

Article

Analysis of Big Data on New Technologies for Port Safety Management in Preparation for Eco-Friendly and Digital Paradigm Transformation

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Abstract

Ports serve as key nodes in eco-friendly and digital logistics networks, and the volume of cargo handled continues to increase in response to growing international trade. However, the increased workload within limited spaces heightens the risk of safety accidents, and the number of casualties in port stevedoring operations has continued to rise. As the era of transition toward eco-friendly and digital paradigms unfolds, the adoption of new technologies in ports presents a strategic opportunity to enhance safety management. As of 13 May 2025, the study conducted a text-mining analysis based on research abstracts related to the keyword “New technology and port safety,” in the context of internal and external environmental changes. Specifically, a total of 639 research abstracts were collected, but 138 abstracts, which were unrelated to port safety, were excluded, and 501 abstracts from the Clarivate Web of Science database were analyzed, focusing on 2676 words that appeared at least twice. The study applied Term Frequency (TF) analysis, TF–Inverse Document Frequency analysis, Semantic Network Analysis, and Topic Modeling. The results indicate that Internet of Things emerged as a core solution for strengthening port safety management. However, challenges remain, including the prevention of security breaches, high infrastructure implementation costs, and limitations in battery life.

Keywords: port safety; big data; text-mining analysis; TF analysis; TF-IDF analysis; semantic network analysis; TM analysis



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1. Introduction

1.1. Background of the Study

Seaports are commercial hubs that play a vital role in maintaining economic growth and development [1–3]. Ports serve as key intermediaries connecting land and sea transportation [4], functioning as terminals in the process of transporting and handling eco-friendly fuels. Economic, social, and geographic viewpoints are used to identify the roles and functions of ports [5]. The volume of cargo that ports must process continues to increase steadily. The port industry is constantly evolving, and this evolution brings about changes in many areas [6]. Ref. [7] have evaluated the most significant innovation trends that are currently being seen in seaports worldwide and discovered that the implementation of innovations in seaports occurs in accordance with almost all the global innovation trends

that have been recognized. The most widely used innovative projects in seaports featured solutions that addressed the following trends: servitization, the sharing economy, smart management, and creative business models for global competitiveness. As seaports adopt innovative solutions for competitiveness and sustainability, the cultural prioritization of safety within the maritime industry is becoming increasingly central to these transformations [8,9]. Also, ref. [10] said that the evolution of intelligent transportation systems in modern ports is pivotal to sustaining global trade efficiency.

Every port and nation must maintain port safety in complete compliance with IMO requirements [11]. Safety performance in seaports is critical for reducing accidents, enhancing operational efficiency, ensuring regulatory compliance, preventing environmental damage, and promoting a robust safety culture [12]. As major incidents will cause port disruptions and ultimately harm the port's growth and efficiency, safety should never be compromised [13,14]. There are also unintended consequences, such as damage to the port's reputation [13]. Safety performance may encompass formal procedures, general rules, and work practices related to promoting workplace safety [15].

The maritime transportation of next-generation eco-friendly fuels such as liquid hydrogen and ammonia is gradually increasing within the global paradigm shift toward carbon neutrality. The greatest number of planned innovative projects in seaports are related to environment-friendly technologies, energy efficiency improvement, energy storage, and provision of low-carbon LNG fuel [7]. In particular, liquid hydrogen and ammonia are high-risk chemical substances that require specialized handling under ultra-low temperatures and high-pressure conditions, making their potential for safety incidents significantly greater than that of conventional container cargo.

Numerous incidents have occurred in the maritime sector globally, and these catastrophes have increased the awareness of academics and policymakers regarding the significance of risk assessment and safety in seaport operations and marine transportation [16].

Accidents occurring within ports can lead to substantial social and economic consequences, including compensation for victims, legal liability for management, and operational shutdowns. Consequently, various legal frameworks related to port safety have been established. Ref. [17] investigated the connection between the safety policy of maritime transport workers at Port Harcourt Seaport and healthcare maintenance. Based on the results, the study concludes that the safety policy of maritime transport workers at Port Harcourt Seaport has a favorable and significant correlation with healthcare maintenance. In South Korea, the death of a stevedore at Pyeongtaek Port in March 2021 drew public attention to the longstanding inadequacies in port safety management. Subsequently, the enforcement of the Serious Accidents Punishment Act in January 2022 and the Special Act on Port Safety in August 2022 has contributed to a growing societal emphasis on port safety management. Nevertheless, a wide range of accidents, from minor incidents to those causing national-level losses, continues to occur in ports.

According to the statistical data from the Korea Port Logistics Association, the number of accidents in port stevedoring operations has shown a consistent upward trend: 99 cases in 2019, 116 in 2020, 128 in both 2021 and 2022, and 142 in 2023. This increase highlights the urgent need to strengthen safety management measures in port operations.

An analysis of the 142 stevedoring-related accidents in 2023 by length of service reveals that workers with over 10 years of experience accounted for the highest proportion, with 68 cases (47.9%). This was followed by 5–10 years with 41 cases (28.9%), less than 1 year with 16 cases (11.3%), 1–3 years with 12 cases (8.5%), and 3–5 years with 5 cases (3.5%). These figures suggest that accidents can occur regardless of job proficiency, underscoring the need to address complacency and overconfidence, which may lead to lapses in safety awareness. In terms of time of occurrence, the majority of accidents took place between

07:00 and 12:00, accounting for 62 cases (43.7%). This was followed by 12:00–17:00 with 39 cases (27.5%), 17:00–22:00 and 22:00–03:00 with 18 cases each (12.7%), and 03:00–07:00 with 5 cases (3.5%). These findings indicate that port stevedoring accidents are most frequent in the morning, suggesting the need for enhanced safety supervision prior to the start of work shifts. Regarding the source of accidents, cargo was the leading cause with 36 cases (25.4%), followed by vehicles with 16 cases (11.3%), handling tools and work environment with 14 cases each (9.9%), and onboard equipment with 12 cases (8.5%). By cargo type, steel products were associated with the highest number of accidents at 27 cases (19.0%), followed by frozen goods with 14 cases (9.9%), bulk cargo with 12 cases (8.5%), and miscellaneous goods with 9 cases (6.3%). These results emphasize the importance of conducting pre-task training tailored to the characteristics of each cargo type, with particular focus on safe handling procedures for steel cargo. In terms of injury severity, outpatient treatment exceeding three weeks was the most common outcome, with 76 cases (53.5%). This was followed by outpatient treatment within three weeks (29 cases, 20.4%), hospitalization over three weeks (24 cases, 16.9%), hospitalization within three weeks (11 cases, 7.7%), and fatalities (2 cases, 1.4%). These statistics demonstrate that accidents in port stevedoring operations often result in serious injuries, indicating a high potential for severe consequences.

1.2. Purpose of the Study

With the advent of the Fourth Industrial Revolution in the early 21st century, the expansion of maritime transportation for next-generation eco-friendly fuels—such as liquid hydrogen, ammonia, LNG, and methanol—has introduced new challenges to port safety management systems while simultaneously offering opportunities for technological innovation. Because of their ultra-low temperature, high-risk, flammable, or explosive properties, these fuels present limitations for conventional cargo handling and safety management approaches. Consequently, the application of advanced technologies to enhance port safety management is being actively explored. Technologies currently undergoing pilot testing and demonstration include AI-based risk prediction and monitoring systems, Internet of Things (IoT)-integrated safety sensor networks, digital twin simulations, VR-based safety training, robotic and remote-controlled cargo handling equipment, and AR-assisted safety devices. These technologies are emerging as key strategies to improve both safety and operational efficiency by detecting potential hazards in the storage, handling, and transportation of liquid hydrogen, ammonia, LNG, and methanol and by enabling real-time response capabilities. In particular, the integration of new technologies is becoming a critical factor in port safety management.

Data mining uses statistical analysis and machine learning techniques to automatically identify patterns within databases [18]. Among these techniques, text-mining has gained increasing attention for its ability to analyze latent knowledge structures embedded in textual data. Text-mining refers to the process of extracting meaningful patterns, trends, and insights from unstructured text data, with the goal of quantifying and structuring the hidden information contained in documents. Text-mining techniques can be used to find useful information from documents [19,20]. Among various types of unstructured text data, research abstracts are particularly rich in expert insights and domain-specific knowledge.

Accordingly, this study conducts a text-mining analysis of research abstracts related to “new technology and port safety” to identify key technologies and derive major challenges for strengthening port safety management. Specifically, 501 abstracts were collected from Clarivate’s Web of Science (www.webofscience.com (accessed on 13 May 2025)). From these abstracts, 5151 words were extracted, and 2676 words with a frequency of 2 or more were selected for analysis. Based on the collected terms, the study sequentially applied Term

Frequency (TF) analysis, Term Frequency–Inverse Document Frequency (TF-IDF) analysis, Semantic Network Analysis (SNA), and Topic Modeling (TM) Analysis. The combined use of term frequency (TF) analysis, inverse document frequency (TF-IDF), semantic network analysis (SNA), and topic modeling (TM) provides a comprehensive view of research trends and key challenges in the field of port security.

Here are contributions of the study.

- First of all, by analyzing 501 research abstracts, this study provides a large-scale, data-driven overview of global academic trends in emerging technologies for port safety management, offering quantitative insights into the evolution of research themes.
- Secondly, the findings highlight the Internet of Things (IoT) as a central enabling technology for enhancing port safety. At the same time, persistent challenges such as cybersecurity risks, high implementation costs, and limited battery life were identified as major constraints to practical adoption.
- Thirdly, in-depth interviews with safety management personnel at Busan New Port were conducted. These interviews validated the relevance of the analytical results and provided practical perspectives on technical limitations, sensor integration, and cost-related barriers.
- Lastly, based on the results, the study presents various implications regarding the role of new technologies in enhancing port safety management amid the ongoing eco-friendly and digital paradigm shift.

2. Review of Previous Studies

2.1. Review of Prior Research on Port Safety Management

Previous studies on port safety management have primarily focused on identifying the causes and risks of accidents within ports and proposing preventive measures. Ref. [21] offer a thorough examination of the hazards present in seaport environments and introduce contemporary methods to enhance safety. They propose strategies to reduce the impact of emergency scenarios in the port region while taking into account the distinctiveness of the decision-making process. Ref. [22] examined the level of risk at the stage of construction of a seaport, with particular emphasis on selected adverse incidents that can significantly affect the timeliness of the investment. To assess the criticality of the hazardous events in a container terminal, ref. [23] incorporated Fuzzy Rule-Based Bayesian Networks into an advanced Failure Mode and Effects Analysis technique. Ref. [24] introduced a novel fuzzy risk assessment method to help seaport operations handle uncertainties and optimize their performance effectiveness in a methodical way. The methodology includes the fuzzy set theory, expected utility, the fuzzy analytical hierarchy process, and the evidentiary reasoning approach. Ref. [25] insisted that there are constraints for improving an area imposed by a finite budget and time.

Some studies have explored the application of emerging technologies to enhance port safety management. Ref. [26] introduced a training platform utilizing virtual reality technology. Ref. [27] proposed a safety solution involving personal protective equipment integrated with RFID technology. Additionally, several studies have discussed the challenges of implementing IoT technologies to realize smart port systems [28–31]. Ref. [32] examined commercial and simulated Information and Communication Technology (ICT) systems designed to improve occupational safety in harsh or invasive work environments—steel, mining, construction, oil & gas, and especially seaports. The study used the Port of Bar (Montenegro, South Adriatic Sea) as a case reference to explore what kinds of ICT safety technologies can be realistically adopted in a developing/transitional environment. Ref. [33] have developed a monitoring system for coastal high-pile piers, including a corresponding implementation scheme, sensor selection, and performance

parameters, and provided stress features and health inspection indicators for the wharf structure. The experimental findings show that the suggested monitoring system is feasible and offer valuable insights for further study in the field. Ref. [34] cover crucial topics such as improving energy efficiency, environmental issues, integrating renewable energy sources, the IoT, and legal and regulatory compliance. Technology strategies such as electrification, digitization, onshore power supply systems, and port energy storage possibilities are also covered in the study.

Big data analysis related to port safety has been conducted as follows. Ref. [35] intended to employ meteorological data over time in conjunction with the data from automatic identification systems gathered around Keelung Harbor as a foundational dataset. Their approach incorporates geographic information systems and decision tree algorithms within a big data analytics framework. Ref. [36] show how such data may be efficiently analyzed with modern text-mining tools to uncover new information on the risk factors for marine accidents. The results show that accident reporting is mostly human-centered and that policymakers and organizational decision-makers must take into account a wider range of actors as maritime transportation becomes more complex.

2.2. Distinctiveness from Previous Studies

Previous studies on port safety management have primarily focused on identifying the causes of accidents and establishing preventive measures, as well as exploring the potential for adopting new technologies. In addition, key topics related to “port safety” have been analyzed using text-mining techniques. With the advent of the Fourth Industrial Revolution, advanced digital technologies such as artificial intelligence (AI), the IoT, big data, and virtual reality (VR) are rapidly being applied across the port industry. In particular, ports—functioning as strategic hubs within global logistics networks—are actively pursuing the development of “smart ports” to enhance efficiency and competitiveness. This shift is not only transforming operational processes but also fundamentally reshaping the paradigm of safety management. Furthermore, as maritime transportation of next-generation eco-friendly ship fuels—such as liquid hydrogen, ammonia, LNG, and methanol—becomes more widespread, ports are facing new challenges in handling high-risk and hazardous materials that differ significantly from conventional cargo. These fuels possess complex risk characteristics, including ultra-low temperatures, flammability, and explosivity, making it essential to establish proactive safety management systems. Accordingly, this study aims to identify key technologies and major challenges in port safety management by conducting a text-mining analysis based on big data.

Through this approach, it is expected that the study will provide a comprehensive understanding of domestic and international research trends in port safety technologies and enable in-depth discussions on various research agendas.

3. Research Design and Analytical Methodology

3.1. Data Collection

As of 13 May 2025, a total of 639 research abstracts were collected from Clarivate’s Web of Science (www.webofscience.com) using the keyword “New technology and port safety.” Among these, 138 abstracts deemed unrelated to port safety were excluded, resulting in a final dataset of 501 abstracts for analysis. Text-mining analysis was conducted using the statistical software package NetMiner 4.0 Academic. In text-mining, the data preprocessing stage has a direct impact on the analytical outcomes and may be performed iteratively [37]. To enhance semantic consistency and analytical reliability, a multi-stage text preprocessing procedure was conducted prior to analyses.

First, all research abstracts were tokenized, converted to lowercase, and filtered through a stop-word removal process using both standard English stop-word lists and domain-specific exclusions.

Second, a thesaurus dictionary was constructed to merge semantically similar terms. For example, “high implementation costs”, “capital cost”, and “investment burden” were unified under the representative term “High implementation costs” and “cybersecurity risk”, “cyberattack”, and “data breach” were standardized as “Cybersecurity Risk”.

Third, domain-relevant concepts crucial to the analytic framework. Third, domain-relevant concepts crucial to the analytical framework, such as “Risk”, “Security Breach”, “Job Displacement”, “Digital Transformation”, and “Artificial Intelligence”, were categorized as defined words, ensuring their preservation during preprocessing.

Fourth, meaningless, overly general, or irrelevant terms (e.g., study, method, model, data, analysis) were grouped as an exception list and excluded to prevent distortion of topic extraction. Finally, duplicate terms were consolidated to yield a final set of 2676 analytically valid words. Based on the refined text data, the following analyses were sequentially conducted: TF analysis, TF-IDF analysis, SNA, and TM analysis. The overall analytical flow is illustrated in Figure 1.

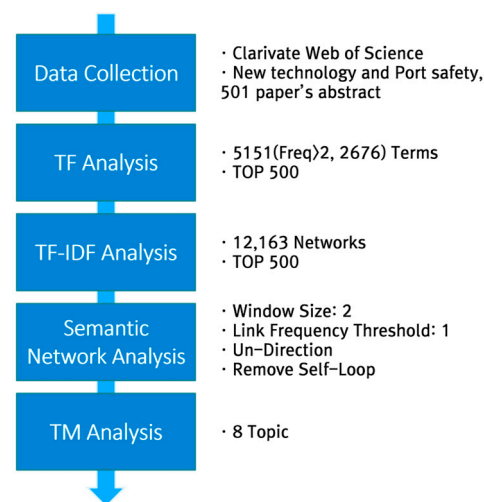


Figure 1. Research process.

3.2. Text-Mining Method

3.2.1. TF Analysis

TF analysis is a fundamental technique in text-mining [38]. It involves extracting frequently mentioned words within a specific document set and evaluating their importance based on the frequency of occurrence [39]. TF analysis serves as the foundation of text analytics and can be visualized using a word cloud. Visualization refers to the use of graphical elements to intuitively represent analytical results, such as network maps, enabling users to better understand complex data. In big data analysis, not only the analytical techniques but also the methods of presenting results—particularly visualization—are critically important. The way data are represented can reveal new trends and patterns that may otherwise remain unnoticed. Among various visualization tools, word cloud is especially useful. It displays words in varying sizes proportional to their frequency within the text, allowing researchers to quickly identify which terms carry significant meaning [40].

3.2.2. TF-IDF Analysis

TF analysis measures how often a specific word appears within a document. A higher TF value generally indicates that the word is considered important. However, commonly

used words may still yield high TF values even if they are not semantically significant. To address this issue, document frequency (DF) is measured to determine how many documents mention a particular term repeatedly and meaningfully [41,42]. TF-IDF is used to identify terms that are specific to individual documents within a large corpus. A phrase that appears frequently in a few reports in a certain area will have the highest TF-IDF score. This makes it easier to spot uncommon words that crop up in a sector's individual business reports. The phrase will have the lowest TF-IDF score if it appears in nearly all reports [43]. That is, by excluding terms with low TF-IDF values, it becomes possible to filter out commonly used but non-distinctive words, thereby allowing the identification of keywords that are truly significant to each document.

3.2.3. SNA

SNA is an advanced form of the previously discussed keyword frequency analysis. It extracts keywords that co-occur within the target documents and analyzes how these keywords are connected to specific topics of interest. Semantic networks can be used to capture the relationships among co-occurring words in a single document [44,45]. In the light of visual analytics, semantic networks can automatically be retrieved from unstructured text data to be used as a medium for visual text analytics [46]. Principally, any words that can be connected to other words can be considered nodes [47]. By classifying keywords according to specific topics and conducting association analysis, it becomes easier to structurally identify frames that represent the relationships among major issues. SNA allows users to configure parameters such as window size, link frequency, directionality, and self-loop removal according to the purpose of the analysis. Window size refers to the range used to define adjacency between words. Link frequency determines the minimum number of links required between a pair of words for them to be extracted. Directionality refers to whether the order of appearance between two or more co-occurring words should be considered. Self-loop removal determines whether repeated occurrences of the same word pair within a single sentence should be excluded from the analysis.

3.2.4. TM Analysis

TM is a methodical and effective way to identify thematic issues across numerous documents within a short period [48]. TM analysis is highly useful as it compensates for the limitations of SNA, which often involves complex network visualizations and lacks statistical clarity in presenting the importance of extracted word pairs. A topic can be defined as a group of words that tend to co-occur and share similar meanings [41,49]. TM statistically analyzes word frequencies within text data to automatically extract and classify latent themes—topics—that span across the entire dataset, making it particularly useful for issue analysis.

Among TM techniques, Latent Dirichlet Allocation (LDA) is the most widely used probabilistic model [50,51]. Proposed by [52], LDA aims to provide the topic composition of each document as a probability distribution. It identifies topics by considering both the keywords most likely to be assigned to each topic and the documents in which those topics are most prevalent. However, as topics may overlap, it is necessary to determine an appropriate number of topics during implementation. To evaluate the degree of similarity among topics, this study employed the coherence score. Topic coherence measures the semantic similarity between high-scoring words within a topic [53]. This score can be used to distinguish between more interpretable and less interpretable topics. Topics with higher interpretability tend to have higher coherence scores, with values approaching zero from the negative range [14].

4. Findings

4.1. Results of TF Analysis

A total of 5151 nouns appeared in the abstracts of 501 research papers. Among these, 2676 words with a frequency of 2 or more were selected for analysis. According to the results of the TF analysis, the word “IoT” appeared most frequently, with 877 occurrences. This was followed by “Challenge” (220 times), “Digital Surveillance” (216 times), “Inefficiency” (149 times), “High implementation costs” (147 times), “Infrastructure” (129 times), “Simulation” (126 times), “Vehicle” (121 times), “Loss” (111 times), and “AI (Artificial Intelligence)” (108 times). Other words were found to have frequencies below 100. Based on the maximum number of word occurrences, the top 500 words were extracted for further analysis. The word cloud visualization of TF results is presented in Figure 2.

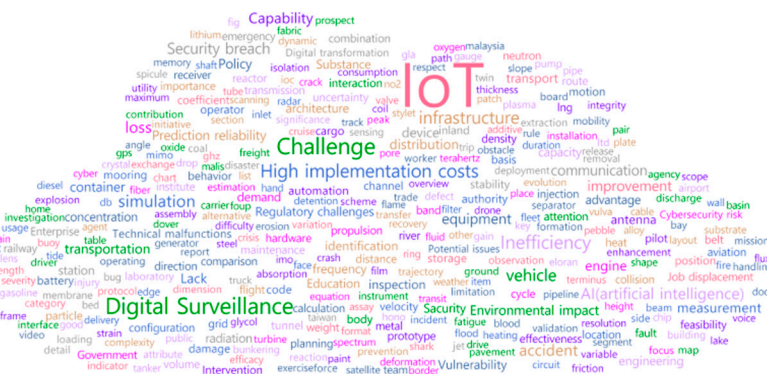


Figure 2. The result of TF analysis.

4.2. Results of TF-IDF Analysis

TF-IDF analysis provides information for determining how important a specific word is within a given document, based on both TF and DF. Among 12,163 networks, a query was applied to simplify meaningless networks. Consequently, only networks with a WEIGHT value of 0.7 or higher were selectively extracted, reducing the total to 9381. According to the TF-IDF analysis, the major keywords related to the agenda “New technology and port safety” in the research abstracts included: “velocity,” “planning,” “operator,” “LTD,” “Location,” “Interface,” “Inspection,” “Force,” “effectiveness,” “density,” “contribution,” “calculation,” and “automation,” each appearing 21 times. These are followed by “volume,” “observation,” “limitation,” “focus,” “configuration,” “concentration,” “job displacement,” and “digital transformation,” each appearing 20 times. Based on the maximum number of word occurrences, the top 500 words were extracted for further analysis. The word cloud visualization of the TF-IDF results is presented in Figure 3.



Figure 3. The result of TF-IDF analysis.

4.3. Results of SNA

The window size was set to 2, allowing links to be generated only between two words that appear adjacent to each other. The link frequency was set to 1, the direction was configured as Un-Directed, and self-loop removal was set to Yes. Based on these settings, the total number of word-to-word links within sentences was identified as 4086. However, visualizing the entire network would result in a highly complex structure, making it difficult to interpret the meaning at a glance. Therefore, only the top 150 links with the highest weight values were selectively visualized to provide analytical insights. The combinations and directions of word pairings within the network can be observed in Figure 4. According to the visualization results, the word “IoT” was positioned at the center, forming various frame structures with statistical (Coefficient), logistical (Container), cost-related (High implementation costs), and security-related (Digital Surveillance) terms. For example, the word “Digital Surveillance” was found to be part of frame structures such as “Lack–Digital Surveillance–IoT,” “Radiation–Digital Surveillance–IoT,” “Deformation–Digital Surveillance–IoT,” and “Policy–Digital Surveillance–IoT,” indicating directional relationships among associated terms.

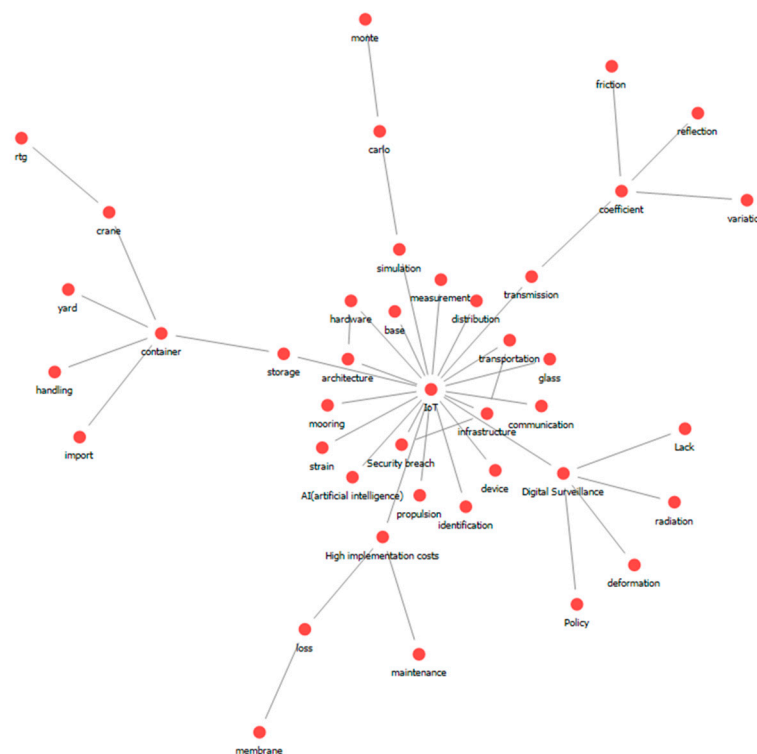


Figure 4. The result of SNA.

4.4. Results of TM Analysis

To measure the coherence score based on LDA, the Evaluation of Topic Models function provided by NetMiner was used, as shown in Figure 5. The analysis revealed that the highest coherence score was 0.535 when the number (#) of topics was set to 8, with α : 0.02, β : 0.02, and the number of iterations: 1000. The parameter α represents the prior probability of how many different topics each document contains, indicating that most documents were strongly assigned to a few specific topics. The parameter β represents the prior probability of how many different words each topic contains, showing that each topic had clearly defined core keywords.

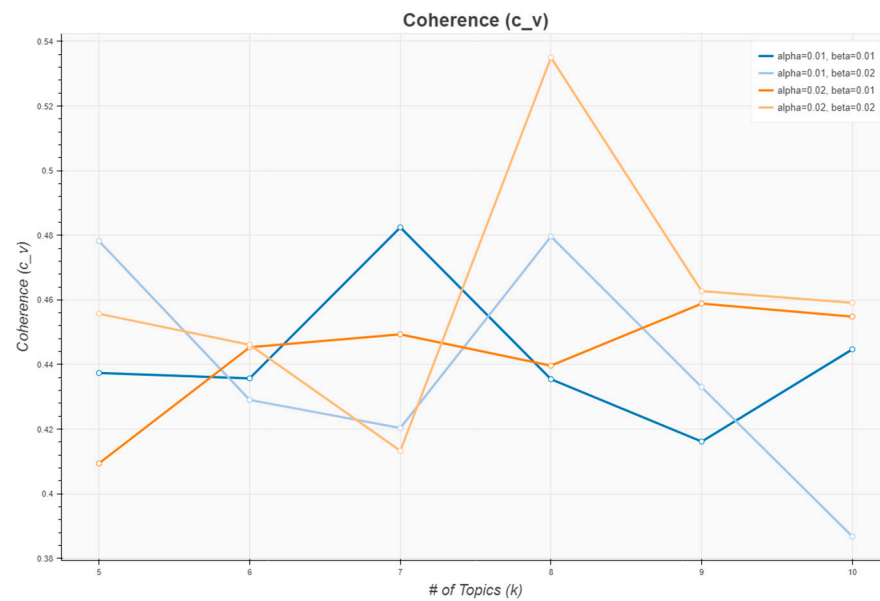


Figure 5. The result of coherence score.

Keywords with high topic assignment probabilities (influence) were presented in Table 1. Among the 501 research papers, Topic 7 was associated with the largest number of documents, totaling 99 papers (approximately 19.8%). This was followed by Topic 1 (91 papers, approximately 18.2%), Topic 8 (67 papers, approximately 13.4%), Topic 2 (61 papers, approximately 12.2%), Topic 3 (56 papers, approximately 11.2%), Topic 6 (45 papers, approximately 9.0%), Topic 5 (43 papers, approximately 8.6%), and Topic 4 (39 papers, approximately 7.8%). These results suggest that Topics 7 and 1 are the most closely related to the core themes of this study.

Table 1. The result of TM.

Topic	Keyword				
	1st	2nd	3rd	4th	5th
1	IoT	Accident	Challenge	AI	Container
N = 91	0.038	0.032	0.017	0.017	0.014
2	IoT	Communication	Challenge	Security breach	Battery
N = 61	0.091	0.025	0.020	0.019	0.017
3	IoT	Antenna	Radiation	Band	MIMO
N = 56	0.035	0.025	0.017	0.013	0.010
4	Digital Surveillance	Tunnel	LNG	Challenge	Belt
N = 39	0.027	0.023	0.017	0.015	0.014
5	Substance	Body	Team	Pavement	Assay
N = 43	0.020	0.014	0.012	0.012	0.011
6	IoT	Mooring	Inefficiency	Velocity	Motion
N = 45	0.035	0.017	0.015	0.015	0.015
7	IoT	Digital Surveillance	Inspection	Security breach	Challenge
N = 99	0.078	0.024	0.014	0.013	0.013
8	IoT	Vehicle	Engine	High implementation costs	Inefficient
N = 67	0.036	0.028	0.022	0.020	0.017

Upon examining the topics, several semantically connected keywords were identified, and the extracted keywords were used to summarize the thematic issues of each topic, as shown in Table 2. Topic 7 (N = 99) can be interpreted as follows: “Although IoT and digital surveillance support inspection, ports still face challenges in preventing security breaches.” Topic 1 (N = 91) was interpreted as follows: “IoT and AI help reduce container accidents, but safety issues in ports still persist.” Topic 8 (N = 67) was interpreted as follows: “Introducing IoT into port vehicles can reduce engine inefficiency, but high implementation costs remain a barrier.” Topic 2 (N = 61) was interpreted as follows: “In port safety, IoT improves communication but faces challenges such as battery limitations and risks of security breaches.”

Table 2. Top issues by topics.

Topic	Context
1	IoT and AI reduce container accidents, but safety challenges in ports still exist
2	IoT enhances communication but faces challenges like battery limitations and risks of security breaches
3	Port IoT systems use MIMO antennas across wide bands to boost safety, yet managing radiation remains a key challenge
4	Digital surveillance in LNG tunnels and belt systems improves port safety but faces operational and environmental challenges
5	The safety team performed an assay on a suspicious substance found on the pavement near a body
6	IoT sensors detect vessel motion and velocity to reduce mooring inefficiencies in port operations
7	Despite IoT and digital surveillance supporting inspection efforts, ports still face challenges in preventing security breaches
8	IoT integration in port vehicles can reduce engine inefficiencies, but high implementation costs remain a barrier

To further explore the practical challenges of implementing IoT technologies in port safety management, a series of in-depth interviews were conducted with 14 safety management employees at Busan New Port on 6 and 17 December 2024.

The participants reported that, although various government-led initiatives have been introduced to promote IoT adoption, the limited understanding of port-specific operational environments remains a significant barrier. Many noted that installing sensors across numerous pieces of equipment is technically and financially constrained, as each terminal faces budgetary limitations and requires government-supported pilot studies for data learning and system adaptation.

In addition, wearable devices such as helmets and smart watches were described as heavy and having short battery life, and their use raises privacy and consent concerns among workers. Interviewees also emphasized that the integration between IoT-based sensors and the existing Terminal Operating System (TOS) is essential, as isolated IoT solutions have limited effectiveness. Further challenges include sensor durability under heavy-equipment conditions and sensing blind spots caused by stacked containers that obstruct signal transmission. Despite these limitations, respondents commonly agreed that IoT remains a critical technology for future port operations. However, they stressed the need for more specialized technical development and cost-effective deployment strategies to ensure sustainable adoption.

5. Conclusions

5.1. Conclusions and Implications

This study conducted a text-mining analysis based on 501 research abstracts related to emerging technologies in port safety management, which are being re-evaluated amid the transition toward eco-friendly and digital paradigms. The findings can be summarized as follows. In the TF analysis, 2676 words with a frequency of 2 or more were extracted, with “IoT,” “Challenge,” and “Digital Surveillance” appearing most frequently. In the TF-IDF analysis, high-frequency keywords included “velocity,” “planning,” “operator,” “LTD,” “Location,” “Interface,” “Inspection,” “Force,” “effectiveness,” “density,” “contribution,” “calculation,” and “automation.” In the SNA, which corresponds to relational analysis, “IoT” was identified as the most central node, indicating its semantic significance. Subsequently, TM analysis yielded eight distinct topics, including: “Although IoT and digital surveillance support inspection, ports still face challenges in preventing security breaches,” and “IoT and AI help reduce container accidents, but safety issues in ports still persist.” As an implication of the analysis, IoT emerged as a core academic focus for enhancing port safety management. In both the TF and semantic network analyses, “IoT” was identified as a key keyword. IoT refers to technologies or environments that enable real-time data exchange between objects via the internet. It can be applied to devices such as port mobile equipment location-sensing systems, wearable devices for workers (e.g., watches, helmets), and port accident risk detection and prediction systems. The location-sensing device for port mobile equipment enhances safe working environments by providing real-time location and status information. Wearable devices for workers improve safety by offering alerts on worker status, location, and surrounding hazards. The accident risk detection and prediction system collects real-time data through various sensors to detect and forecast signs of accidents, thereby improving port safety. Specifically, early collapse detection and alert services using IoT technology can help prevent safety incidents in disaster-prone facilities. Since April 2019, the Ministry of Oceans and Fisheries has conducted integrated testing of the IoT-based Intelligence Port Logistics Technology (IPLT) project at Busan Port BPT. According to the IPLT R&D plan (2017) by the Korea Institute of Marine Science & Technology Promotion, the introduction of a smart terminal operation system using IoT is expected to reduce port worker accidents by approximately 30%.

However, the application of IoT still faces several challenges. According to the major topics derived from TM, while IoT is effective in improving port safety, issues such as security breaches, high implementation costs, and limited battery life persist. Attaching sensors to various port equipment requires a substantial investment, which may exceed budget constraints. Wearable devices for workers have short battery lives and require prior consent for personal data usage to prevent security breaches. Additionally, port workers may resist the exposure of their location data through IoT, and conflicts with labor unions and budgetary concerns must be carefully considered. Nevertheless, as indicated by Topic 1, even with the introduction of new technologies, safety blind spots in ports are likely to persist.

5.2. Limitations and Future Research Directions

This study holds significance because it identifies research trends and key topics related to emerging technologies for port safety management from an academic perspective, within a growing consensus on the importance of port workers’ safety. However, the analysis was limited to research abstracts. Future studies should consider expanding the scope to include unstructured text sources such as news articles, reports, and policy documents. This broader approach is expected to provide a more holistic understanding of how emerging

technologies such as IoT, AI, and automation are being interpreted, adopted, and governed across both research and practice.

Also, topic extraction was conducted exclusively using the Latent Dirichlet Allocation (LDA) algorithm implemented in NetMiner 4.0. Alternative topic modeling techniques such as BERTopic or Non-negative Matrix Factorization (NMF) were not applied in order to maintain methodological consistency throughout the analytical framework. However, future research could extend the analysis by employing hybrid or transformer-based models to cross-validate topic stability and enhance the interpretive robustness of the results.

Additionally, this study did not conduct a temporal keyword trend analysis to examine how the prominence of technologies such as IoT and AI has evolved over time. Future research could extend this work by performing a longitudinal frequency analysis to identify chronological shifts in technological focus within port safety studies.

Lastly, the introduction of new technologies within ports—necessary for the sustainable advancement of eco-friendly and digital paradigms—requires substantial capital investment.

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