape, enhancing security, efficiency and transparency across various processes.

2.3. Port industry stakeholders

Figure 2 depicts the forthcoming aspiration of GSBN (Global Shipping Business Network) as an inclusive and open platform. Certain port authorities and terminal operators have taken part in this platform. Global Shipping Business Network (GSBN) is a not-for-profit data exchange platform in the global shipping industry. Its mission is to facilitate the sector's digital transformation by utilizing blockchain technology to securely share verified logistics and cargo data. GSBN includes major carriers like Cosco, Orient Overseas Container Line and Hapag-Lloyd, along with terminal operators such as Hutchison Ports, SPG Qingdao Port, PSA International, Shanghai International Port Group and Cosco Shipping Ports [6]. Figure 2 illustrates GSBN's future roadmap and vision. By examining the diagram, it becomes evident that blockchain technology holds significant potential for extensive utilization in transmitting files and information within port operations, indicating its multifaceted capabilities. Utilizing blockchain acts as a fast and prominent method for linking all involved stakeholders by facilitating the exchange of information (including documents like the Certificate of Origin, Packing List, Commercial Invoice and Bill of Lading). The records integral to port operations can be seamlessly digitized using blockchain technology. This enables real-time transmission, updates and seamless exchange of information between the port and all pertinent stakeholders.

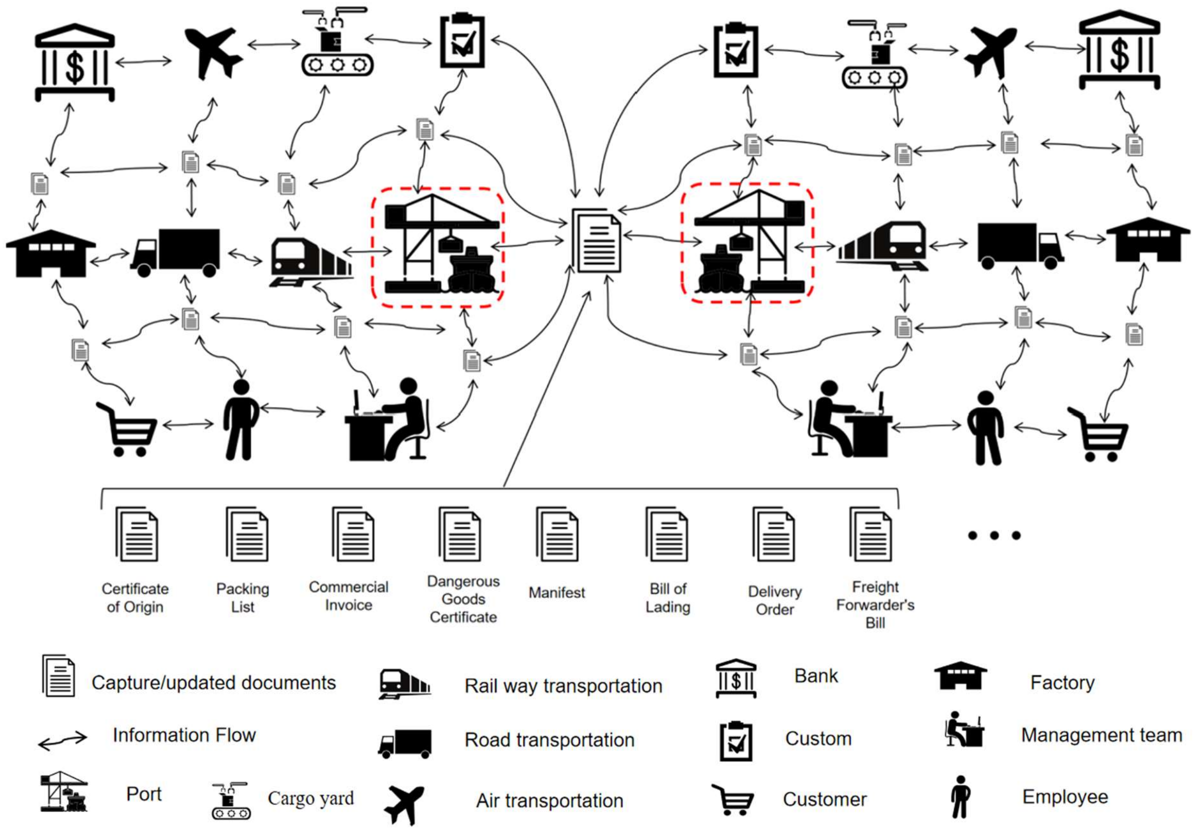

Figure 2. Future vision of GSBN as an open platform (based on GSBN website [34]).

The port industry operates within a complex and interconnected network of stakeholders, encompassing shipping companies, port authorities, customs and others, each with its interests and responsibilities (see Table 1). This intricate ecosystem poses unique challenges to blockchain adoption in ports compared to other industries. Port operations require the exchange of diverse information from various sources, making data integration on a unified blockchain platform complex [35]. Security and privacy concerns are paramount, given the sensitive cargo and contract details involved. Moreover, compliance with diverse regulatory and environmental standards across regions further complicates blockchain implementation [10]. While blockchain can potentially enhance various aspects of port operations, navigating these hurdles and achieving widespread adoption requires a tailored approach and collaboration across the port community. These stakeholders' multifaceted interests and priorities need adept coordination to harmonize conflicting objectives and ensure seamless collaboration [36]. The classification by Langen underscores the significance of internal stakeholders such as managers and employees, external stakeholders encompassing terminal operators and supporting industries, crucial port customers and the influence of legislative bodies and community stakeholders in shaping the blockchain adoption landscape within ports [6,36,37].

2.4. Theoretical frameworks

The combination of TOE (Technology-Organization-Environment) and TAM (Technology Acceptance Model) frameworks can help understand the barriers to blockchain adoption within internal and external organizational settings because each framework provides a unique perspective on the factors that influence technology adoption in port [22].

The Technology-Organization-Environment (TOE) framework is a commonly used model for understanding the factors influencing technology adoption within organizations [40]. It considers three key factors: The technology itself, the organizational context in which it will be used and the broader external environment that may affect its adoption. The TOE framework provides a holistic view of the factors influencing an organization's decision to adopt a particular technology, such as blockchain [20].

On the other hand, the Technology Acceptance Model (TAM) is a well-known model used to explain user acceptance and adoption of technology [20]. It considers two factors: Perceived usefulness (the degree to which a user believes that a particular technology will improve their performance or make their life easier) and perceived ease of use (the degree to which a user believes that technology is easy to use) [40].

We use a combination of the TOE and TAM frameworks to identify the internal and external barriers to blockchain adoption. Specifically, we can use the TOE framework to identify the internal and external contextual factors that may influence blockchain adoption within an organization and the TAM framework to understand how users perceive the technology and how these perceptions may affect adoption [21].

For example, using the TOE framework, we consider factors such as the organizational culture, the availability of resources and the regulatory environment. We can then use the TAM framework to explore how users within the organization perceive the usefulness and ease of use of blockchain technology and their attitudes toward it [40].

The Technology Acceptance Model (TAM) and the Technology Organization Environment (TOE) framework have been widely used in IT and data innovation research [20]. These two models complement each other as TAM can capture a person's acceptance behaviors and is adaptable to external variables. Furthermore, TOE acknowledges the technical, environmental and organizational factors that affect technology acceptance and adoption at the organizational level [21]. Numerous studies have integrated TAM and TOE to understand technology adoption comprehensively. For instance, researchers have employed the integration of TAM and TOE to examine cloud adoption at the organizational level [40]. This combined approach ensures that blockchain adoption's technological and human aspects are addressed, fostering a more holistic and effective strategy to drive adoption within internal and external organizational contexts.

Table 1. Stakeholders of the port industry.

Group	Stakeholders		Role and responsibilities
Internal stakeholders [6,36,38]	Port authorities		Manage and operate specific ports, make development decisions.
	Port management board or committee		The board or committee responsible for strategic decisions and governance of the port.
	Shareholders		The majority of national ports function as state-owned enterprises, while certain private terminals and ports may possess shareholders.
	Port workers and various employees		Carry out cargo handling, administrative tasks, maintenance, security
	Labor unions		Collaborate for labor rights
Supply chain stakeholders [36,37,39]	Terminal operators		Companies that manage and operate specific terminals within the port
	Shipping companies		Rely on ports for cargo loading, unloading and transshipment.
	Shipping agents and brokers, freight forwarders/3PLs		Facilitate communication, assist with documentation and logistics.
	Cargo owners and importers/Exporters		Rely on ports for timely movement of goods.
	Logistics and transportation companies (Air/Railways/Road transport companies)		Depend on ports for cargo exchange between transportation modes.
	Technology providers		Develop and offer technological solutions for port operations.
	Other service providers		Bunkering, Towing, Warehouse, Equipment rental providers, etc.
	Investors and financial institutions		Provide funding or financial service for port infrastructure projects，like Bank，Insurance companies
Environment stakeholders [6,36,37]	Community stakeholders	Environmental groups	Advocate for environmentally friendly port practices
		Local communities	Voice concerns about environmental impact and quality of life
		Resource-competing firms	Companies utilizing identical resources but not within the identical supply chain
		Security and law enforcement agencies	Ensure port security and prevent illegal activities
	Legislation and public policy stakeholders	National government/Authorities	National Regulate, license, oversee and develop port operations.
		Non-governmental organizations	IMO (International Maritime Organization)
		Customs and border protection Agencies/trade associations	Regulations Regarding Imports and Exports
		Local and regional government	Contribution to regional economy, contribution to regional tax income, effective transformation of port/city interface

Table 2. Organization Internal Barriers.

NO.	Internal Barriers	Description	References
I1(B1)	Lack of commitment and support from the management team	Executive commitment is pivotal in surmounting the barrier of inadequate support for blockchain implementation, as skepticism and risk aversion among top or middle leadership can impede progress and decision-making clarity	[17,18,43]
I2(B2)	Lack of Internal Information Transparency	While blockchain technology promises transparency through encryption, the absence of clear information-sharing policies can lead to data silos, obstructing analysis and planning; concerns about confidentiality and privacy further hinder its adoption.	[17,18,41,42]
I3(B3)	Lack of New Organizational Policies/Standards (Port authority)	Effective adoption of blockchain necessitates the establishment of organizational policies aligned with industry standards, regulatory demands and strategic objectives to ensure responsible implementation.	[44,45]
I4(B4)	Lack of Knowledge and Expertise	Successful blockchain implementation requires organizations to invest in acquiring expertise in both blockchain technology and sustainable supply chains, as a lack of comprehensive understanding hampers progress.	[6,17,24]
I5(B5)	Difficulty in Changing Organizational Culture	Integrating sustainable technology into organizational culture relies on embedding it within the vision and mission; resistance to change and geographical disparities can hinder this transformation, potentially wasting resources.	[44, 45, 46]
I6(B6)	High Cost	The adoption of blockchain technology can be impeded by high upfront and ongoing costs, mainly when uncertainties surround returns on investment and implementation challenges.	[14,18,47,48]

2.5. Barriers to port adoptions of blockchain

Combining the Technology-Organization-Environment (TOE) and Technology Acceptance Model (TAM) frameworks enhances the comprehension of blockchain adoption in organizational contexts. The TOE framework considers technological attributes, organizational characteristics and external factors, providing a comprehensive view of the ecosystem in which adoption occurs [20]. Moreover, TAM delves into user perceptions of usefulness and ease of use, illuminating individual-level influences on adoption [22].

2.5.1. Internal barriers

Organizations seeking to implement blockchain technology face internal barriers that can be overcome with strategic managerial actions, such as creating evaluation workgroups, identifying knowledge gaps and prioritizing transparent communication [17,41,42].

When applied to internal settings, the combination of TOE and TAM sheds light on the alignment between blockchain's features and the organization's structure, resources and readiness for change. Simultaneously, employee perceptions of blockchain's usefulness and ease of use offer insights into potential adoption barriers and training needs; specific hurdles are shown in Table 2.

To achieve successful implementation, organizations must tackle distrust, resistance to change, misunderstandings about innovation benefits and uncertainties in applying new technology [49]. This process requires a focused mindset and adaptation to various organizational and cultural differences.

Table 3. Organization external barriers.

NO.	External barriers	Description	References
S1(B7)	Lack of Customer Awareness	Customer understanding of blockchain technology and its relevance to supply chain sustainability practices is lacking, due to ineffective communication and conflicting goals among partners. Addressing this requires engaging stakeholders through constructive dialogue.	[6,17,18]
S2(B8)	Lack of External Stakeholders' Involvement	Insufficient support from influential stakeholders for sustainable practices and blockchain adoption.	[6,17,51]
S3(B9)	Collaboration and Coordination Challenges	Challenges in collaborating with diverse partners due to cultural and geographical differences. Inconsistent performance systems, varying values, customs and traditions complicate collaboration among supply chain partners. Stakeholder reluctance due to trust issues or concerns.	[17,49,52]
E1(B10)	Lack of Governmental Policies/Standardization	The lack of clear government regulations and standardized frameworks for blockchain technology in sustainability practices creates uncertainty and inhibits widespread adoption. However, the lack of standardized policies, frameworks for sustainability and engagement from external stakeholders hinders the advancement of an integrated system.	[17,53]
E2(B11)	Market Competition and Uncertainty	Time-consuming sustainable practices and blockchain adoption affect market competitiveness. Uncertainty about product demand and future sales adds to challenges.	[17,51]
E3(B12)	Lack of Early Adopters	A limited number of early adopters slow down overall adoption as organizations prefer to wait and observe trends.	[6]

2.5.2. External barriers

External barriers to adopting blockchain technology in port applications are multi-faceted, involving governments, industries, institutions and communities [17,50]. These barriers include the absence of supportive government policies, market competition, uncertainty and limited external stakeholder engagement in sustainability and blockchain [17,50]. A notable obstacle is the lack of customer awareness about blockchain's role in sustainability, stemming from ineffective communication and collaboration [45].

In the external organizational setting of the combination of TOE and TAM, the industry's regulatory landscape plays a pivotal role in determining how blockchain can be effectively integrated. Blockchain's decentralized nature can challenge traditional regulatory frameworks, often relying on centralized control and oversight.

These external barriers can be divided into two categories [17]:

a. Barriers within the Supply Chain: Challenges within the supply chain itself, such as data sharing difficulties, resistance to change and the need for collaboration between stakeholders (Table 3, S1–S3).

b. Barriers in the Broader External Environment: Factors beyond the immediate supply chain, including regulatory constraints, economic conditions, geopolitical factors and technological trends, hinder blockchain adoption in port operations (Table 3, E1–E3).

Addressing these external barriers is essential for blockchain adoption in ports to realize the technology's potential benefits, including increased transparency, reduced paperwork, streamlined processes, enhanced security and improved collaboration among stakeholders [10].

3. Structure

Barriers to blockchain adoption in the seaports arise from internal and external factors (Figure 3), slowing down the technology's integration despite its potential to enhance efficiency and security [43]. The synthesis of TOE and TAM enables a holistic perspective on blockchain adoption. It considers not only the technology's attributes and fit within the organization but also the attitudes and reactions of those interacting with it. This comprehensive understanding empowers organizations to make informed decisions, mitigate challenges and enhance the likelihood of successful blockchain implementation within their operations and in response to broader industry dynamics [20]. Expert interviews are then systematically conducted to refine our understanding of these obstacles. This culminates in ranking barriers, allowing for a targeted reassessment of port practices and implementing strategic modifications where necessary. The Fuzzy-DEMATEL method is employed to identify key barriers and their relationship. Our objective is to facilitate the successful integration of blockchain technology within port operations by systematically overcoming the identified barriers, thereby enhancing efficiency and security in maritime logistics. Based on Figure 3, it is evident that the literature review lays the foundation for the upcoming expert interviews. Additionally, it offers theoretical insights and points of reference concerning the practical challenges blockchain faces in the port context for the interviewees. This forms the theoretical basis for how ports can address barriers through practical application and achieve successful blockchain adoption.

Internal barriers within seaport organizations include resistance to changing existing processes, mistrust from past failed IT projects and a lack of technical expertise to accurately evaluate blockchain's benefits [49]. These challenges are compounded by infrastructure constraints and coordination difficulties among various stakeholders, especially in ports with intricate governance structures [6,18].

Externally, outdated regulations and standards pose significant challenges [17]. Compliance concerns related to data storage and privacy regulations deter adoption, and slow-moving industry standards struggle to keep pace with technological advancements, hindering organizations from making a solid business case for investing in blockchain solutions [17]. These combined internal and external factors contribute to the slow adoption of blockchain in the port industry despite its promising capabilities.

The literature review concludes with an acknowledgment of the benefits of blockchain in the port industry. It emphasizes addressing internal and external barriers to unlock its full potential. Future research will investigate these challenges and practices in blockchain adoption for the port industry. This is the groundwork for investigating how ports can effectively surmount obstacles to embracing blockchain technology.

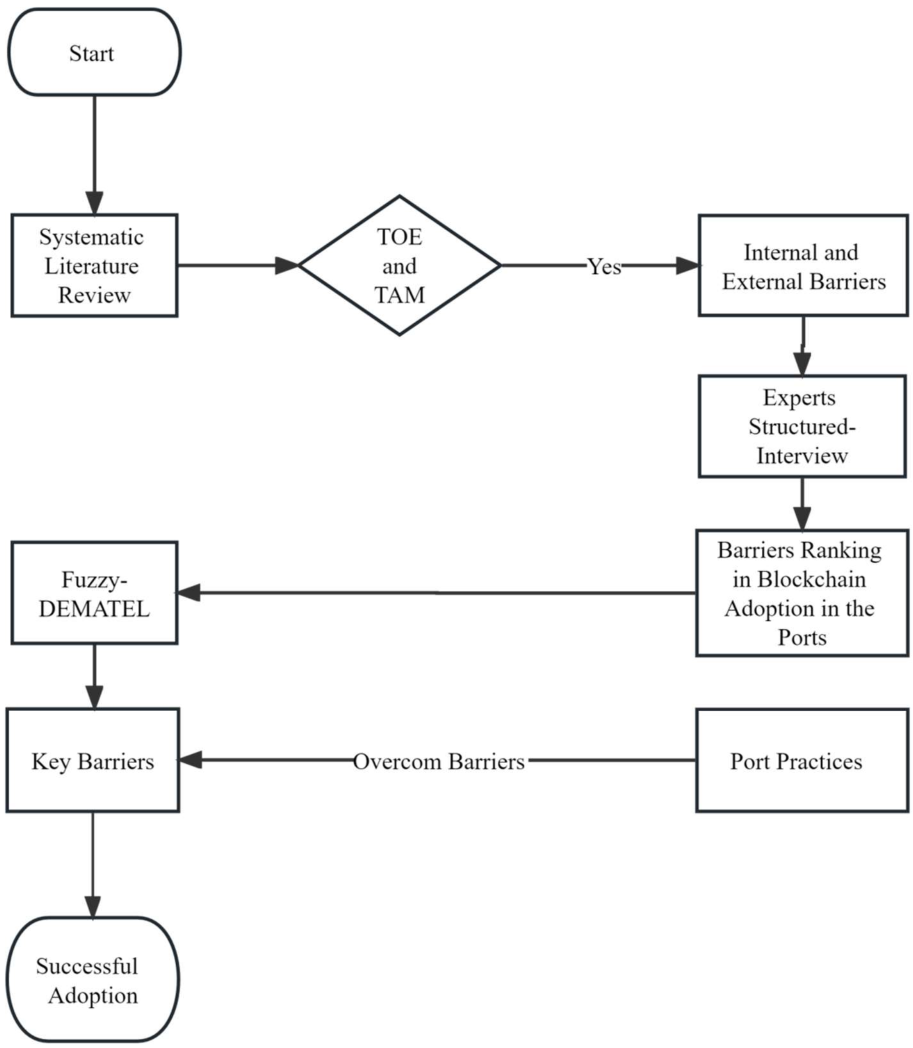

Figure 3. Research structure.

4. Methods

We employed a rigorous mixed-methods research design to comprehensively investigate the adoption of blockchain technology in ports and its associated barriers [54–56]. The research design comprised three major phases: A systematic literature review, structured interviews and a Fuzzy DEMATEL analysis.

4.1. Systematic literature review

A meticulous literature review was conducted to discern common barriers to blockchain adoption across different sectors, leading to the identification of 12 prevalent challenges from 104 relevant articles (literature review). The research design combined this systematic literature review with structured interviews, drawing insights from experts in blockchain technology and port operations. This integrative strategy offered a comprehensive perspective on the obstacles to blockchain application in ports.

4.2. Sampling and data collection

The expert group comprised 18 individuals and nine distinguished scholars with significant experience researching port digitalization. The other nine members were practitioners actively involved in the port industry. The average work experience of scholars and practitioners was 14.33 and 11.33 years, respectively. All experts possessed extensive knowledge of blockchain applications in ports. Before proceeding with the formal questionnaire administration, the experts received training on the background knowledge of blockchain applications in ports and were briefed about the research context. For more details and information about the expert group, see Table 4.

Each participant underwent a structured interview. At the start of the interview, all participants were requested to prioritize 12 barriers. Then, the objective was to fill the grid and establish their perception of the relationships between barriers [57]. While asking them about this and filling in the grids on paper with them, they were asked to elaborate verbally on any key relationships. The interviews were recorded and therefore created quantitative (the grid of relationships) and qualitative (verbal commentary) data [23].

Third, we used the fuzzy-DEMATEL technique to the interview data, establishing causal-effect maps to uncover relationships between the identified barriers [58]. This approach offered a comprehensive understanding of the barriers' underlying causes, providing essential insights for future initiatives to improve blockchain adoption in the port industry.

The research design facilitated in-depth analysis of the barriers to blockchain adoption in ports by integrating insights from the literature review and expert interviews. Using mixed methods and the fuzzy DEMATEL technique enriched the study's findings. The study adhered to all relevant ethical guidelines and secured ethics approval from the University of Otago Human Ethics Committee. This study obtained written informed consent from all participants, ensuring their voluntary participation and understanding (Table 4) and prioritizing participant confidentiality.

Table 4. Evaluator profiles and demographics.

NO.	Academic/ Practitioner	Organization	Cultural Background	Position	Year of Work
P1	Academic	University/Research Institution A	Asia	Professor	23
P2	Academic	University/Research Institution A	Asia	Senior Lecturer	5
P3	Academic	University/Research Institution A	Asia	Professor	18
P4	Academic	University/Research Institution A	Asia	Associate Professor	14
P5	Academic	University/Research Institution B	Asia	Associate Professor	11
P6	Academic	University/Research Institution B	Asia	Associate Professor	9
P7	Academic	University/Research Institution C	Europe	Professor	15
P8	Academic	University/Research Institution D	Europe	Associate Professor	6
P9	Academic	University/Research Institution D	Europe	Vice-Chancellor/ Professor	28
P10	Practitioner	Port E	Asia	Middle manager	7
P11	Practitioner	Port E	Asia	Senior engineer	17
P12	Practitioner	Port E	Asia	Senior manager	13
P13	Practitioner	Port F	Asia	Senior manager	7
P14	Practitioner	Port F	Asia	Senior engineer	13
P15	Practitioner	Port G	Asia	Senior manager	6
P16	Practitioner	Port H	Europe	Senior engineer	18
P17	Practitioner	Port I	Europe	Senior manager	13
P18	Practitioner	IMO (International Maritime Organization)	Global	Senior manager	8

4.3. Fuzzy-DEMATEL

In the third step of the research process, the Fuzzy-DEMATEL method was employed to analyze the data on blockchain adoption barriers in the port industry [59]. The method involved constructing a Fuzzy-DEMATEL model to identify potential barriers and their interconnections, with experts rating each barrier for its influence on others [60]. This analysis yielded a matrix illustrating the strength and direction of relationships between barriers, identifying key barriers to address first for promoting blockchain adoption in ports [23].

The choice of employing the Fuzzy Decision-Making Trial and Evaluation Laboratory (Fuzzy DEMATEL) method for analyzing barriers to blockchain adoption in a port, rather than other methods like ISM, ANP, AHP, SEM or traditional DEMATEL, is likely motivated by the method's ability to handle uncertainty, capture complex interrelationships, accommodate subjective data, provide qualitative insights into barrier interactions and offer context-specific analysis [43].

These decision-making techniques offer diverse approaches to understanding the relationships among variables. DEMATEL specializes in unveiling causal interactions and categorizing them as cause-and-effect groups. In contrast, ISM identifies contextual interactions based on driving potential and dependencies [61]. AHP, while valuable for decision-making, doesn't explicitly reveal interdependencies [62]. ANP, although capable of uncovering such interdependencies, is less commonly used for barrier studies due to its complexity [62]. SEM primarily serves theoretical development but requires a substantial sample size for application [63]. These techniques provide a spectrum of tools for analyzing complex systems, each with unique strengths and limitations, tailored to decision-making processes' specific context and objectives [43].

Fuzzy DEMATEL, an advanced variant, is often employed to handle the inherent vagueness and uncertainty in human judgments. Many studies, including those in the sustainable production and consumption domain, have successfully applied these techniques, showcasing their effectiveness in addressing complex decision problems and causal relationships between system variables, such as food waste management [23].

The Fuzzy-DEMATEL method utilized fuzzy logic, which incorporates uncertainty and imprecision, to represent vague or uncertain information using degrees of membership [57]. It integrated fuzzy sets, fuzzy numbers and fuzzy matrices to capture qualitative and quantitative data, combining participants subjective opinions and observations [43].

The application of this method followed a step-by-step process outlined by Liu et al. (2021). In the preliminary stage, an indicator system of influencing factors was derived through questionnaire surveys, literature research and expert consultations [43]. Experts were then invited to assess the degree of influence between factors using semantic operators. Their original evaluations were transformed into triangular fuzzy numbers representing the perceived degree of influence [58].

These triangular fuzzy numbers define membership functions and were represented as A = (a, b, c), where A denoted the expected interval of evaluation results for each influencing factor evaluated by the experts [58]. The process accounted for all influencing factors and experts' perceptions to comprehensively understand the barriers to blockchain adoption in ports [57].

4.4. Fuzzy DEMATEL calculations

Our study involved a comprehensive approach, incorporating literature research, expert interviews and expert consultations. We identified 12 key barriers that influence blockchain applications in ports through these methods. To assess the mutual interactions and strengths of these influencing factors, we sought the expertise of relevant professionals, including port executives and scholars specializing in port digitalization. This process involved scoring each factor based on their input [43].

Step 1: In the preliminary stage, an indicator system of influencing factors, as shown in Tables 2 and 3, is derived through questionnaire surveys, literature research and expert consultations. The 12 barriers are B1, B2, B3, B4...B12.

Step 2: Experts were invited to assess the degree of influence between factors using semantic operators such as "No Influence (N)," "Very Low Influence (VL)," "Low Influence (L)," "High Influence (H)," and "Very High Influence (VH)." The experts' original evaluations were transformed into triangular fuzzy numbers, representing the degree of influence of factor **i** on factor **j** as perceived by the k experts [43].

Triangular fuzzy numbers are interval numbers that define membership functions. Let A = (a, b, c) represent the expected interval of evaluation results. Assuming there are N influencing factors, evaluated by P experts according to Table 5.

Table 5. Linguistic operators and values of triangular fuzzy numbers.

Semantic Variables	Triangular Fuzzy Number	Specific Values
N (No Influence)	(0, 0, 0.25)	0
VL (Very Low Influence)	(0, 0.25, 0.5)	1
L (Low Influence)	(0.25, 0.5, 0.75)	2
H (High Influence)	(0.5, 0.75, 1)	3
VH (Very High Influence)	(0.75, 1, 1)	4

Step 3: Generating the Fuzzy Initial Direct Relation Matrix (A)

In this step, we constructed the fuzzy initial direct relation matrix (A) using Triangular Fuzzy Numbers (TFN), which are represented by a triplet $\left(e_{ij}, f_{ij}, g_{ij}\right)$. To clarify, for a given kth expert (where 1 ≤ k ≤ K) by $x_{ij} = e_{ij}, f_{ij}, g_{ij}$, the value x_{ij}^{k} in the matrix signifies the fuzzy evaluation of the extent to which barrier i influences barrier j.

By gathering inputs from all participants, we create an $n \times n$ matrix denoted as $X^{k} = x_{ij}^{k}$, where N represents the number of barriers. In this matrix, each element x_{ij} captures the fuzzy assessment provided by the respective expert regarding the impact of barrier i on barrier j. The variable 'n' represents the number of experts in the decision panel and it takes values from 1 to n, where k = 1, 2, 3, 4, ..., n.

$$\mathrm{a}_{ij} = \frac{1}{k \sum x_{ij}^{k}}, \quad \mathrm{a}_{ij} = \frac{\sum x_{ij}^{k}}{k} \tag{1}$$

Fuzzy numbers are not directly suitable for matrix operations. Transforming fuzzy numbers into crisp numbers was necessary to facilitate further calculations, which involved a defuzzification process. In this context, we employed the weighted average method to de-fuzzify the fuzzy direct relation matrix, as Eq (2) described. This process allowed us to obtain a crisp matrix that enables straightforward mathematical operations and analysis.

$$I_{T} = \frac{1}{6}\left(e + 4f + g\right) \tag{2}$$

Step 4: Computing the Normalized Initial Direct Relation Matrix (D)

$$m = \min\left[\frac{1}{\max \sum_{j=1}^{n} \left|a_{ij}\right|}, \frac{1}{\max \sum_{i=1}^{n} \left|a_{ij}\right|}\right] \tag{3}$$

$$D = m \times A \tag{4}$$

During this stage, we calculated the normalized initial direct relation matrix (D) utilizing Eqs (3) and (4).

Step 5: Constructing the total-relation matrix

$$T=\left(1-D\right)^{-1} \tag{5}$$

Where, I: Identity matrix; T: Total relation matrix,

$$T=\left[t_{ij}\right]_{n\times n} \tag{6}$$

Step 6: Calculating the sum of rows (R) and the sum of columns (C)

$$R=\left[\sum_{j=1}^{n}t_{ij}\right]_{n\times 1} \tag{7}$$

$$C=\left[\sum_{i=1}^{n}t_{ij}\right]_{1\times n} \tag{8}$$

Step 7: Finalizing the Cause-Effect Graph

In this crucial step, we used the dataset (R + C; R − C), where (R + C) and (R − C) serve as the horizontal and vertical axes, respectively. The (R + C) axis represents the measure of the significance of study barriers, indicating their influenced and influential power. On the other hand, the (R − C) axis sheds light on the cause-and-effect relationships between these barriers [43,57].

By analyzing the data, factors that exhibit a positive value on the (R − C) axis were placed into the causal group, signifying their role as causal factors. Conversely, barriers with a negative (R − C) value were categorized into the effect group, indicating their impact as barriers.

This decision-making method involved processing fuzzy data by converting it into matrices, followed by normalization. Subsequently, the total-relation matrix is computed to construct the cause-effect graph, which aids in making informed decisions based on the provided information [43,58].

5. Results

Our main objective of this study was to identify the critical barriers hindering the adoption of blockchain technology in the port industry. We employed the Fuzzy-Decision-Making Trial and Evaluation Laboratory (Fuzzy-DEMATEL) method to explore the interrelationships between identified barriers and facilitators. We aimed to determine their relative importance in obstructing or facilitating blockchain technology adoption in ports. Through this exploration, we aimed to uncover the cause-and-effect links that define this multi-faceted system, enabling a better understanding of the decision-making challenges and opportunities in blockchain adoption within the seaport industry.

At first, drawing from the average assessments provided by 18 experts who evaluated the 12 barriers (as detailed in Table 6), the top five barriers exerting influence on the application of blockchain in ports have been identified as follows: Lack of commitment and support from management (B1), high cost (B6), challenges in collaboration, communication and coordination across the supply chain (B9), absence of governmental policies (B10) and lack of engagement and resistance from external stakeholders (B8). It is important to note that while the precise order of these barriers may exhibit minor variations compared to the outcomes of centrality analysis using Fuzzy-DEMATEL, the fundamental significance of these factors remains consistently evident.

Table 6. Evaluator's ranking.

Respondent	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
P1	3	11	7	5	6	4	10	9	1	12	2	8
P2	3	9	8	4	10	5	11	7	6	1	2	12
P3	1	10	11	2	7	3	9	4	5	6	12	8
P4	5	6	12	1	3	2	4	7	11	8	9	10
P5	3	11	5	6	7	2	10	8	1	4	12	9
P6	3	9	8	10	7	11	12	2	4	1	6	5
P7	3	11	8	9	5	2	10	6	1	4	12	7
P8	2	9	7	8	5	1	10	6	3	4	11	12
P9	2	1	3	5	4	6	10	11	12	7	8	9
P10	7	8	9	10	11	2	12	6	5	4	3	1
P11	1	5	6	7	11	4	10	8	2	9	12	3
P12	10	8	4	11	2	1	6	3	7	12	9	5
P13	9	1	7	5	12	2	10	4	3	8	10	6
P14	1	9	3	11	8	6	10	5	2	4	7	12
P15	1	4	5	6	7	3	9	8	2	11	12	10
P16	2	5	4	12	7	3	9	8	1	6	11	10
P17	1	10	4	11	6	5	12	7	2	3	8	9
P18	2	9	5	11	7	3	12	6	1	4	11	8
Average	3.28	7.56	6.44	7.44	6.94	3.61	9.78	6.39	3.83	6	8.72	8
Rank	1	9	6	8	7	2	12	5	3	4	11	10

Table 7. Total-relation matrix.

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
B1	0.64	0.57	0.58	0.59	0.60	0.73	0.61	0.66	0.69	0.70	0.64	0.66
B2	0.62	0.41	0.49	0.49	0.49	0.60	0.50	0.53	0.59	0.55	0.51	0.53
B3	0.74	0.57	0.52	0.59	0.58	0.71	0.60	0.65	0.69	0.68	0.61	0.66
B4	0.58	0.46	0.47	0.42	0.46	0.59	0.49	0.51	0.54	0.55	0.50	0.53
B5	0.64	0.49	0.51	0.51	0.43	0.61	0.52	0.55	0.58	0.58	0.51	0.55
B6	0.61	0.46	0.48	0.50	0.45	0.53	0.49	0.54	0.56	0.57	0.53	0.55
B7	0.58	0.47	0.49	0.48	0.48	0.59	0.46	0.57	0.59	0.57	0.54	0.56
B8	0.70	0.55	0.57	0.57	0.56	0.71	0.62	0.58	0.69	0.68	0.64	0.65
B9	0.71	0.55	0.58	0.59	0.57	0.70	0.63	0.67	0.61	0.68	0.63	0.64
B10	0.58	0.46	0.48	0.48	0.47	0.60	0.52	0.55	0.57	0.50	0.53	0.55
B11	0.57	0.44	0.47	0.46	0.45	0.58	0.50	0.55	0.57	0.57	0.45	0.54
B12	0.63	0.48	0.52	0.51	0.49	0.65	0.56	0.60	0.61	0.63	0.57	0.52

Note: Ø = 0.67; Significant relationships greater than Ø3: B1-B3-B8-B9-B10

Analyzing the data presented in Tables 7, 8 and Figure 4 reveals the hierarchy of driving factors based on the magnitude of their R+C values. The ranking of these factors is as follows: B1 > B9 > B8 > B6 > B3 > B12 > B10 > B7 > B11 > B5 > B2 > B4. This ranking implies that the foremost inhibiting factor is the endorsement from the management team (B1), closely followed by supply chain coordination, commonly denoted as the trust factor (B9). Additionally, hindrance from stakeholders within the supply chain (B8) is another influential inhibiting factor, and the consistent mention of high cost (B6) by various researchers is also reaffirmed in this study. The identified barriers are categorized into cause-and-effect groups based on their positive and negative R-C values. Among these, B1, B2, B3, B5, B8 and B9 are classified as causative factors, with organizational internal policies and standards (B3) demonstrating the highest value and influence on other factors. In contrast, B4, B6, B7, B10, B11 and B12 belong to the effect group, signifying their susceptibility to external influences. Notably, high cost (B6) holds the largest absolute value in this category, making it the most directly obstructive factor in adopting blockchain technology in ports. The graphical representation in Figure 3, depicting directed causal relationships, reveals that when values surpass the threshold θ, B6 and B10 are notably impacted by B1, B3, B8 and B9, with mutual influences observed between B1 and B8, as well as between B9 and B10. By analyzing insights gathered from interviews, it became evident that the Technology-Organization-Environment (TOE) framework is more closely related to the Organization-Environment-Technology (OET) framework in terms of its contribution as a barrier to the adoption of blockchain within port operations.

Table 8. Rankings of barriers.

Barriers	R	C	R + C	R − C	Evaluator's Ranking	DEMATEL Ranking by R+C value	DEMATEL Ranking by R-C value	Cause/Effect
B1	7.68	7.61	15.29	0.07	1	1	6	Cause
B2	6.32	5.91	12.23	0.41	9	11	4	Cause
B3	7.62	6.16	13.78	1.46	6	5	1	Cause
B4	6.09	6.20	12.29	−0.11	8	12	7	Effect
B5	6.48	6.04	12.53	0.44	7	10	3	Cause
B6	6.28	7.62	13.90	−1.34	2	4	11	Effect
B7	6.37	6.51	12.88	−0.14	12	8	8	Effect
B8	7.52	6.96	14.48	0.55	5	3	2	Cause
B9	7.58	7.29	14.86	0.29	3	2	5	Cause
B10	6.30	7.27	13.57	−0.98	4	7	10	Effect
B11	6.16	6.66	12.82	−0.50	11	9	9	Effect
B12	6.77	6.92	13.69	−0.14	10	6	8	Effect

A further analysis categorized the 12 barriers (Table 8) into the cause or effect groups based on their R-C values. The cause group comprised barriers such as lack of management commitment and support (B1), lack of new organizational policies/standards for using blockchain technology (B3), lack of external stakeholders' involvement (B8) and problems in collaboration, communication and coordination within the supply chain (B9). These factors significantly influenced the effect group, which consisted of barriers such as high cost (B6), lack of governmental legal and regulatory/standardization (B10) and lack of early adopters (B12). The cause group factors played a pivotal role in shaping the challenges faced in adopting and implementing blockchain technology in the port industry while addressing the effect group factors became imperative to overcome hindrances and promote the successful integration of blockchain solutions in port operations. Establishing new policies and standards accommodating blockchain technology can significantly enhance its implementation in port operations. Additionally, fostering collaboration with external stakeholders, as emphasized by B8, plays a crucial role in creating a conducive environment for the successful integration of blockchain in the supply chain.

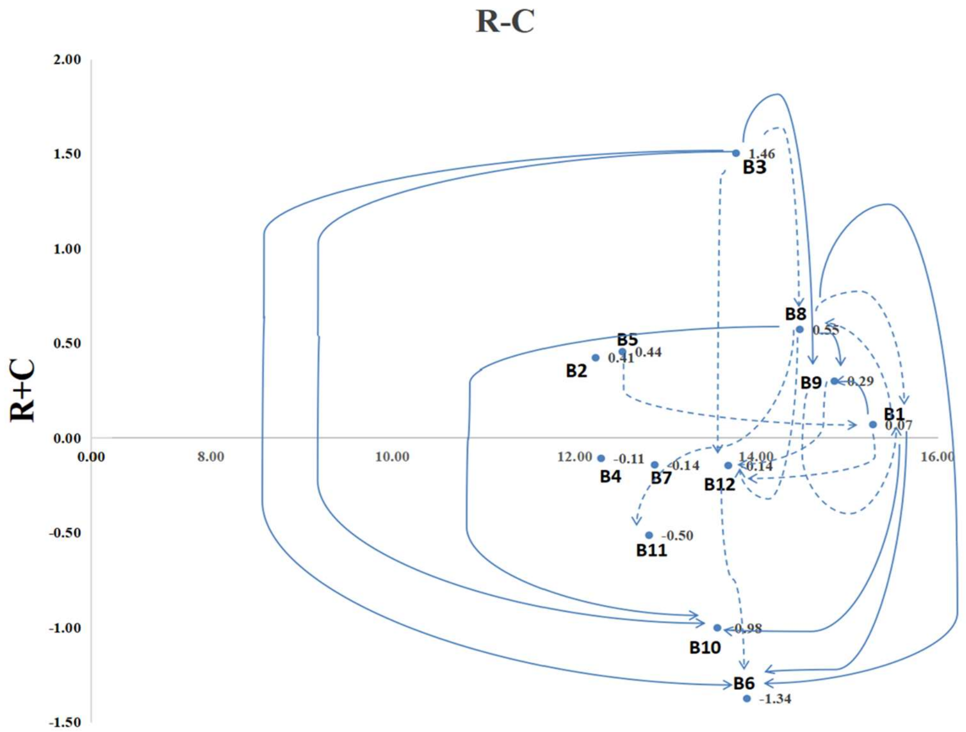

Figure 4. Cause-effect graph.

This directed causal graph (Table 9) underscores the significance of management support (B1) in successfully implementing blockchain technology within the port industry. The centrality value (R + C) attributed to management support emphasizes its pivotal role in overcoming challenges and propelling the adoption of blockchain solutions. Furthermore, obstacles such as the absence of engagement and resistance from external stakeholders (B8) and challenges related to collaboration, communication and coordination across the supply chain (B9) also significantly influence the adoption of blockchain in port operations. Collectively, these barriers play a critical role in shaping the successful integration of blockchain technology in the port industry. Consequently, addressing these challenges becomes imperative to facilitate the effective adoption and utilization of blockchain solutions in port operations.

This comprehensive study investigated barriers hindering the implementation of blockchain technology in the port industry and yielded several key findings. The primary obstacle was the need for more management commitment and support, highlighting the importance of solid support from management for successful blockchain implementation. High costs were identified as the most significant barrier, emphasizing the financial implications of blockchain adoption. Challenges related to collaboration, communication and coordination within the supply chain were substantial hindrances, underscoring the importance of practical cooperation among stakeholders. Additionally, insufficient engagement of external stakeholders and the absence of governmental policies/standards were highlighted as critical factors affecting blockchain adoption. Surprisingly, the lack of knowledge and expertise was not a significant barrier. We emphasized high costs, supply chain challenges, governmental policies/standards and limited early adopters as key driving factors for applying blockchain technology in the port industry. It identified complex relationships between certain elements, suggesting comprehensive approaches to address them.

Table 9. Barriers with the highest prominence and net cause-effect values.

Indicator	Barrier's description	Key cause barriers	Most prominent barriers
B1	Lack of management commitment and Support	√	
B2	Lack of internal information transparency		×
B3	Lack of new organizational policies for using blockchain technology (Port authority)	√	×
B4	Lack of knowledge and expertise		
B5	Difficulty in changing organizational culture		×
B6	High cost (High investment costs and High maintenance cost)	√	
B7	Lack of customers awareness		
B8	Lack of External Stakeholders' Involvement and Resistance	√	×
B9	Problems in collaboration, communication and coordination in the supply chain	√	×
B10	Lack of governmental policies		
B11	Market competition and uncertainty		
B12	Lack of early adopters		

6. Discussions

Using Fuzzy-DEMATEL centrality analysis and conducting a literature review, 12 distinct barriers were categorized into cause-and-effect groups, offering valuable insights for port decision-making. Surprising findings challenge conventional perceptions, emphasizing the pivotal role of the management team and the need for collaborative efforts between stakeholders.

6.1. Significant internal barriers

6.1.1. Lack of management commitment and support

The Lack of Management Commitment Support barrier emerges as the most critical factor, underscoring the influence of the management team in decision-making processes. This finding contradicts Balci and Surucu-Balci [6], which did not assign a high significance level to this barrier; yet, they omitted mention of the substantial impact wielded by the management team. Given its substantial impact on the port industry, obtaining management support is crucial to effectively overcome this barrier. While this study downplays the significance of organizational culture in blockchain adoption within ports, many interviewees contend that it remains intricately intertwined with the management team support and cannot be dissociated.

Within Chinese state-owned enterprises (SOEs), a hierarchical structure with centralized decision-making grants top leadership significant authority and power [64]. In contrast, decision-making in Europe shipping and port companies involves input from middle management and operators. The unique culture of Chinese SOEs, prioritizing social mission and responsibility over profitability, can hinder agility and innovation. Stringent regulations and bureaucratic procedures further slowdown decision-making and innovation in industries like shipping and port operations.

The adoption of blockchain technology in Chinese ports faces challenges due to this entrenched culture and bureaucratic procedures. While China's 14th Five-Year Plan emphasizes the development of technologies like blockchain, effective strategic planning and a progressive mindset are required to embrace digitization and maximize efficiency [65].

In Port E, there is a focus on streamlining work processes through electronic billing. However, the insistence on maintaining paper copies for accountability and traceability introduces an additional workload for grassroots employees. This finding highlights the need for a shift in management thinking towards embracing electronic processes and maximizing efficiency.

6.1.2. High costs

In the hierarchy of barriers, elevated expenses rank as the fourth most crucial overall and the second most vital among internal impediments. The study identified High Cost as a pivotal barrier to blockchain adoption, corroborating previous research [17,18]. Our findings showed management support was essential, as shown in past studies [6]. Within the context of the ongoing national initiative to advance blockchain adoption, it is imperative to delve deeper into methods of providing enhanced support to ports.

While significant ports similar to Port E can take in considerable investments, most smaller businesses encounter substantial investment requirements when delving into blockchain technology. As an illustration, the initial investment made by Port F in the Global Shipping Business Network (GSBN) can be estimated at nearly half a million USD, accompanied by an annual membership fee of approximately half a million USD starting from 2023. These costs pose a considerable financial burden on Port F, especially when factoring in the absence of immediate financial gains. The administration of Port F conveyed their discontent regarding the situation where, despite being the initial investing shareholder of GSBN, they are required to fulfil membership dues.

Additional costs related to workforce deployment and daily maintenance for GSBN are critical considerations for Port F. The financial commitment extends beyond the initial membership fee, requiring careful evaluation of these supplementary costs when assessing GSBN's feasibility. The elevated expense of implementing blockchain technology in port operations can be attributed to various factors. One primary consideration is the necessity for blockchain to synergize with a range of existing technologies, including Global Positioning System (GPS), Automatic Identification System (AIS), Radio-Frequency Identification (RFID), Electronic Data Interchange (EDI) and the Internet of Things (IoT) [28]. This integration mandates significant upgrades to the existing infrastructure. Furthermore, addressing compatibility issues with legacy systems represents a substantial undertaking, demanding considerable human and material resources investment.

Despite significant expenses associated with blockchain technology, Port E is pursuing independent blockchain database development. The initial capital has already exceeded tens of millions of RMB, underscoring the substantial costs typical to both ports. The high infrastructure costs, hardware expenses, ongoing maintenance requirements, continuous research, development and staff training investment make managing the financial burden of blockchain technology essential [66].

Both Port E and Port F face financial challenges with blockchain technology implementation. Despite the decentralized nature of blockchain necessitating substantial initial investments and ongoing expenses for updates, security and skilled staff, both ports must commit resources to continuous research and development to harness blockchain benefits while managing its associated costs [67].

6.2. Significant External Barriers

6.2.1. Collaboration, communication and coordination challenges−decentralization or centralization

The hindrance presented by collaboration, communication and coordination not only claims the second highest level of significance among all barriers but also secures the top position among external impediments. Another significant barrier the study explored was collaboration, communication and coordination challenges within the supply chain. Although past studies have acknowledged the significance of collaboration within the supply chain, it did not offer precise insights into how this aspect is interconnected with the port industry [6,17]. There is a lack of confidence in blockchain technology among stakeholders, while in contrast, port management has increased trust toward blockchain technology [6]. The underlying reason for this distrust stems from reservations regarding the reliability of blockchain collaborators. We addressed this gap by examining the port industry's unique attributes, highlighting the critical role of efficient supply chain coordination for successful blockchain implementation. This obstacle is interconnected with the concepts of enterprise decentralization and the 'trust' elements highlighted in numerous studies.

Concerns about blockchain originators' dominant power were noted, with University B scholars suggesting potential resistance to decentralization due to the associated uncertainties. In its supply chain, a port inherently possesses a central attribute. Despite fears of losing control, it's important to note that blockchain's decentralization can enhance transparency, efficiency and collaboration, allowing companies to maintain influence and adapt to market changes [2,18]. Companies can leverage blockchain benefits by aligning with decentralization while mitigating concerns [68]. The perception of decentralization as depowering stems from its disruptive potential on traditional power structures [42,69].

In decentralized networks involving entities like Port E, conflicts may arise with dominant players like Maersk, who seek to retain power contrary to blockchain's transparency. Like e-commerce platforms' decision-making overshadowing merchants, stakeholders might have reservations to join a blockchain network due to data privacy and control concerns.

Addressing these issues, the current architecture involves multiple entities and enhances standardization, security, traceability and confidentiality through blockchain implementation, improving data management and collaboration [18,43]. For instance, the Port of H, Germany, adopted Verified Gross Mass (VGM) weighing for containers, associating container numbers with essential information to address traditional VGM process challenges. This approach is considered astute as it doesn't impact core interests and involves less sensitive data, making it an ideal starting point for blockchain implementation. Employing blockchain for transmitting VGM information can foster trust among participants and encourage additional data sharing. Demonstrating blockchain's effectiveness in handling VGM information could promote broader participation and collaboration within the network.

Seaport practitioners regard blockchain as a beneficial technology that aligns with the Internet's Peer-to-peer (P2P) decentralized communication model [42]. Nevertheless, they express concerns about its potential consequences given its complexities and irreversibility, drawing parallels with human genetic coding and an unstoppable nuclear bomb, with concerns that there may be no turning back once Pandora's box of blockchain is opened. One interviewee asked, "What is the cage of this behemoth?" These concerns highlight the fear of irreversibility once the technology is widely adopted. Another concern raised is the possibility that widespread blockchain adoption could lead to a loss of enterprise uniqueness due to homogeneity in business development on the chain.

6.2.2. Lack of external stakeholders' involvement

The study identified the Lack of External Stakeholders' Involvement as a critical obstacle, ranking third behind Lack of Management Commitment and Support. It ranks second most important in external barriers. This barrier's importance had not been previously delineated compared to other impediments [17,50]. Previous studies underestimated the influence of secondary revenue stakeholders within the ports and maritime industry. This influence notably impacts the integration of blockchain technology in ports, particularly given that these stakeholders are not considered primary actors [6].

Notably, blockchain technology could disrupt traditional shipbroking roles. However, the impact varies and does not necessarily entail job loss. Shipbrokers, as intermediaries in maritime transactions, have certain tasks that may become automated or simplified with blockchain adoption, potentially reducing demand for some services [70].

In Shanghai, the government-backed entity M Company is pivotal in coordinating data transmission among shipping firms, customs, terminals and regulatory bodies. Despite its importance, concerns have arisen due to M Company's expensive pricing model, which levies substantial fees based on data size. Nonetheless, its strong affiliations with customs and the local government have cemented its position akin to a governmental department, leading businesses like Maersk, aiming to establish a foothold in Shanghai, to rely on M Company for electronic document transfers, resulting in significant annual expenses amounting to tens of millions of dollars. This reliance is despite the actual data transmission costs being minimal, as M Company essentially acts as an intermediary, adding significant financial burden to the process.

Blockchain could also deter cargo transportation fraud. Currently, cargo loss or damage up to 0.5% is accepted internationally, but some captains misuse this allowance for personal gain. Blockchain's transparency could prevent fraudulent practices [25].

Moreover, blockchain could address false cargo weight reporting by ensuring accurate, tamper-proof records and enhancing transaction integrity. While disrupting some shipbroking aspects, blockchain could transform roles and create opportunities in the maritime sector, bringing efficiencies and security to all stakeholders [6].

6.3. Unveiling unique performance barriers: A comparative analysis with past literature

The primary obstacles to consider in Fuzzy-DEMATEL calculations are "Lack of Experts and Capability", "Lack of Customer Awareness" and "Lack of Internal Policy/Standard". Interestingly, their cause-and-effect relationships have proven to be unexpected, deviating from the conventional importance and causality highlighted in previous research. In previous literature, Vafadarnikjoo et al. (2021) once assumed that the successful implementation of blockchain technology in ports would demand a considerable cadre of experts. However, real-world instances have demonstrated that many ports, when choosing to outsource blockchain implementation, do not actually require a substantial number of experts [18]. Furthermore, despite Kouhizadeh et al. [17], previously emphasising the importance of raising customer awareness our analysis has revealed that numerous ports are embracing blockchain technology based on their growth trajectory and a desire to lead in technological advancements. Additionally, government policies play a pivotal role in shaping corporate policies [6]. However, this study has uncovered instances where influential state-owned ports can influence the formulation of government policies. Despite these findings, as ports embark on their blockchain adoption journey, they must remain vigilant regarding the dynamic interplay among these barriers.

6.3.1. Lack of experts and capability

The Lack of Knowledge and Expertise was less critical in the port industry context [6]. Therefore, outsourcing strategies have been emphasized for blockchain technology [41,43]. As exemplified by IBM's contributions to blockchain development, external expertise can effectively address ports' blockchain challenges [17,71].

By adopting blockchain technology, ports can leverage outsourcing to access specialized expertise. For instance, Port F's partnership with GSBN minimizes the need for in-house blockchain knowledge by guiding the port through the implementation process [72].

Outsourcing alleviates the resource burden of recruiting and training an in-house team of blockchain experts, enabling the port to focus on core activities and entrust technical aspects to experts, optimizing resource allocation and efficiency [73].

Moreover, outsourcing mitigates risk as experienced partners can handle potential complexities and regulatory considerations [73]. For instance, Port F noted that COSCO SHIPPING (GSBN originator) could reduce costly mistakes. Working with an established outsourcing partner also provides access to pre-existing frameworks or ready-to-use solutions, accelerating the implementation and transition to blockchain technology [53].

6.3.2. Lack of customer awareness

While the Lack of Customer Awareness had limited relevance within the port industry framework, it stemmed from customer demands not driving dedicated blockchain platforms' inception. Instead, the port proactively invested in its autonomous development, in contrast with previous findings [17,45].

As per the statements from individuals interviewed at Port E, the utilization of blockchain technology exerts minimal influence on customers (such as shipping companies). This similarity can be likened to substituting the conventional electronic bill of lading with a blockchain-based bill of lading, wherein there appears to be no discernible variance in the customer's senses [10]. Consequently, the operational platform has experienced limited alterations, much like how the replacement of 4G with 5G technology has yet to yield any apparent modification in the appearance of the website page users' access.

The port industry's unconventional approach, where the lack of customer awareness was of limited concern, showcased a strategic vision transcending immediate customer demands. Rather than being driven solely by customer requests, the port took the initiative to invest in the autonomous development of dedicated blockchain platforms. This approach allowed the port to position itself as an industry innovator, offering solutions that catered to present needs and anticipated future requirements. Proactively embracing blockchain technology, the port demonstrated its commitment to long-term value creation, operational vision and mission.

6.3.3. Lack Internal policy/standard

Port Authorities hold a pivotal role in managing and developing ports, serving as regulatory bodies that steer innovation within the port industry. Standardization presents a significant challenge in the port industry's blockchain adoption due to varying institutional document requirements. The study highlighted the correlation between the Lack of Governmental Legal and Regulatory/Standardization and the Lack of New Organizational Internal Policies/Standards for Using Blockchain Technology. This mutual influence underscored the port's strong governmental affiliation and the influence of oligopolistic enterprises on government policies. This influence is evident through the managerial responsibilities undertaken by the Port Authority within the port [74]. Among the spectrum of barriers, the absence of internal policies and standards assumes the fifth most pivotal position overall and the third most significant standing within the realm of internal impediments. It challenges the conventional notion that government regulations exclusively shape corporate policies [6].

To fully exploit blockchain advantages, ports need comprehensive business process re-engineering, including operational review, workflow streamlining and data management optimization [75]. Workforce deployment adjustments may be needed for employees to manage blockchain platforms and maintain customer interactions [17,76].

Developing new internal policies is critical to govern blockchain use, ensure data privacy and maintain security. As ports transition from traditional to online systems, a digital transformation is necessary for effective blockchain integration, enabling real-time data sharing and enhancing efficiency and accuracy [16]. Data standardization and security become paramount as the industry moves towards blockchain adoption, requiring standardized formats and robust security measures adherence [17,18].

6.4. Solutions for overcoming the obstacles

Previous studies [6,17,18] did not address strategies for overcoming these obstacles and facilitating the adoption of blockchain in ports. This paper compiles essential approaches to promote the utilization of blockchain in ports based on insights gathered from interviews.

A comprehensive process re-engineering strategy is essential to overcome barriers in seaport operations. Business Process Re-engineering (BPR) is a management concept and methodology aimed at redesigning and improving existing business processes within an organization [77]. Business Process Re-engineering (BPR) finds its origins in diverse fields, encompassing four primary domains that transform within BPR initiatives: 1) Organization, 2) Technology, 3) Strategy and 4) People [77,78]. These dimensions are unified under a process-oriented perspective, serving as a shared framework for analyzing and addressing these aspects. This framework involves establishing cross-departmental collaboration and modernizing the internal information flow process. Blockchain technology enables the integration of personnel work rules and information flow rules, creating a three-chain parallel collaboration [79,80]. Port E, Port F and the parent company of GSBN have undertaken initiatives such as departmental restructuring, process optimization and more.

Overcoming barriers to blockchain adoption requires embracing a blockchain-centric mindset within the seaport industry. This approach involves understanding and embracing fundamental principles such as decentralization, transparency and security [2,10]. It encourages exploring peer-to-peer transactions, reducing the need for intermediaries and transaction costs while challenging conventional notions of trust [81]. It fosters a culture of transparency, accountability and inclusivity, promoting collaboration, open standards and community-driven governance within blockchain networks [44].

This strategy effectively leverages digital technologies to create value and enhance organizational agility [82]. Moreover, cultivating a culture that empowers employees, promotes experimentation and supports continuous learning is crucial for successful blockchain adoption. The absence of such a culture can lead to failure. Embracing risk-taking, experimentation, a fail-forward mentality and iterative approaches will enable organizations to adjust to the digital era and foster long-term success [8].

7. Conclusion, limitations and future research

7.1. Conclusions

In this study, we shed light on the barriers hindering the adoption of blockchain technology in the port industry, a crucial sector striving for more innovative and sustainable operations. We effectively pinpoint notable barriers to the adoption of blockchain within this field, with a specific emphasis on the intricate environment of ports. Additionally, particular barriers differ considerably from prior literature regarding their impact, a variance attributed to the complex stakeholder dynamics within the port environment. “Lack of External Stakeholders’ Engagement”, as well as challenges related to “Collaboration, Communication and Coordination,” emerged as more significant barriers in the Fuzzy-DEMATEL calculations than previously noted in the literature. On the other hand, “Lack of Experts and Capability”, “Lack of Customer Awareness”, and “Lack of Internal Policy/Standard”, while not ranking as the foremost barriers in the Fuzzy-DEMATEL analysis, demonstrated unexpected cause-effect relationships. These findings diverge from the conventional emphasis on their importance and causality in existing literature. The study addresses a specific gap by focusing on the seaport industry. In this sector, the adoption of blockchain technology is less widely explored than in other domains. This targeted focus contributes new knowledge to the field, especially in understanding the unique challenges and opportunities presented by the port industry.

The study's contributions are multi-faceted. First, it is the first research to address blockchain adoption barriers in ports using expert panels from the port industry. This approach provides a comprehensive examination of the challenges faced by ports in adopting blockchain technology. In prior research on blockchain technology, there was a notable absence of studies concerning its application in the context of ports. This article represents a pioneering effort as it marks the first exploration of blockchain adoption barriers within the port industry, utilizing Fuzzy-DEMATEL as the chosen research approach. Drawing insights from previous literature, it becomes evident that Xue Li's work in 2022 primarily summarized the factors contributing to the successful implementation of blockchain in the maritime industry rather than delving into the obstacles faced [51]. A past DEMATEL analysis of barriers in the maritime industry spanned the entire maritime sector and overlooked the unique characteristics of the port industry [6]. On the other hand, Nguyen et al [53] focused exclusively on analyzing impediments to blockchain adoption by container ship companies. Similarly, Raza et al. [8]examined challenges related to using digital technology in liner shipping without explicitly addressing the adoption of blockchain technology within the port sector. Second, the study effectively identifies significant barriers through a systematic literature review and the Fuzzy DEMATEL method and uncovers causal relationships between them. This offers valuable insights into the underlying causes of these barriers, laying a solid foundation for future initiatives aiming to improve blockchain adoption in ports. It quantifies these relationships in a way that not have been extensively explored in previous research.

The practical contributions of the study are noteworthy as well. The results present a structured approach to address identified barriers within the port industry. Our research contributes novel insights into the blockchain challenges specific to ports, filling a gap in existing literature. This study focuses on the unique challenges ports face in adopting blockchain technology, a process complicated by the intricate nature of port operations and the involvement of multiple international stakeholders, including port authorities. It aims to identify and explain the barriers unique to ports in this context, offering strategies and insights to help these ports navigate and overcome these obstacles in implementing blockchain. The study identifies four primary obstacles to blockchain adoption in seaports and explores the interdependencies among these barriers. By emphasizing management team support, cross-departmental collaboration and BPR (business process re-engineering), the study provides clear pathways for enhancing blockchain adoption in ports. The research also highlights the importance of informed decision-making considering intercultural backgrounds and aligning governmental policies with the reality of major ports. The study extends beyond academic analysis to offer practical implications for policymakers and industry practitioners. By revealing the interdependencies among barriers, it provides a roadmap for strategic planning and policy formulation to foster successful blockchain integration.

The study's theoretical contribution rests on the Technology-Organization-Environment (TOE) and Technology Acceptance Model (TAM) frameworks. This integration facilitates a comprehensive comprehension of the obstacles impeding the adoption of blockchain technology within diverse organizational settings. By considering not only the technological aspects but also the internal organizational dynamics, external environmental influences and user perceptions, this combined framework offers a more holistic and nuanced perspective on the challenges that hinder the successful integration of blockchain technology.

The results show critical barriers such as management team support, collaboration within the supply chain, lack of knowledge, customer awareness, external stakeholder involvement and high costs. The correlation between the absence of governmental policies/standards and limited early adopters is emphasized, underscoring the need for internal standards to shape blockchain adoption in ports.

In conclusion, this study provides valuable insights into the sustainability barriers of blockchain adoption in ports, enabling informed decision-making, collaboration and innovation within the industry. By addressing these barriers, the port sector can lead in the intelligent and sustainable transformation driven by blockchain technology. The business sector recognizes that the utilization of business process re-engineering (BPR) and the strategic application of blockchain technology are pivotal approaches for overcoming the challenges hindering the widespread adoption of blockchain in port operations.

7.2. Limitations

This study necessitates acknowledging several limitations. First, potential selection bias may exist as the sample was drawn from specific sources, potentially not fully representing the entire population of port operators, supply chain managers and blockchain technology experts. The reliance on experts' perspectives and experiences to identify and evaluate interrelationships between factors introduces the possibility of bias. Second, using interview data exposes the study to social desirability bias, where participants may respond to what they perceive as socially acceptable rather than their genuine views or experiences. Last, the study's cross-sectional nature prevents establishing causal relationships between adopting blockchain technology and perceived barriers. Longitudinal studies or experimental designs would be more suitable for determining causality. Despite these limitations, this study offers valuable insights into blockchain adoption in ports and associated barriers, paving the way for future research and advancements in the field.

7.3. Future research

Future research should explore practices to overcome barriers to blockchain adoption in ports and implement solutions based on leading industrial practices and effective metrics. For instance, in what ways might strategies like support from the management team and restructuring business processes address the four primary obstacles highlighted in this article? Additionally, investigating the impact of emerging technologies on the port industry and identifying additional factors influencing blockchain adoption will be essential. Ongoing enhancement and innovation in port operations are crucial for sustaining competitive edge and environmental viability in the dynamically changing realms of technology and commerce. Specifically, implementing blockchain technology in ports significantly contributes to traceability and transparency within the food supply chain. On the one hand, a firm's practices and routines can act as barriers if they are incompatible with the new technology or if the firm is resistant to change. On the other hand, the same practices and routines can also help it absorb and integrate new technologies by providing a foundation of shared knowledge and understanding. The practice-based view (PBV) perspective offers a comprehensive experience of a company's performance and its relationship with integrating blockchain technology [83]. This viewpoint focuses on assessing the influence of everyday operational activities. Moving forward, an in-depth exploration of these practices through the lens of PBV will play a pivotal role in conducting a comprehensive analysis of blockchain adoption in the port industry.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare there is no conflict of interest.

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