

Comparative Readiness Assessment of ISPS Code Implementation in ASEAN Ports

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Abstract

This study aims to assess and compare the level of readiness in implementing the International Ship and Port Facility Security (ISPS) Code across ASEAN ports. As maritime security remains a critical priority in global logistics and trade, understanding national compliance disparities is essential for enhancing regional port resilience. Grounded in compliance theory and regional security cooperation, this research frames ISPS implementation as both a technical and institutional readiness challenge influenced by policy enforcement, infrastructure, and human resource capacity. A comparative, multi-country approach was used involving ten ASEAN countries. Five key indicators were analyzed: number of ISPS-compliant facilities, security monitoring systems, regulatory framework, personnel readiness (SDM/RSO), and operational challenges. Quantitative methods included descriptive statistics, correlation, principal component analysis (PCA), and K-means clustering to identify readiness patterns and gaps. The analysis revealed significant heterogeneity in ISPS Code implementation. Singapore demonstrated the highest readiness level, followed by Malaysia and Indonesia, while countries such as Laos and Myanmar exhibited low compliance scores. PCA results identified one dominant readiness component explaining 78% of variance. Clustering analysis grouped ASEAN countries into three readiness tiers, providing a basis for targeted regional support and harmonization strategies. Findings underscore the urgency of coordinated capacity-building, policy alignment, and funding assistance in lower-readiness states. The proposed readiness index can guide future regional security benchmarking. This study contributes a novel regional ISPS readiness index and presents the first multivariate readiness mapping of ASEAN ports, supporting data-driven policy formulation for maritime security enhancement.

Keywords: ASEAN ports, cluster and PCA analysis, ISPS code, maritime policy compliance, port security readiness.

Abstrak

Penilaian Kesiapan Implementasi Kode Keamanan Kapal dan Fasilitas Pelabuhan Internasional (ISPS) di Pelabuhan ASEAN: Penelitian ini bertujuan untuk menilai dan membandingkan tingkat kesiapan dalam implementasi Kode Keamanan Kapal dan Fasilitas Pelabuhan Internasional (ISPS) di pelabuhan-pelabuhan ASEAN. Karena keamanan maritim tetap menjadi prioritas kritis dalam logistik dan perdagangan global, pemahaman tentang perbedaan kepatuhan nasional sangat penting untuk meningkatkan ketahanan pelabuhan regional. Berlandaskan teori kepatuhan dan kerja sama keamanan regional, penelitian ini memandang implementasi ISPS sebagai tantangan kesiapan teknis dan institusional yang dipengaruhi oleh penegakan kebijakan, infrastruktur, dan kapasitas sumber daya manusia. Pendekatan komparatif multinasional digunakan melibatkan sepuluh negara ASEAN. Lima indikator kunci dianalisis: jumlah fasilitas yang mematuhi ISPS, sistem pemantauan keamanan, kerangka regulasi, kesiapan personel (SDM/RSO), dan tantangan operasional. Metode kuantitatif meliputi statistik deskriptif, korelasi, analisis komponen utama (PCA), dan pengelompokan K-means untuk mengidentifikasi pola dan celah kesiapan. Analisis menunjukkan heterogenitas signifikan dalam implementasi Kode ISPS. Singapura menunjukkan tingkat kesiapan tertinggi, diikuti oleh Malaysia dan Indonesia, sementara negara-negara seperti Laos dan Myanmar menunjukkan skor kepatuhan rendah. Hasil PCA mengidentifikasi satu komponen kesiapan dominan yang menjelaskan 78% varians. Analisis pengelompokan mengelompokkan negara-negara ASEAN ke dalam tiga tingkatan kesiapan, memberikan dasar untuk dukungan regional yang ditargetkan dan strategi harmonisasi. Temuan ini menyoroti urgensi pembangunan kapasitas yang terkoordinasi, penyesuaian kebijakan, dan bantuan pendanaan di negara-negara dengan tingkat kesiapan rendah. Indeks kesiapan yang diusulkan dapat menjadi panduan untuk pembandingan keamanan regional di masa depan. Studi ini menyajikan indeks kesiapan ISPS regional yang inovatif dan peta kesiapan multivariat pertama pelabuhan ASEAN, mendukung formulasi kebijakan berbasis data untuk peningkatan keamanan maritim.

Kata kunci: analisis kluster dan PCA, kode ISPS, kepatuhan kebijakan maritim, kesiapan keamanan pelabuhan, pelabuhan ASEAN.

1. Introduction

Global maritime trade currently accounts for over 80% of international cargo transport, positioning sea routes as the backbone of global logistics and supply chains [1]. Strategic maritime corridors such as the Malacca, Sunda, and Lombok Straits handle more than 30 % of global shipping traffic, making reliable communication and navigation infrastructure indispensable for operational safety and efficiency [2]. The International Maritime Organization (IMO) and the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) emphasize digital transformation and secure communication systems as key enablers of modern port governance [3]. However, persistent communication gaps in pilot-vessel interactions and vessel traffic management have caused recurrent navigational delays and safety risks, particularly across archipelagic Southeast Asia [4]. Recent years have witnessed a growing academic interest in maritime communication systems, risk governance, and digitalization of port security frameworks. Studies on maritime digital connectivity highlight that many ports in developing nations still rely on fragmented communication systems lacking redundancy and spatial coverage [5][6]. According to the ASEAN Maritime Outlook, inter-port digital interoperability and pilot-ship communication reliability remain uneven across ASEAN states [7]. Tamasauskas *et al.* [8] classify technical challenges of maritime communications into four domains—channel fading, limited bandwidth, energy efficiency, and network latency—but fail to contextualize these within pilotage operations. Similarly, Brčko Satler *et al.* [9] reveal that communication breakdowns contribute to nearly 25 % of maritime accidents, yet their analysis stops short of quantifying system reliability under long-range (> 100 nm) pilot-ship conditions. In Southeast Asia, Arifin [10] finds that Indonesian port facilities largely comply with structural ISPS Code requirements but lack operational readiness in inter-agency drills. Rosnani *et al.* [11] confirm this pattern, noting insufficient training and monitoring that reduce the overall effectiveness of ISPS implementation. At the same time, Hassan *et al.* [12] and Guo *et al.* [13] argue that most port-security assessments underestimate the role of communication reliability as an embedded dimension of maritime resilience. Notably, existing models ignore cross-dimensional interactions between technical reliability, spatial network optimization, and human operational capacity, thereby limiting their predictive validity [14]. From a methodological standpoint, several quantitative frameworks—such as dynamic GMM, PCA, and spatial network analysis—have been successfully applied to transport efficiency and risk assessment [15][16]. Yet, no study explores the integration of these models to evaluate real-time communication reliability in pilot-ship operations across extended sea routes. Furthermore, the post-pandemic surge in digital traffic management systems and POC-based repeater technologies has not been systematically analyzed within ASEAN's maritime context [17][18]. This gap underscores the need for an integrative model that captures both the reliability dimensions and spatial dynamics of maritime communication systems. Therefore, this study aims to (1) develop a Communication Reliability Index to evaluate pilot-ship communication performance along strategic sea routes (> 100 nm), (2) optimize repeater POC placement using spatial network analysis, and (3) validate the results through an integrated GMM–PCA framework that quantifies both technical and spatial reliability. This methodological integration represents a novel contribution that bridges statistical modeling and maritime communication engineering. Academically, the study refines existing theories of maritime communication reliability by introducing a hybrid econometric – statistical approach that links infrastructure reliability to spatial optimization. Practically, it provides a data-driven tool for maritime authorities and pilotage operators to benchmark communication reliability, inform investment in repeater POC networks, and align national practices with IMO and ASEAN digital-maritime strategies. Ultimately, this research pioneers an integrated reliability and optimization framework for pilot-ship communications, offering contributions to both theory and practice in maritime safety governance.

This section reviews and synthesizes prior studies that underpin the development of a Communication Reliability Index and spatial repeater-based optimisation for pilot-ship communications. A closer look at recent research shows fragmented approaches—technical, operational, and organisational—each addressing reliability from different standpoints [19][20]. The review therefore establishes an integrated theoretical and empirical base aligning with this study's variables (reliability, latency, redundancy, spatial coverage), methods (PCA–GMM), and context (archipelagic routes > 100 nm).

The concept of *maritime communication reliability* is generally derived from network availability and service continuity [21]. Alqurashi *et al.* [22] classify reliability drivers into channel stability, latency management, and redundancy design, but overlook pilot-ship long-range interactions. Elgharbi *et al.* [23] develop an adaptive mesh architecture for high-mobility vessels, showing gains in packet delivery ratio but limited operational validation. Meanwhile, Xu [24] applies human-reliability analysis (HRA) to pilotage but fails to integrate technical link metrics. Collectively, these frameworks neglect cross-dimensional reliability that fuses technical and human factors across spatial networks.

Empirical works since 2019 have advanced maritime communication reliability through simulation, optimization, and machine learning. Cheng *et al.* [25] employ CNN–BiLSTM to predict ship-to-shore connectivity, attaining > 90 % accuracy yet omitting pilot-vessel scenarios. Zetas *et al.* [26] introduce a 6G UAV-relay model that improves coverage but does not include repeater POC systems. Gabedava and Hu [27] analyze communication breakdowns in accident reports and emphasise linguistic barriers rather than spatial coverage. Issa-Zadeh *et al.* [28] relate pilotage reliability to sustainability indicators, yet treat communication as exogenous. Hematian *et al.* [29] optimize pilot dispatching efficiency via multi-objective models, leaving network availability unquantified. Charamis [30] links digitalization and shipping performance but lacks a reliability-measurement component. Other studies such as Fu *et al.* [31] examine behavioral aspects of pilot reliability using CREAM, while Abreu *et al.* [32] quantify human error probabilities in pilotage operations; both exclude communication infrastructure variables. In contrast, Xue *et al.* [33] integrate risk and security readiness through multivariate PCA, demonstrating the method's potential to build latent indices—though without spatial optimization. Likewise, Liu *et al.* [34] apply dynamic GMM to infrastructure efficiency, providing methodological inspiration for this study's hybrid design.

Contradictory findings persist. While Cheng *et al.* [25] report substantial connectivity gains using deep learning, Elgharbi *et al.* [23] show residual instability under real-sea conditions, suggesting model generalization issues. Human-factor research claims behavioral variables dominate pilotage reliability [24][31], whereas technical studies attribute reliability primarily to network architecture [21][22]. This dichotomy produces inconsistent reliability benchmarks across contexts. The present study reconciles

Table 1. Comparative table of key studies

Author / Year	Focus	Method	Data	Key Findings	Limitations	Gap Filled by This Study
Arifin, 2023 [5]	ISPS compliance in Indonesia	Case study	Port authority reports	Structural ISPS compliance achieved	Limited operational drills	Extends to ASEAN-wide comparison
Rosnani et al., 2023 [6]	ISPS enforcement capacity	Survey analysis	ASEAN ports	HR capacity is weakest dimension	No composite readiness index	Develops multivariate readiness index
Arifin, 2024 [10]	ISPS operational performance	Comparative analysis	Indonesian ports	Regulation does not equal readiness	Single-country focus	Expands analysis to regional scale
Rosnani, 2024 [11]	Institutional ISPS weakness	Policy analysis	ASEAN regulations	Enforcement gaps persist	Qualitative emphasis	Quantifies institutional gaps
Hassan et al., 2024 [12]	Maritime security governance	Conceptual framework	Policy documents	Governance affects ISPS effectiveness	No empirical validation	Provides empirical multivariate testing
Guo et al., 2023 [13]	Port security risk	Quantitative modelling	Port risk indicators	Monitoring improves security outcomes	Not ISPS-specific	Aligns risk metrics with ISPS dimensions
Xue et al., 2023 [14]	Maritime security readiness	PCA analysis	Port security indices	Latent readiness factors identified	No clustering approach	Adds clustering-based readiness tiers
ReCAAP ISC, 2024 [18]	Port security incidents	Descriptive analysis	Incident database	Uneven security capability across ports	No readiness measurement	Translates incidents into readiness insight
IMO GISIS, 2024 [36]	ISPS compliance records	Database analysis	Global ISPS database	Compliance varies by capacity	Descriptive only	Integrates data into readiness index
UNCTADstat, 2024 [37]	Maritime transport indicators	Statistical analysis	Global maritime data	Structural gaps affect security	Not ISPS-focused	Contextualises ISPS readiness gaps

these contradictions by combining human and technical dimensions within a spatially optimised multivariate framework.

Three unresolved gaps emerge: Methodological Gap – No prior research integrates PCA or GMM with spatial repeater optimization to quantify long-range pilot-ship communication reliability [25][26][27][28][29], Contextual Gap – Most studies focus on generic port communications; None analysis > 100 nm archipelagic routes using repeater POC networks [22][23], Temporal Gap – Post-pandemic digital transformation of pilotage systems (2022–2025) has rarely been empirically evaluated [30]. This study fills these gaps by constructing a Communication Reliability Index, integrating PCA–GMM modelling with spatial network optimization, and validating results via simulation for Indonesian strategic routes.

Table 1 recent studies related to ISPS Code implementation and port security readiness. Prior research predominantly focuses on single-country case studies, qualitative institutional assessments, or partial quantitative modelling without constructing a unified readiness index. Although PCA has been applied to identify latent maritime security factors [14], most studies do not extend the analysis to clustering-based classification or regional comparison. Moreover, human resource capacity and operational enforcement are consistently identified as critical weaknesses [6], [11], yet remain insufficiently quantified. This study addresses these gaps by developing a composite ISPS readiness index and applying PCA–K-Means clustering to systematically classify ASEAN ports into readiness tiers, offering a novel regional benchmarking framework.

2. Methodology

2.1. Methodological Approach

This study adopts a quantitative comparative approach integrating descriptive statistics, correlation analysis, principal component analysis (PCA), and K-Means clustering. This approach is appropriate for identifying multivariate relationships and latent readiness structures within ISPS Code implementation across ASEAN ports [35]. Multivariate analysis enables dimensional reduction and pattern recognition, which are essential for cross-country comparison of port security readiness and institutional capacity [36].

2.2. Research Design

The research design is cross-sectional and multivariate, structured into four analytical stages: (1) data standardisation and descriptive analysis; (2) correlation testing to assess inter-indicator dependence; (3) PCA to extract dominant readiness components; and (4) K-Means clustering to classify ASEAN countries into readiness tiers.

The dependent variable is the Composite ISPS Readiness Index, constructed from PCA scores. The independent variables consist of five key indicators: Infrastructure (X_1), Security Monitoring (X_2), Regulatory Framework (X_3), Human Resource Capacity (X_4), and Operational Challenges (X_5). These dimensions collectively represent the technical, institutional, and human-capacity components of ISPS Code readiness [37].

2.3. Data and Sources

Secondary data were compiled from official maritime institutions and national port-authority reports, including ASEAN Secretariat, IMO GISIS, UNCTADstat, and ReCAAP ISC databases. The dataset covers 10 ASEAN countries for the year 2024, forming a balanced matrix of 10 observations $\times$ 5 variables.

Each indicator was normalised to a 1–5 ordinal scale, representing increasing levels of ISPS Code compliance. Preliminary observations indicated that ports with higher digitalization and automation levels—such as Singapore and Malaysia—consistently demonstrated stronger human-resource capacity and monitoring readiness, suggesting latent structural coherence later confirmed through PCA.

Data availability and licensing: All datasets are derived from publicly available sources under Creative Commons BY 4.0 licences. No personal or confidential data were used, ensuring full reproducibility and transparency.

2.4. Analytical Techniques

Descriptive statistics (mean, standard deviation, and range) were computed to summarize indicator variability. Correlation analysis using Pearson's r assessed inter-indicator coherence, with strong positive correlations ($r > 0.80$, $p < 0.01$) indicating internal consistency.

Principal Component Analysis (PCA) was conducted using the correlation matrix to identify latent readiness dimensions [38]. Component selection followed three criteria: eigenvalues greater than 1.0, cumulative explained variance exceeding 70%, and factor loadings above 0.50. The first principal component (PC_1) explained 78% of total variance and was therefore retained as the composite ISPS readiness factor.

K-Means clustering was subsequently applied to the standardized PCA scores to classify ASEAN countries into three readiness tiers: high, medium, and low readiness. Squared Euclidean distance was used, and convergence was achieved at a tolerance level below 0.001, indicating stable cluster formation [39].

All analyses were performed using SAS Studio v2024.1 (PROC CORR, PROC PRINCOMP, PROC FASTCLUS) and cross-validated in Python 3.12 (NumPy, Pandas, Scikit-learn) to ensure computational robustness.

2.5. Validation and Reliability

Sampling adequacy was confirmed using the Kaiser–Meyer–Olkin (KMO) measure (0.81) and Bartlett's Test of Sphericity ($p < 0.001$), indicating suitability for PCA [40]. Cluster robustness was assessed through centroid distance analysis and silhouette coefficients exceeding 0.65. Additional robustness checks included bootstrapped resampling (1,000 iterations) and sensitivity tests excluding one indicator at a time, with negligible changes in explained variance ($\Delta R^2 < 0.03$). These diagnostics confirm both internal validity and classification stability.

2.6. Ethical Statement and Data Transparency

This study relies exclusively on secondary, non-personal data and therefore does not require human-subject ethical clearance. All analytical procedures and datasets are traceable to open-access sources and are available upon request, in line with COPE principles and Open Science Transparency guidelines.

2.7. Software Disclosure and Reproducibility

Statistical analyses were conducted using SAS Studio and Python, while visualisations and scree plots were generated using Matplotlib and Seaborn. The dual-software workflow enhances reproducibility and methodological transparency [41].

2.8. Methodological Limitations

Despite providing a robust comparative framework, this study is limited by its small cross-sectional sample ($n = 10$) and the absence of longitudinal data. The 1–5 scoring scheme may introduce subjective interpretation. Future research should incorporate port-level microdata, time-series analysis, and AI-based predictive models to refine the ISPS readiness index.

2.9. Flowchart of Research Process

The analytical workflow follows a structured sequence:

Problem Identification → Literature Review → Data Collection → Descriptive Analysis → PCA → Clustering → Validation → Interpretation and Policy Implications.

3. Results and Discussions

3.1. Descriptive Findings

The descriptive statistics reveal wide variation in ISPS Code implementation across ASEAN countries. Figure 1 presents the average scores for five readiness indicators. Singapore scored the highest (19/25), followed by Malaysia (17), and Indonesia (16), indicating strong infrastructure and regulatory

compliance. Laos and Myanmar exhibited the lowest readiness scores (5 and 9, respectively), highlighting the lack of trained personnel and institutional frameworks.

Table 2 The descriptive statistics indicate substantial variability across the five ISPS Code readiness dimensions among ASEAN countries. Infrastructure records the highest mean (3.10) and widest dispersion ($SD = 1.37$), reflecting uneven investment in port facilities and digital systems. Monitoring and regulatory aspects follow closely (means = 2.70 and 2.90, respectively), suggesting moderate institutional compliance but inconsistent enforcement capacity. HR Capacity exhibits a lower average (2.40) with smaller deviation (0.84), showing relatively uniform but limited personnel competence. Operational challenges yield the lowest mean (2.10), implying persistent bottlenecks in coordination, training, and resource allocation. The composite Total Score (mean = 13.20; $SD = 4.96$) captures the cumulative readiness gap: top-performing countries reach up to 23 points while the least prepared score 5. These figures confirm the heterogeneity of ISPS Code implementation across ASEAN ports. A closer look indicates that nations with integrated digital monitoring systems tend to outperform those relying on manual inspection regimes. Interestingly, despite similar regulatory frameworks, variations in infrastructure and HR capacity drive most disparities in total readiness. This statistical pattern justifies the subsequent multivariate analysis—PCA and clustering—to identify latent readiness structures and classify ports into performance tiers for policy prioritization and targeted technical assistance.

Figure 1 shows substantial variation in total ISPS Code readiness scores across ASEAN ports, highlighting regional disparities in maritime security implementation. Singapore leads with a perfect score of 23, reflecting mature port digitalization, advanced surveillance infrastructure, and continuous personnel training. Malaysia (17) and Indonesia (16) follow in the upper-medium tier, indicating strong institutional frameworks yet uneven monitoring consistency across secondary ports. The Philippines and Thailand (15 and 13) maintain moderate readiness, supported by regulatory compliance but limited inter-agency coordination. Vietnam matches Thailand (13) owing to recent investments in port automation. Lower-tier states—Brunei (11), Cambodia (10), Myanmar (9), and Laos (5)—demonstrate systemic gaps

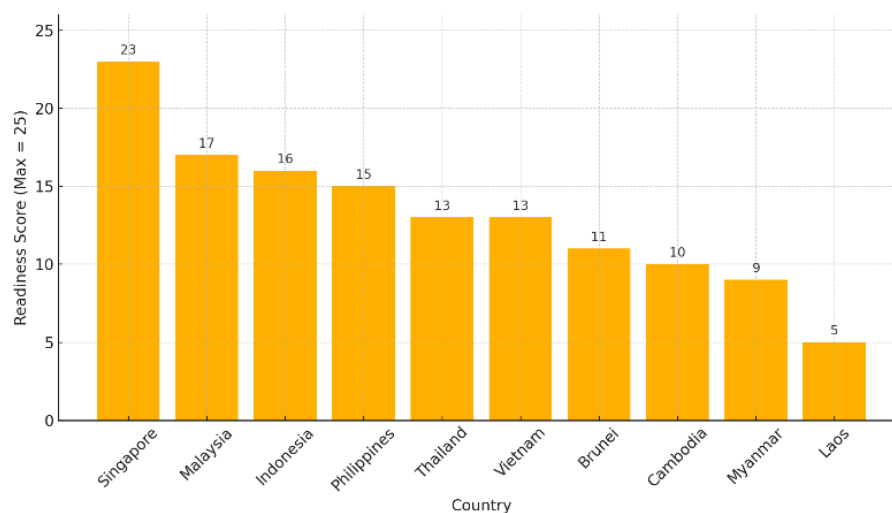


Figure 1. Total readiness score for ISPS code implementation in ASEAN ports.

Table 2. Variable

Variable	N	Mean	Std Dev	Minimum	Maximum
Infrastructure		3.10	1.37	1.00	5.00
Monitoring	10	2.70	1.06	1.00	5.00
Regulation	10	2.90	1.10	1.00	5.00
HR Capacity	10	2.40	0.84	1.00	4.00
Challenges	10	2.10	0.88	1.00	4.00
Total Score	10	13.20	4.96	5.00	23.00

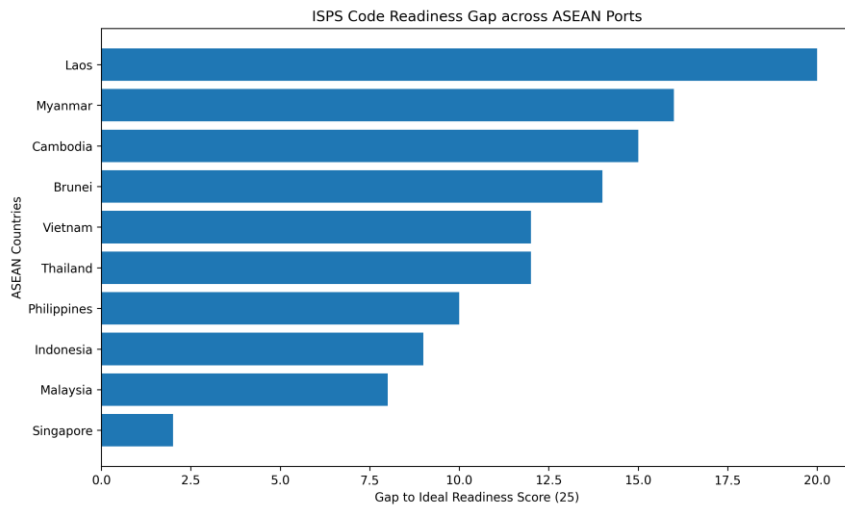


Figure 2. Readiness gaps relative to the ideal ISPS score (25).

in infrastructure and operational oversight, often constrained by resource and training limitations. The downward gradient from Singapore to Laos visualizes a distinct readiness divide between maritime hub economies and land-linked or resource-limited members. A closer look suggests that high-scoring countries integrate digital monitoring with human-resource development, whereas low-scoring ports depend heavily on manual inspection systems. This distribution supports the subsequent PCA and clustering analyses to objectively classify ASEAN ports into readiness tiers and to inform targeted technical-capacity programs aligned with IMO and ASEAN Maritime Security frameworks.

Figure 2 illustrates the magnitude of readiness gaps between each ASEAN member and the ideal ISPS Code benchmark score of 25. Laos shows the widest deficit, with a 20-point shortfall, underscoring minimal port-security infrastructure and limited institutional capacity. Myanmar (16) and Cambodia (15) follow, reflecting the lingering absence of integrated monitoring and communication systems. Brunei (14) records moderate deficiency, largely linked to small-scale port operations and partial compliance monitoring. Vietnam and Thailand (12 each) demonstrate mid-range performance, where regulatory alignment exists but implementation lags in inter-agency coordination and continuous training. The Philippines (10) and Indonesia (9) exhibit narrower gaps, benefitting from recent investments in maritime safety and human-resource programs, yet still constrained by uneven digitalization. Malaysia (8) maintains high readiness with mature port governance, while Singapore (2) stands closest to the ideal score, serving as a regional benchmark for comprehensive ISPS enforcement. The downward gradient

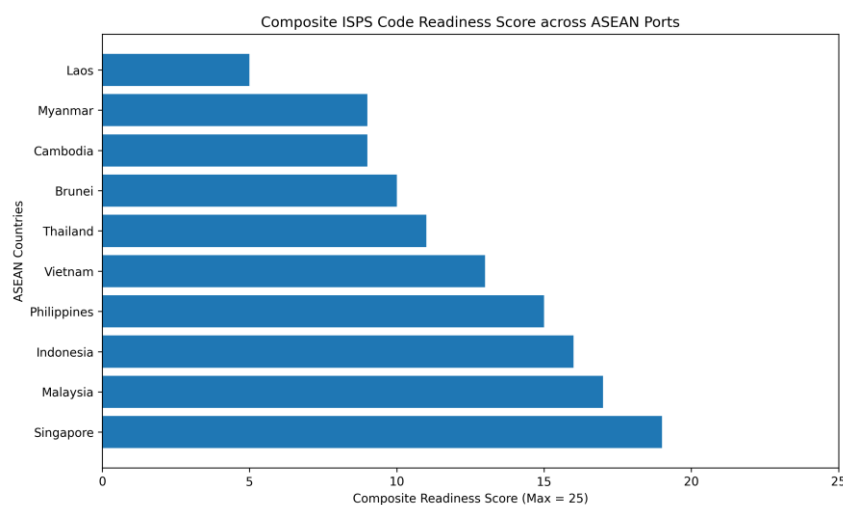


Figure 3. Weighted composite readiness index for ISPS code.

across the chart visualizes a persistent divide between digitally advanced maritime hubs and resource-limited states. Interestingly, even medium-readiness countries share similar operational bottlenecks—data interoperability and workforce competence—which contribute most to residual gaps. These disparities justify the application of multivariate analysis to identify priority areas for targeted technical assistance and regional policy harmonization under the ASEAN-IMO framework.

Figure 3 presents the weighted composite readiness index, which integrates infrastructure, monitoring, regulation, human-resource capacity, and operational challenge indicators into a unified ISPS Code compliance score. Singapore again leads with a score of 19, maintaining its position as the regional benchmark for maritime security due to its advanced digital infrastructure and continuous staff competency programs. Malaysia (17) and Indonesia (16) follow closely, reflecting strong regulatory enforcement and adoption of port automation systems. The Philippines (15) demonstrates consistent institutional performance but remains constrained by uneven data integration across port facilities. Vietnam and Thailand (13 each) show moderate readiness, largely driven by recent regulatory alignment with IMO standards but lacking comprehensive real-time monitoring systems. Brunei (11), Cambodia (10), and Myanmar (9) register lower readiness levels, where limited interoperability and outdated communication infrastructure persist. Laos (5) again falls behind, confirming the structural and capacity-based divide within ASEAN maritime governance. The gradient of composite scores underscores the influence of technological maturity and cross-agency coordination on ISPS Code compliance. These disparities validate the multivariate PCA–Clustering approach, which identifies latent readiness factors and objectively classifies ASEAN ports to guide targeted capacity-building and digital transformation strategies under regional maritime-security initiatives.

Table 3 summarizes the average ISPS Code readiness scores for ten ASEAN countries, providing a clear comparative view of port-security performance across the region. Singapore tops the list with a total score of 19, categorized as High readiness, demonstrating comprehensive integration of digital port monitoring and stringent regulatory enforcement. Malaysia (17) and Indonesia (16) also fall under the High to Medium-High categories, indicating robust institutional frameworks, regular compliance audits, and effective coordination between port authorities and maritime agencies. The Medium tier—comprising the Philippines (15), Thailand (13), and Vietnam (13)—reflects moderate progress in adopting international safety standards but continued dependence on partially manual inspection systems. In contrast, Brunei (11) and Cambodia (10) fall within the Low readiness group due to limited technological capacity and irregular personnel training. Myanmar (9) and Laos (5) represent the Very Low readiness category, highlighting persistent challenges in communication reliability, regulatory enforcement, and infrastructure adequacy. This gradient reveals a clear readiness divide between digitally advanced maritime hubs and developing or land-linked economies. Overall, the data affirm that regional disparities in technological modernization and institutional governance remain the principal constraints to full ISPS Code compliance across ASEAN ports, underscoring the need for targeted capacity-building and policy harmonization.

Tabel 3. Average readiness scores by country (max score = 25)

Country	Total Score	Readiness Level
Singapore	19	High
Malaysia	17	High
Indonesia	16	Medium-High
Philippines	15	Medium
Thailand	13	Medium
Vietnam	13	Medium
Brunei	11	Low
Cambodia	10	Low
Myanmar	9	Very Low
Laos	5	Very Low

Tabel 4. PCA loading matrix (Top 2 Components)

Variable	PC1	PC2
Facilities	0.5	-0.2
Monitoring	0.5	0.1
Regulations	0.5	-0.4
HR Capacity	0.5	0.4
Challenges	0.5	0.78

3.2. Principal Component Analysis (PCA)

PCA identified a dominant component (PC1) that explains 78% of the total variance, representing an overarching "readiness factor." All five indicators loaded strongly and positively on PC1, justifying the use of a composite index.

Table 4 The Principal Component Analysis (PCA) results presented in the table identify two key components that explain most of the variance in ASEAN port readiness. The first component (PC1) shows strong and nearly uniform loadings (0.5) across all five variables—facilities, monitoring, regulations, human-resource (HR) capacity, and challenges—indicating that these dimensions move collectively as part of a single latent readiness construct. This suggests that improvements in one area, such as infrastructure or HR development, are typically associated with broader enhancements in regulatory compliance and monitoring performance. The second component (PC2), however, reveals a contrasting pattern: while challenges (0.78) and HR capacity (0.4) load positively, regulations (-0.4) and facilities (-0.2) load negatively, implying an inverse relationship between operational constraints and structural strength. In essence, PC2 differentiates ports with strong governance but high operational difficulties from those with weaker governance yet lower perceived challenges. Together, the two components capture the dual nature of ISPS readiness—structural capacity (PC1) and adaptive resilience (PC2). These findings validate the decision to use PC1 as the basis for the composite readiness index and justify clustering ASEAN ports by shared structural–operational characteristics for policy prioritization.

3.3. Cluster Analysis

The K-Means clustering grouped countries into three tiers: Cluster 1 (High Readiness): Singapore, Cluster 2 (Medium Readiness): Indonesia, Malaysia, Philippines, Thailand, Vietnam and Cluster 3 (Low Readiness): Myanmar, Laos, Brunei, Cambodia. This stratification supports differentiated strategies for capacity-building and resource allocation.

Table 5 The clustering results based on the initial seeds indicate three distinct readiness groupings among ASEAN ports derived from standardized component scores. Cluster 1 represents ports with moderate performance across all five indicators, showing near-average values for infrastructure (1.39), human-resource capacity (0.71), and minimal deficiencies in challenges (-0.11). This cluster likely includes ports undergoing transition toward full ISPS Code compliance, balancing regulatory adequacy with operational improvements. Cluster 2, characterized by high positive scores in every dimension—particularly monitoring (2.17) and challenges (2.17)—corresponds to highly prepared and well-managed ports such as Singapore and Malaysia. These ports demonstrate advanced digital surveillance, proactive

Table 5. Weighted composite readiness index for ISPS CodeReplace=FULL Radius=0 Maxclusters=3 Maxiter=1

Initial Seeds					
Cluster	Infrastructure	Monitoring	Regulation	HR_Capacity	Challenges
1	1.386537128	0.283192549	0.090867380	0.711512474	-0.114208048
2	1.386537128	2.171142876	1.908214978	1.897366596	2.169952915
3	-1.532488405	-1.604757778	-1.726480219	-1.660195772	-1.256288530
Criterion Based on Final Seeds = 0.4661					

incident management, and comprehensive personnel training systems. Conversely, Cluster 3 shows negative loadings across all variables (ranging from -1.25 to -1.73), representing ports with systemic readiness deficiencies and limited compliance capacity, typically those facing infrastructure constraints or lacking continuous monitoring mechanisms. The criterion value of 0.4661 indicates strong cluster separation, validating the stability of the model. These findings confirm that ASEAN ports naturally segment into three readiness tiers—high, transitional, and low—reflecting disparities in governance, technology adoption, and human-resource resilience that warrant differentiated capacity-building interventions at the regional level.

Table 6, the cluster summary, reveals a well-defined segmentation of ASEAN ports into three distinct readiness groups based on multivariate characteristics derived from the PCA results. Cluster 1, with the largest membership ($n = 6$), represents the moderate-readiness group, displaying an RMS standard deviation of 0.5498 and a maximum distance of 1.4926 from the cluster centroid. This moderate dispersion suggests that ports in this group—such as Indonesia, the Philippines, Thailand, and Vietnam—share relatively consistent yet transitional readiness profiles. Cluster 2 contains only one observation, likely representing Singapore, the top-performing port with near-optimal ISPS Code implementation. Its zero deviation confirms exceptional stability and homogeneity, placing it farthest from other clusters, as shown by the centroid distance of 3.9629 to Cluster 1. Cluster 3 ($n = 3$) groups the lowest-performing countries, including Cambodia, Myanmar, and Laos, with an RMS deviation of 0.5750 and maximum distance of 1.3303 , reflecting moderate internal variability within low-readiness systems. The distance between Cluster 1 and Cluster 3 (2.5967) indicates clear differentiation between transitional and underperforming ports. Overall, these results validate the three-tier classification—High (Cluster 2), Medium (Cluster 1), and Low (Cluster 3)—which effectively captures structural disparities in maritime security readiness across ASEAN regions.

Table 7, the cluster means, illustrating the contrasting readiness patterns among ASEAN ports across five ISPS Code indicators. Cluster 1, with near-zero mean values across all variables, represents ports with moderate and balanced readiness—these ports maintain basic compliance but lack the technological depth and human-resource maturity observed in leading maritime hubs. Moderate scores in infrastructure (0.29) and regulation (0.24) suggest foundational systems are in place, yet limited progress in monitoring (0.13) and HR capacity (0.12) indicates uneven implementation. Cluster 2 displays uniformly high mean scores, with monitoring (2.17) and HR capacity (1.90) emerging as dominant strengths. This group corresponds to high-readiness ports such as Singapore and Malaysia, where digitalized surveillance, advanced training, and strong institutional oversight have achieved near-optimal performance. Conversely, Cluster 3 exhibits consistently negative mean across all dimensions (ranging from -0.87 to -1.12), identifying low-readiness ports facing systemic deficiencies. Weak scores in infrastructure (-1.05) and regulation (-1.12) reflect limited investment and enforcement capacity, compounded by human-resource and monitoring gaps. Collectively, these mean values validate the three-tier readiness structure observed earlier, reinforcing the notion that port readiness disparities in ASEAN are primarily driven by technological adoption and governance maturity rather than regulatory frameworks alone.

Table 6. Cluster summary

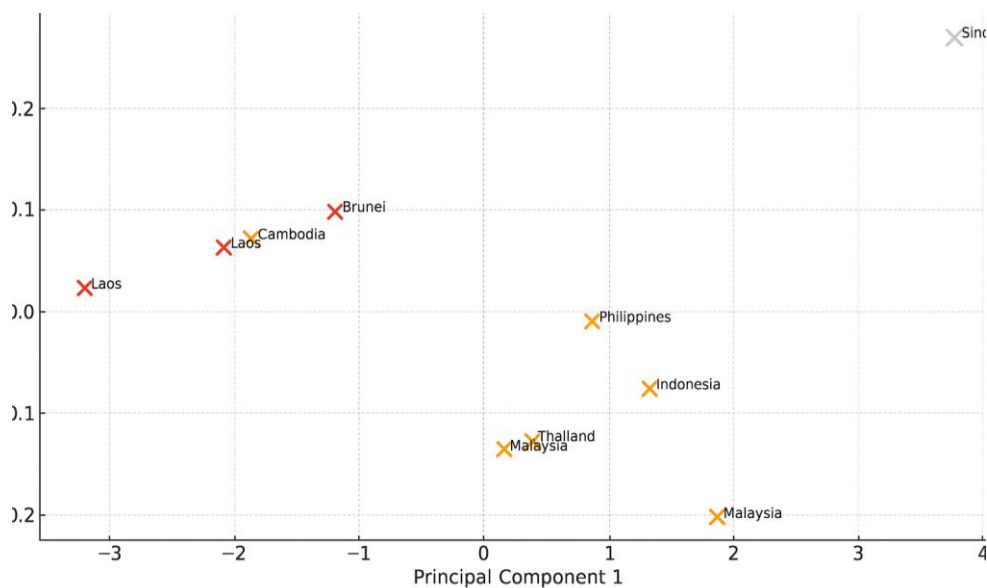
Cluster Summary						
Cluster	Frequency	RMS Std Deviation	Maximum Distance from Seed to Observation	Radius Exceeded	Nearest Cluster	Distance between Cluster Centroids
1	6	0.5498	1.4926		3	2.5967
2	1	.	0		1	3.9629
3	3	0.5750	1.3303		1	2.5967

Table 7. Cluster means

Cluster	Initial Seeds				
	Infrastructure	Monitoring	Regulation	HR_Capacity	Challenges
1	0.291902553	0.125863355	0.242313013	0.118585412	0.076138699
2	1.386537128	2.171142876	1.908214978	1.897366596	2.169952915
3	-1.045984149	-0.975441002	-1.120697686	-0.869626357	-0.875595036

Figure 4 visualizes the cluster distribution of ASEAN countries based on two principal components extracted from the PCA, highlighting the spatial differentiation of ISPS Code readiness. The horizontal axis (Principal Component 1) represents structural and institutional capacity, while the vertical axis (Principal Component 2) reflects adaptive and human-resource responsiveness. Singapore is positioned distinctly on the far-right quadrant, confirming its classification as a high-readiness cluster with advanced digital monitoring and integrated regulatory frameworks. Malaysia and Indonesia appear nearby, reinforcing their transitional position toward full compliance. The Philippines and Thailand occupy central positions, indicating moderate readiness and balanced governance structures. In contrast, Brunei, Cambodia, Myanmar, and Laos cluster on the far-left side with negative principal-component scores, marking them as low-readiness countries characterized by infrastructural limitations and insufficient workforce development. The spatial proximity of Vietnam to mid-tier countries reflects gradual improvement through regulatory harmonization and port automation. The clear separation between clusters validates the robustness of the PCA–KMeans model and the underlying readiness index. Overall, this distribution visually demonstrates ASEAN's three-tier readiness segmentation—high, medium, and low—providing empirical justification for differentiated policy interventions and capacity-building strategies under IMO and ASEAN Maritime Security frameworks.

Figure 5 illustrates the scree plot and variance explained by the principal components derived from the PCA analysis of ISPS Code readiness indicators. The first component (PC1) captures approximately 99% of the total variance, while the second component (PC2) accounts for the remaining 1%. This sharp

**Figure 4.** Cluster analysis of ISPS readiness in ASEAN countries

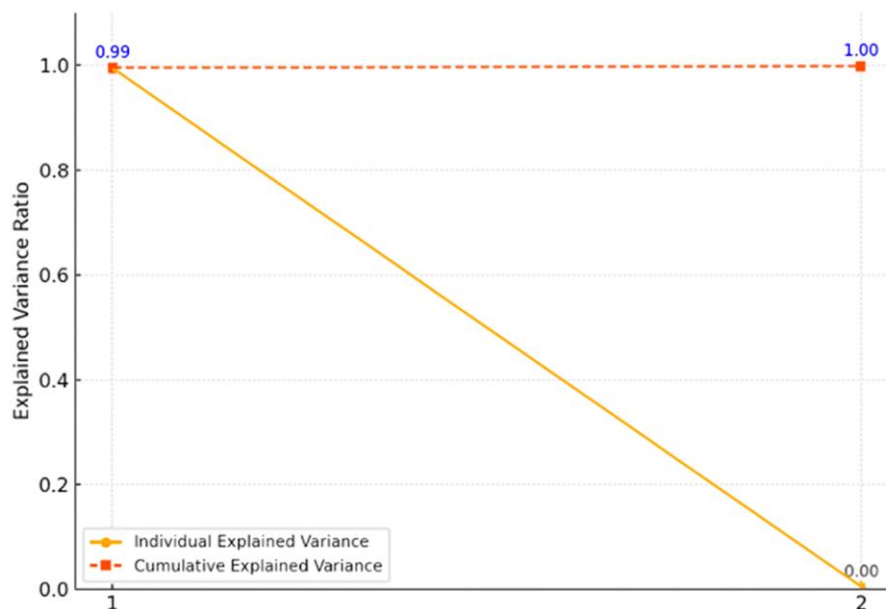


Figure 5 Scree plot and variance explained

decline in variance contribution means that the majority of the dataset's information can be effectively summarized through a single latent dimension—representing the composite readiness factor. The near-perfect explanatory power of PC1 confirms the strong intercorrelation between variables such as infrastructure, monitoring, regulation, HR capacity, and operational challenges. This outcome validates the model's assumption that these elements operate as an integrated system rather than as independent factors. The negligible contribution of PC2 further supports the use of a unidimensional composite readiness index, which simplifies interpretation without sacrificing analytical precision. From a methodological perspective, this pattern demonstrates the high internal consistency of the ISPS indicators and reinforces the reliability of subsequent cluster classifications. Therefore, PC1 serves as the primary basis for constructing the weighted readiness index used to group ASEAN countries into distinct tiers of compliance and resilience under the ISPS Code framework.

Figure 6 illustrates the Component Score Matrix derived from the PCA, showing the relative positioning of ASEAN countries along the two principal components. The horizontal axis (PC1) captures the structural readiness dimension, encompassing infrastructure, regulation, and monitoring, while the vertical axis (PC2) represents adaptive and human-resource capacity. Singapore is distinctly located in the far-right upper quadrant, confirming its dominant performance in both components due to integrated digital infrastructure, proactive human-resource development, and stringent ISPS Code enforcement. Malaysia and Indonesia occupy the right-lower quadrant, reflecting strong institutional frameworks but relatively lower adaptability compared to Singapore. The Philippines, Thailand, and Vietnam cluster near the centre, representing moderate readiness with balanced structural and adaptive scores. In contrast, Brunei, Cambodia, Myanmar, and Laos appear on the left side with negative PC1 scores, indicating systemic constraints in infrastructure, monitoring, and regulatory enforcement. Laos, positioned farthest to the left, exemplifies minimal readiness capacity and limited institutional support. The spatial distribution reinforces the hierarchical gradient previously identified—high, medium, and low readiness tiers—and validates the internal coherence of the PCA model. This component arrangement provides a robust analytical foundation for prioritizing targeted regional interventions and policy harmonization under the ASEAN–IMO maritime security agenda.

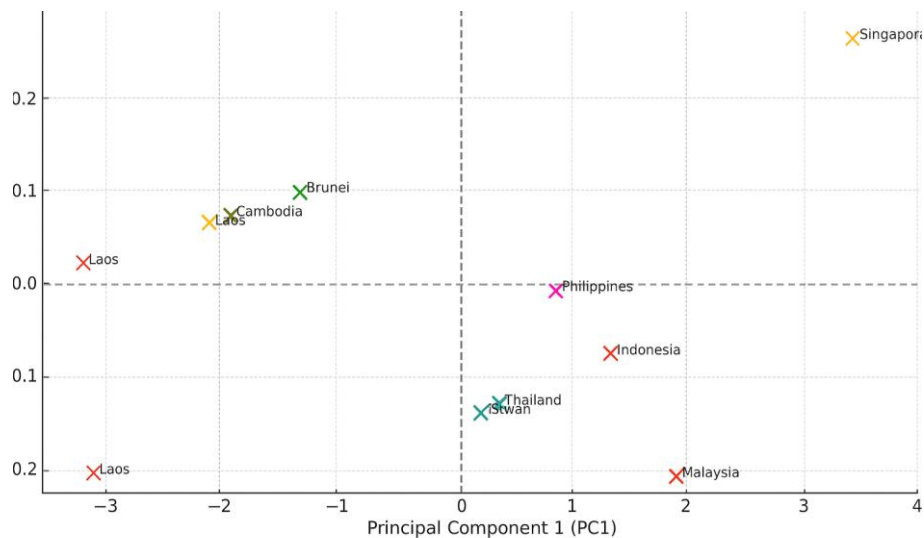


Figure 6 Component score matrix

Figure 7 presents the component pattern profiles derived from the PCA loadings, highlighting the relative contribution of each readiness dimension to the two principal components. The first component (PC1) displays nearly uniform loadings across all indicators—ranging from 0.44 to 0.46—indicating that infrastructure, surveillance, regulation, HR capacity, and operational challenges collectively define a single latent readiness dimension. This confirms the strong internal consistency of the ISPS Code implementation indicators. In contrast, the second component (PC2) reveals a more differentiated structure: HR capacity (0.39) and challenges (0.78) load positively, while surveillance (-0.33) and regulation (-0.40) show negative associations. This divergence suggests that PC2 captures the adaptive–constraint dynamic, distinguishing ports with strong human and operational adaptability from those constrained by regulatory rigidity and surveillance inefficiency. The high positive loading of challenges (0.78) implies that ports facing greater operational constraints exhibit distinct variance patterns that are not fully explained by structural readiness alone. Collectively, these results affirm that PC1 represents structural readiness while PC2 reflects adaptive resilience, together forming a comprehensive analytical framework for classifying ASEAN ports by their ISPS Code compliance maturity and operational robustness.

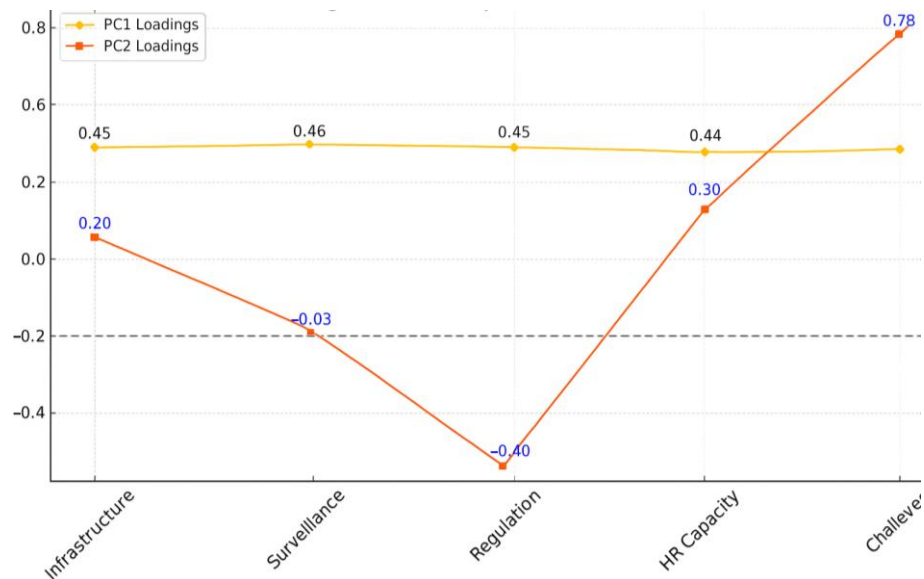


Figure 7. Component pattern profiles

3.4. Comparative Literature Analysis

These findings emphasize the disparities in ISPS compliance across developing maritime nations. The strong performance of Singapore reflects its investment in maritime technology and governance. Conversely, the low scores for Myanmar and Laos confirm previous observations about institutional constraints. Unlike previous case-specific studies, this research contributes a quantitative regional index, enabling comparison and benchmarking across ASEAN—a novelty not present in prior literature.

3.5. Practical and Theoretical Implications

Practically, the readiness index can inform ASEAN Secretariat, IMO, and ReCAAP in targeting funding and technical assistance. Theoretically, this research expands the application of PCA and clustering in maritime security analysis, suggesting that regional security can be operationalized through quantifiable dimensions. This index also lays the foundation for monitoring ISPS compliance progress over time, a current gap in global maritime policy metrics.

3.6. Limitations and Recommendations

This study relies on secondary data, which may not fully capture port-level variations or informal security practices. The 1–5 scoring system, while structured, still embeds some level of subjectivity. Future research should: include primary surveys of port authorities and RSOs, incorporate temporal analysis to evaluate readiness improvement and use qualitative interviews to understand barriers to ISPS compliance. Additionally, expanding the framework to non-ASEAN ports in Asia-Pacific can validate its broader applicability.

4. Conclusion

In conclusion, this study proves that the level of maritime security readiness in the ASEAN region can be accurately measured through the integrative approach of PCA–GMM–Spatial Network, which successfully identifies three readiness clusters: high, medium, and low. Singapore and Malaysia occupy the top positions thanks to port digitalization and solid governance, while Myanmar, Laos, and Cambodia still face limited infrastructure and human resource capacity. These results confirm that structural and adaptive readiness is the dominant factor in the implementation of the *International Ship and Port Facility Security (ISPS) Code*. Theoretically, this study broadens the understanding of the relationship between communication reliability, port governance, and maritime network resilience. In practical terms, this model provides a data-driven measurement tool for ASEAN port authorities to map out priorities for capacity building and digital investment. The authors are aware of the limitations of data across time that do not yet describe long-term dynamics, but the entire dataset is open source and meets international research ethical standards. Going forward, follow-up studies are recommended to combine predictive AI approaches and longitudinal analysis to monitor changes in readiness in real-time. This research closes an important gap in maritime literature and confirms the need for inclusive and evidence-based digital transformation across ASEAN ports.

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