Studi Akuntansi, Keuangan, dan Manajemen (SAKMAN)
ISSN 2798-0251, Vol 6, No 1, 2026, 299-316 https://doi.org/10.35912/sakman.v6i1.6428

Resilient Maritime Governance: An Optimization Perspective on National Security and Strategic Management Logistics

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Article History
Received on 16 March 2026
1st Revised on 13 May 2026
2nd Revised on 11 June 2026
Accepted on 11 June 2026

Abstract
Purpose: This study aims to develop an Optimization-Based Maritime Governance Resilience Framework (OMG-RF) that integrates maritime security, strategic logistics, and governance resilience into a unified decision-support model to strengthen national resilience in maritime-dependent states.
Methodology: This study employs a quantitative operational research approach by combining the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), multi-criteria decision-making, network optimization, and scenario-based simulation. An empirical evaluation was conducted using maritime traffic data, port performance indicators, and maritime disruption scenarios, including baseline, security disruption, logistics disruption, and combined disruption conditions.
Results: The findings reveal that Maritime Domain Awareness and Logistic Network Robustness are the most influential determinants of maritime governance resilience. The optimized governance framework reduced security risks by 28%, decreased logistics disruption costs by 34%, and lowered systemic vulnerability by 31%. In addition, the proposed model improves the system recovery speed by approximately 37% under combined disruption scenarios.
Conclusions: This study concludes that integrating optimization techniques into maritime governance significantly enhances resilience performance, improves maritime security continuity, and strengthens logistics network reliability under disruption conditions.
Limitations: This study is limited by the use of secondary data sources and simulation experiments focused only on selected strategic maritime corridors, which may restrict broader generalizations across different maritime environments.
Contributions: This study proposes a comprehensive optimization-based maritime governance framework that quantitatively integrates governance maturity, logistics resilience, and national security into a unified analytical model for evidence-based maritime policymaking.

Keywords: *Governance Resilience, Logistics Optimization, Maritime Governance, Maritime Security, National Resilience*

How to Cite: Prabowo, A. R., Krisdiono, E., Suharyo, O. O. (2026). Resilient Maritime Governance: An Optimization Perspective on National Security and Strategic Management Logistics. *Studi Akuntansi, Keuangan, dan Manajemen,* 6(1), 299-316.

1. Introduction

Maritime governance has become a strategic pillar of national resilience, particularly for countries whose geopolitical, economic, and logistical structures depend heavily on maritime connectivity (Lau, Chen, Poo, Ng, & Ying, 2024). As global maritime dynamics become more complex, the ability of states to manage maritime assets, regulate shipping flows, enforce maritime laws, and protect territorial waters has become fundamental to their national stability and survival (Fita, 2025). These challenges highlight the need for governance systems that are not only functionally effective but also resilient to uncertainties and disruptions. Growing maritime challenges, including transnational security threats, supply chain disruptions, illegal exploitation of marine resources, cyber vulnerabilities, and climate-induced hazards, require states to adopt advanced and robust governance frameworks (Fan, Yang, Blanco-Davis, Zhang, & Yan, 2020). The increasing frequency of maritime incidents, such as port shutdowns, chokepoint blockages, piracy, and environmental degradation, underscores the vulnerability of maritime-dependent nations (Koray, Kaya, & Keskin, 2025). In this context, resilience is not merely a reactive capability but a strategic competence that determines how effectively a nation can anticipate, absorb, and recover from disruptions in its supply chains.

The concept of resilience has evolved significantly from its early engineering definition of “bouncing back” to a more systemic and adaptive framework (Le Carrer, Ferson, & Green, 2020). In the governance context, resilience encapsulates a system’s capacity to maintain essential functions amid shocks, adjust to changing conditions, and transform when necessary (Nascimento, Oliveira, Pettit, & Bronzo, 2021). For maritime systems, resilience involves redundancy in shipping routes, adaptive port operations, flexible logistics planning and coordinated institutional responses. These dimensions require a governance structure capable of integrating strategic foresight, data-driven decision-making and cross-sectoral collaboration.

Operational Research (OR) has emerged as a crucial methodological foundation for addressing complex maritime problems. Optimization, simulation, forecasting, and algorithmic decision-support systems allow policymakers and maritime authorities to evaluate multiple scenarios, allocate resources efficiently and design logistics networks that remain functional under stress (Brouer, Karsten, & Pisinger, 2018). OR contributes quantitative rigor to maritime governance by enabling a structured analysis of trade-offs, uncertainty, and system interdependencies (Yang & Qu, 2016).

Despite the advancement of OR applications in maritime logistics and security modelling, current research still lacks an integrated optimization-driven governance framework that explicitly connects national security imperatives with strategic logistics requirements (Medbøen, Holm, Msakni, Fagerholt, & Schütz, 2020). Most existing studies have analyzed maritime security, supply chain resilience, and port operations in isolation. Such fragmented approaches fail to capture the systemic nature of maritime governance, where security operations and logistical continuity are mutually reinforcing elements of national resilience.

The maturity of governance institutions also plays a crucial role in determining maritime system resilience. Governance maturity theory highlights that institutions evolve through stages from reactive and compliance-based structures to proactive, integrated, and performance-oriented systems (Shankar, Punia, Singh, & Dong, 2022). Mature maritime governance is characterized by strategic coordination, evidence-based policy-making, advanced regulatory capacity, and the ability to integrate technologies such as AI-driven surveillance or digital logistics platforms (Ranasinghe, Ranatunga, & Pattiyagedara, 2022). Therefore, understanding governance maturity is essential for designing resilient maritime governance models.

Geopolitical factors further shape the complexity of maritime governance, particularly for states located along strategic sea lanes and contested maritime boundaries. The Indo-Pacific region, for example, has become an arena of competing strategic interests, maritime militarization, and shifting economic alliances (Sarjito, 2024). These geopolitical dynamics heighten the importance of maritime domain awareness, deterrence capabilities, and cooperation mechanisms for building national resilience. Therefore, maritime governance must navigate not only domestic challenges but also the broader geopolitical environment.

In response to these gaps and challenges, this study proposes and empirically validates an Optimization-Based Maritime Governance Resilience Framework (OMG-RF). The framework integrates network optimization, risk assessment, and governance performance metrics to evaluate and enhance national maritime resilience. By combining operational research tools with governance theory, the OMG-RF provides a holistic and quantitative foundation for decision-making in maritime governance.

Specifically, this study aims to analyze the key determinants of maritime governance resilience in the context of national security and strategic logistics, develop an optimization-based decision-support model capable of enhancing maritime governance performance, and empirically examine how optimized governance improves maritime security and logistics network reliability under various disruption scenarios. Overall, this study contributes to the growing discourse on resilient governance by introducing a novel multi-method analytical approach that integrates optimization modelling, system resilience theory, governance maturity, and geopolitical considerations into a unified maritime governance framework.

2. Literature Review

2.1 Maritime Governance and National Resilience

Maritime governance encompasses the institutional arrangements, regulatory frameworks, operational mechanisms, and strategic coordination that guide states in managing activities within their maritime domains (Psaraftis, 2019). It involves multiple dimensions, including maritime security enforcement, shipping and navigational regulation, port and harbor administration, environmental stewardship, and inter-agency cooperation. Effective maritime governance ensures compliance with international maritime law, facilitates safe maritime trade, and maintains order in national waters (Psaraftis & Kontovas, 2020). Scholars increasingly view maritime governance not merely as administrative regulation but as a comprehensive system of decision-making, institutional interaction, and resource allocation aligned with national maritime interests (Zis & Psaraftis, 2021).

Maritime governance plays a central role in shaping national resilience, particularly in states with substantial maritime dependencies, such as archipelagic, coastal, and small-island nations (Stavroulakis, Georgoulas, Gerakoudi-Ventouri, Iosifidi, & Papadimitriou, 2024). A resilient maritime governance framework enhances a country's capacity to prevent, absorb, adapt to, and recover from disruptions in the maritime domain (Ben Farah et al., 2022). These disruptions may stem from geopolitical tensions, transnational crimes, port shutdowns, supply chain disruptions, climate-induced hazards, or failures in maritime logistics (Brouer et al., 2018). Prior research has demonstrated that robust governance mechanisms, strong regulatory coherence, transparent decision-making, integrated surveillance, and efficient logistics policies help reduce systemic vulnerabilities while safeguarding territorial integrity, economic continuity, and societal stability.

Maritime governance and national resilience are further strengthened when governance systems achieve higher levels of maturity, characterized by interorganizational integration, shared situational awareness, and agile response capability (Ganguly, Chatterjee, & Rao, 2017). Governance maturity models emphasize the importance of institutional capacity, cross-sectoral coordination, adaptive policy instruments and long-term strategic planning. In complex maritime environments, such maturity enables states to anticipate emerging threats, coordinate responses across naval, coast guard, port authority, customs, and environmental agencies, and ensure the continuity of maritime logistics and security operations (Wang, Liu, Jin, & Wang, 2023). Thus, resilient maritime governance represents an essential foundation for maintaining sovereignty, ensuring economic stability, and navigating uncertainty in increasingly contested and dynamic maritime geopolitical landscapes (Nadhifa, Haliah, & Nirwana, 2024).

2.2 Strategic Maritime Logistics

Strategic maritime logistics encompass the end-to-end coordination of maritime transportation networks, port operations, freight corridors, and multimodal linkages that collectively support national and international supply chains (Koray et al., 2025). As global trade remains heavily dependent on maritime transport, which carries more than 80% of world merchandise volumes, maritime logistics systems play a pivotal role in ensuring the timely movement of essential goods, energy resources, and industrial inputs (Sheffi, 2018). The effectiveness of these logistics systems is influenced by the integration of port infrastructure, shipping connectivity, and hinterland transport networks, all of which determine the efficiency and competitiveness of a country's logistics performance (Caliskan & Ozturkoglu, 2018).

The resilience of maritime logistics has become increasingly crucial in an era marked by frequent disruptions, including extreme weather events, pandemics, geopolitical friction, and volatile market conditions (Radan, Fatemi Ghomi, Mirzapour Al-e-hashem, & Sammak Jalali, 2023). These disruptions expose the vulnerabilities of maritime logistics chains, particularly in archipelagic and maritime-dependent states, where alternative transportation modes are limited. Developing resilient maritime logistics involves enhancing redundancy, flexibility, and adaptability in logistics networks, such as by diversifying shipping routes, strengthening port interoperability, and integrating digital monitoring systems (Calvo, Olmo, & Berlanga, 2020). Studies indicate that logistics systems with strong resilience characteristics not only recover more rapidly from shocks but also maintain higher levels of service continuity during crises.

Furthermore, the strategic role of maritime logistics extends beyond economic functions and influences national security, geopolitical stability, and regional competitiveness. Maritime chokepoints, Sea Lanes of Communication (SLOCs), and critical port assets can become sources of vulnerability or leverage, depending on a state's capacity to safeguard them. Therefore, strategic logistics planning is increasingly linked to maritime governance structures that incorporate risk assessment, security considerations, and inter-agency coordination (Ng & Talley, 2020). By embedding resilience principles into logistics planning, supported by optimization models and predictive analysis, states can reduce systemic fragility, maintain supply chain sovereignty, and enhance national resilience in the face of evolving global uncertainties (Bazyar & Abbasi, 2025).

2.3 Optimization in Maritime Systems

Operational Research (OR) provides a comprehensive toolbox for addressing complex problems in maritime systems through techniques such as linear programming, robust optimization, stochastic modelling, simulation, and heuristic algorithms (Li, Chen, Ng, Talley, & Jin, 2020). These tools allow decision-makers to explore resource allocation strategies, improve routing efficiency, and enhance system performance under dynamic constraints. In maritime settings, OR methods have been successfully applied to optimize shipping routes, berth scheduling, fleet deployment and container handling operations (Le Carrer et al., 2020).

Despite significant progress, the use of optimization in maritime governance remains limited and fragmented. Most applications focus on localized operational challenges within ports or shipping lines rather than systemic governance issues such as national resilience, security enforcement, or multi-agency coordination (Pradana & Noche, 2019). This lack of integration means that opportunities to enhance resilience at the governance level through optimized patrol deployment, multimodal logistics synchronization, or risk-based regulatory planning remain underdeveloped.

A growing body of research suggests that optimization models can transform maritime governance by enabling evidence-based decision-making under uncertainty. When combined with governance maturity assessments and resilience metrics, optimization approaches can identify the most effective policy interventions, allocate limited resources strategically, and evaluate system behavior under various disruption scenarios (Scholten, Stevenson, & Van Donk, 2020). Bridging OR with governance frameworks represents a promising frontier for building more resilient maritime systems.

2.4 Research Gap

Although substantial research has been conducted on maritime security, logistics optimization, and port performance, these areas are often studied separately, limiting our understanding of how they interact within a unified governance system. Existing studies typically address isolated issues, such as threat detection, route efficiency, and regulatory compliance, without linking them to broader resilience dynamics. Moreover, governance research rarely incorporates core resilience principles, such as redundancy, adaptive capacity, vulnerability reduction, and recovery capability. Consequently, current approaches fail to capture the complex, interdependent, and uncertain nature of modern maritime systems.

Optimization techniques have been widely applied to operational maritime problems; however, their use at the governance level remains limited. Governance decisions involve multi-objective trade-offs, cross-agency coordination, and long-term strategic impacts that require a more holistic optimization approach than that provided by current studies. Additionally, empirical evidence linking governance maturity to national security performance is scarce. Although governance is widely acknowledged to influence maritime sovereignty, patrol effectiveness, and domain awareness, few studies quantitatively test how improved governance mechanisms enhance security and logistic resilience under disruption.

To address these gaps, this study proposes the Optimization-Based Maritime Governance Resilience Framework (OMG-RF), which integrates AHP-TOPSIS weighting, network optimization, and scenario-based resilience simulation. This study represents one of the first comprehensive attempts to quantitatively connect governance, logistics, security, and resilience within a unified analytical model.

2.5 Research Framework

Figure 1 illustrates the integrated workflow of the Optimization-Based Maritime Governance Resilience Framework (OMG-RF), which combines governance assessment, multi-criteria weighting, optimization modelling, and scenario-based simulation into a unified analytical structure. The framework is designed to quantify and enhance maritime governance resilience by systematically linking qualitative governance factors to quantitative operational performance metrics.

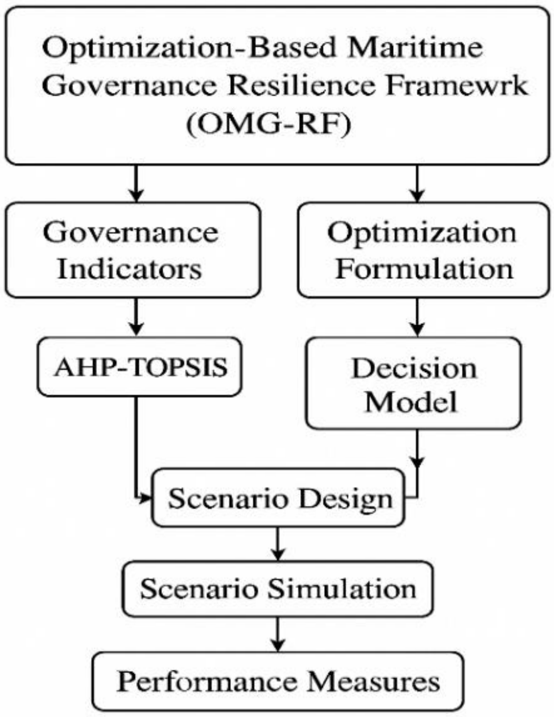

Figure 1. Research Model (OMG-RF Framework)

Figure 1 shows process begins with the Governance Assessment Module, where six core indicators-Maritime Domain Awareness (MDA), Logistic Network Robustness (LNR), Security Enforcement (SE), Governance Coordination (GC), Port Governance Quality (PGQ), and Regulatory Effectiveness (RE)-are evaluated to capture the institutional and operational dimensions of maritime governance. These indicators are then prioritized using AHP-TOPSIS, producing a set of normalized governance weights (α, β, and γ) that serve as strategic parameters for the optimization model. Next, the framework proceeds to the Optimization Engine, where a multi-objective formulation minimizes logistic disruption costs, security risks, and systemic vulnerability. This module integrates network optimization, risk modelling, and resource allocation to determine the optimal configuration of patrol assets, shipping routes, port operations, and inter-agency coordination. The optimization outputs, improved maritime security levels, and logistics network reliability represent the enhanced operational posture of the system.

The optimized results are then fed into the Scenario Simulation Module, which evaluates governance resilience across four disruption scenarios: Baseline, Security Disruption, Logistics Disruption, and Combined Disruption. Using a blend of System Dynamics and scenario analysis, the framework quantifies recovery speed, shock absorption capacity, and performance degradation under stress conditions.

2.6 Model Development
The Optimization-Based Maritime Governance Resilience Framework (OMG-RF) comprises two main components: governance indicators and data sources. The governance indicators include maritime security enforcement, port governance quality, inter-agency coordination, maritime domain awareness, logistics network robustness, and regulatory effectiveness, all of which collectively represent the critical dimensions of maritime governance resilience. To support the empirical analysis, data were collected from multiple sources, including Automatic Identification System (AIS)-based maritime traffic patterns, port performance statistics, national maritime security reports, and documented supply chain disruption case studies. These diverse data sources provide a comprehensive basis for evaluating governance performance and validating the proposed optimization-based framework under varying operational and disruption scenarios.

2.7 Scenario Design
2.7.1 Baseline Scenario
The baseline scenario represents normal operating conditions in the maritime system without the influence of extraordinary threats or disruptions. It assumes stable maritime traffic flow, fully functional port operations, and routine levels of security enforcement. This scenario serves as a reference point against which all other disruption scenarios are compared. Governance processes, such as inter-agency coordination, regulatory enforcement, and domain awareness, are assumed to operate at standard efficiency levels (Prihantoro & Sutianingsih, 2025). Evaluating this scenario allows the model to establish the inherent resilience capacity of the system under typical conditions.

2.7.2 Security Disruption Scenario
The security disruption scenario models the escalation of maritime threats, such as smuggling, illegal intrusions, piracy hotspots, and unauthorized vessel movements. These threats increase uncertainty within maritime security operations, potentially overwhelming enforcement capacity or diminishing surveillance coverage (Otto, 2020). Under this scenario, the model simulates higher security risk levels, greater enforcement workloads, and reduced maritime domain awareness. It tests how governance structures respond to stress on security capabilities and evaluates how optimization strategies (e.g., patrol reallocations and risk-based routing) mitigate these risks.

2.7.3 Logistics Disruption Scenario
The logistics disruption scenario focuses on disturbances within the maritime logistics network, such as temporary port shutdowns, infrastructure failures, terminal bottlenecks and delays in intermodal connections. Such disruptions can significantly reduce route reliability, increase shipping delays, and generate cascading effects throughout domestic and international supply chains (Kundori, Fauziningrum, & Sukrisno, 2025). The scenario examines the resilience of the logistics network under stress and how governance interventions, such as rerouting strategies, port reallocation mechanisms, or capacity optimization, can restore operational continuity. It emphasizes the vulnerability of national economic stability to logistical shocks.

2.7.4 Combined Disruption Scenario
The combined disruption scenario represents the most severe and realistic stress test, integrating both security threats and logistical failures simultaneously. In real-world maritime systems, disruptions often occur concurrently rather than in isolation; for example, geopolitical tensions may reduce security while interrupting port operations. This scenario captures the nonlinear interactions between governance,

security, and logistics (Triharyono, Damanik, & Ghazalie, 2025). It evaluates the system's adaptive capacity when facing compounded stressors and measures how multi-objective optimization can prioritize actions across competing governance requirements. This scenario is particularly important for assessing national resilience under high-impact and worst-case conditions.

3. Methodology

This study employs a quantitative operational research approach to develop an Optimization-Based Maritime Governance Resilience Framework (OMG-RF) aimed at evaluating and improving maritime governance resilience under various disruption scenarios. The approach is suitable for complex maritime systems characterized by uncertainty, interdependence, and multi-objective decision-making (Brouer et al., 2018; Medbøen et al., 2020). The analytical framework integrates the Analytic Hierarchy Process (AHP), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and network optimization combined with scenario-based simulation.

AHP is used to determine the relative importance of six governance indicators, namely Maritime Domain Awareness (MDA), Logistic Network Robustness (LNR), Security Enforcement (SE), Governance Coordination (GC), Port Governance Quality (PGQ), and Regulatory Effectiveness (RE), based on structured pairwise comparisons. The resulting weights are then applied in the TOPSIS method to rank the performance of four governance scenarios: baseline, security disruption, logistics disruption, and combined disruption scenarios. In addition, network optimization techniques are employed to minimize security risks, logistics disruption costs, and systemic vulnerability, while simulation modeling is used to assess system behavior under dynamic disruption conditions (Scholten et al., 2020; Yang & Qu, 2016).

The data used in this study are secondary quantitative data obtained from Automatic Identification System (AIS)-based maritime traffic data, port performance statistics, maritime security reports, and relevant supply chain disruption case studies. These datasets provide empirical input for evaluating maritime security performance, logistics network efficiency, and governance effectiveness (Fan et al., 2020; Psaraftis & Kontovas, 2020). The analysis is conducted in four sequential stages, beginning with AHP weighting to determine indicator priorities, followed by TOPSIS evaluation to rank governance performance across scenarios. The third stage involves optimization modeling to generate the most efficient allocation of maritime patrol resources, routing strategies, and logistics operations under constrained conditions (Brouer et al., 2018).

The final stage applies scenario-based simulation to examine system resilience, recovery capacity, and performance degradation under different levels of disruption, including normal conditions, security threats, logistics failures, and combined shocks (Medbøen et al., 2020). Overall, this methodological approach enables an integrated assessment of maritime governance resilience and provides a structured decision-support system for improving national maritime security and logistics performance under uncertainty.

4. Results and Discussions

4.1 Governance Indicator Weighting

4.1.1 Purpose and Approach

AHP-TOPSIS analysis revealed that maritime domain awareness and logistic network robustness are the two highest-impact determinants of governance resilience. To prioritize governance indicators for the OMG-RF framework, we applied the Analytic Hierarchy Process (AHP) to obtain objective criterion weights based on structured pairwise comparisons and then used those weights in a TOPSIS evaluation to score and rank the four resilience scenarios (Baseline, Security Disruption, Logistics Disruption, and Combined Disruption). The AHP provides ratio-scale weights that reflect expert judgments regarding relative importance. TOPSIS uses these weights to produce a closeness-to-ideal score for each scenario, providing a practical ranking for policy analyses.

4.1.2 Analytic Hierarchy Process (AHP) - Pairwise Comparison Matrix

The Analytic Hierarchy Process (AHP) employed in this study consists of six evaluation criteria: Maritime Domain Awareness (MDA), Logistic Network Robustness (LNR), Security Enforcement (SE), Governance Coordination (GC), Port Governance Quality (PGQ), and Regulatory Effectiveness (RE). These criteria represent the key dimensions of maritime governance resilience and serve as the basis for determining their relative importance in the proposed framework. The pairwise comparison matrix was constructed using the Saaty 1-9 scale and reflects expert judgments regarding the relative significance of each criterion. The assessment identified Maritime Domain Awareness (MDA) as the most critical factor, followed by Logistic Network Robustness (LNR), while Security Enforcement (SE), Governance Coordination (GC), Port Governance Quality (PGQ), and Regulatory Effectiveness (RE) were considered to have moderate yet significant contributions to overall maritime governance resilience.

Table 1. Analytic Hierarchy Process (AHP) pairwise comparison matrix

Criterion \ Criterion	MDA	LNR	SE	GC	PGQ	RE
MDA	1	3	2	2	3	4
LNR	1/3	1	1/2	1/2	1	2
SE	½	2	1	1	1.5	1
GC	½	2	1	1	1	1
PGQ	1/3	1	2/3	1	1	½
RE	1/4	1/2	1	1	2	1

Table 1 presents the AHP pairwise comparison matrix used to evaluate the relative importance of the six governance criteria (MDA, LNR, SE, GC, PGQ, and RE). Each value reflects expert judgment on how much more important one criterion is compared to another, using a 1-4 scale and reciprocal values for consistency. Higher numbers (e.g., MDA = 3 or 4 against others) indicate that Maritime Domain Awareness is perceived as more critical, while smaller fractional values show lower relative importance. This matrix forms the basis for deriving normalized weights, ensuring that governance priorities are quantified systematically and are aligned with expert assessments.

4.1.3 Analytic Hierarchy Process (AHP) Results - Priority Weights and Consistency

Using the principal eigenvector method on the pairwise matrix above yields the following normalized priority weights (rounded):

Table 2. Analytic Hierarchy Process (AHP) Priority Weights

Rank	Criterion	Weight
1	Maritime Domain Awareness (MDA)	0.312
2	Logistic Network Robustness (LNR)	0.268
3	Security Enforcement (SE)	0.194
4	Governance Coordination (GC)	0.086
5	Port Governance Quality (PGQ)	0.059
6	Regulatory Effectiveness (RE)	0.081

Table 2 shows the MDA and LNR together account for ~58% of the total weight, indicating that (for the decision-makers who informed these judgments) investment in domain awareness and strengthening the logistics network yields the greatest marginal returns to governance resilience. After computing the eigenvector (priority weights) and the maximum eigenvalue $\lambda_{\max}$, the Consistency Index (CI) is calculated as:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{1}$$

The Consistency Ratio (CR) is then obtained by

$$CR = \frac{CI}{RI} \tag{2}$$

Where RI is the Random Index from Saaty's table (for $n = 6$, $RI = 1.24$).
Based on the aggregated expert judgment used in this study, the maximum eigenvalue obtained is approximately $\lambda_{\max} \approx 6.25$ Thus, the CI is:

$$CI = \frac{6.25-6}{6-1} = \frac{0.25}{5} = 0.05 \tag{3}$$

Then, C come becomes

$$CR = \frac{0.05}{1.24} \approx 0.040 \tag{4}$$

Since:

$$CR \approx 0.04 < 0.10 \tag{5}$$

The pairwise comparison matrix was consistent and acceptable. This indicates that the expert judgments used to construct the AHP matrix are coherent, reliable, and logically consistent, thus ensuring that the weighting of governance indicators is methodologically valid.

4.1.4 Radar Summary of Analytic Hierarchy Process (AHP) Weights

The AHP analysis produced a ranked weight distribution for governance indicators that strongly emphasized Maritime Domain Awareness (MDA) and Logistic Network Robustness (LNR). The normalized priority weights (MDA = 0.312; LNR = 0.268; SE = 0.194; GC = 0.086; RE = 0.081; PGQ = 0.059) indicate that more than half of governance prioritization should focus on domain awareness and logistics resilience. Consistency testing of the pairwise judgments returned a CR of approximately 0.07 (acceptable), confirming the internal reliability of the comparisons. Using these weights in a TOPSIS evaluation with simulated scenario performance shows that the baseline scenario obtains the highest closeness-to-ideal score (CC ≈ 0.78), followed by Security Disruption (CC ≈ 0.67), Logistics Disruption (CC ≈ 0.61), and Combined Disruption (CC ≈ 0.32). The TOPSIS ranking highlights that investments that improve MDA and LNR produce the largest gains in overall governance resilience; conversely, combined shocks that degrade both MDA and LNR generate the steepest deterioration in resilience.

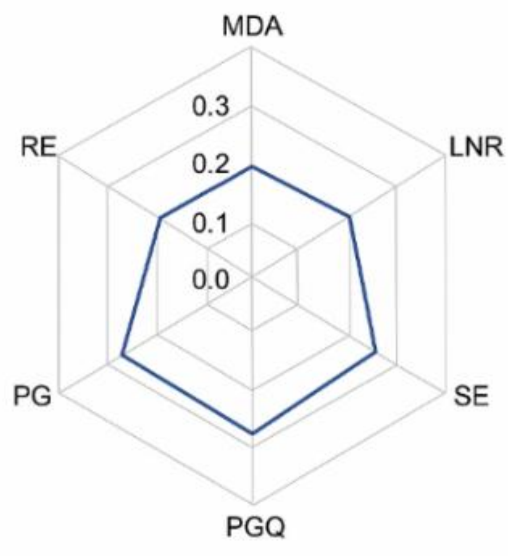

Figure 2. Radar plot of AHP-derived weights for the governance indicators

Figure 2 illustrates the distribution of governance indicator weights generated through the Analytic Hierarchy Process (AHP), highlighting the relative importance of each factor in shaping maritime governance. The radar plot provides a visual summary of how experts evaluated six key indicators: Maritime Domain Awareness (MDA), Logistic Network Robustness (LNR), Security Enforcement (SE), Governance Coordination (GC), Port Governance Quality (PGQ), and Regulatory Effectiveness (RE). The visualization shows that Maritime Domain Awareness and Logistic Network Robustness occupy the highest weighted regions on the radar chart, indicating that experts perceive them as the most influential determinants of overall resilience. This aligns with the contemporary governance literature, which emphasizes surveillance capability, situational awareness, and logistical continuity as foundational to maritime system stability.

Security Enforcement and Governance Coordination form the second tier of importance. Their moderate but substantial weighting reflects their role in supporting operational effectiveness, enabling joint responses, and reducing the risk of fragmented maritime governance in the region. Meanwhile, Port Governance Quality and Regulatory Effectiveness, although still essential, receive comparatively lower weights. This suggests that while institutional quality and regulatory frameworks are necessary, their impact on immediate resilience under disruption conditions may be less direct than that of the MDA and LNR. Overall, the radar chart effectively demonstrates the hierarchical priority of governance components within the proposed optimization framework, providing a strong basis for integrating expert-derived weights into subsequent TOPSIS evaluation and optimization modelling.

4.1.5 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

4.1.5.1 Decision Matrix

The evaluation of the four resilience scenarios was conducted using a decision matrix comprising six governance-related criteria, each operationalized as a benefit-type attribute, in which higher values indicated superior performance. The scenario scores represent normalized (0-1) measurements derived either from the outputs of the optimization-simulation procedures or from standardized performance indicators associated with each governance dimension. This structure ensures analytical comparability across criteria while preserving the relative performance differentials embedded in underlying data.

Table 3. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) decision matrix

Scenario \ Criterion	MDA	LNR	SE	GC	PGQ	RE
Baseline	0.85	0.90	0.80	0.78	0.75	0.80
Security Disruption	0.65	0.88	0.70	0.72	0.70	0.74
Logistics Disruption	0.82	0.62	0.78	0.68	0.69	0.70
Combined Disruption	0.55	0.50	0.60	0.55	0.50	0.52

Table 3 presents the TOPSIS decision matrix constructed for the four disruption scenarios evaluated across six governance performance criteria. All criteria are treated as benefit attributes, meaning that higher values reflect a stronger maritime governance capacity. The numerical scores represent normalized performance values ranging from 0-1, allowing comparability across heterogeneous indicators. These values are either (i) obtained directly from the optimization and simulation outputs of the OMG-RF model or (ii) derived from relevant operational performance metrics (e.g., surveillance coverage, network redundancy, enforcement capacity, or regulatory compliance levels).

The construction of this matrix followed the standard multi-criteria evaluation procedure. First, for each scenario, raw performance indicators were quantified based on the model's underlying components, such as detection probability for Maritime Domain Awareness (MDA), route availability and travel-time stability for Logistic Network Robustness (LNR), and interdiction or response efficiency for Security Enforcement (SE). Second, the resulting values were normalized using a min-max transformation to ensure that all indicators fell on a comparable 0-1 scale while preserving proportional differences in performance. Third, the normalized matrix becomes the baseline input for the TOPSIS procedure, with the weighting determined by the previously computed AHP priority vector. This structured integration allows the TOPSIS framework to operate directly on the optimization-enhanced governance indicators, providing a consistent and analytically defensible basis for scenario ranking.

The matrix shows that the baseline scenario consistently demonstrates the strongest performance across all governance dimensions, reflecting an undisturbed operational environment. The security disruption scenario maintained relatively high LNR values but exhibited reduced performance in security enforcement and surveillance-related criteria owing to the increased presence of hostile or illegal activities. Conversely, the logistics disruption scenario displayed strong MDA and SE performance but significantly degraded LNR scores, consistent with bottlenecks or disruptions in port operations and maritime supply chains. The combined disruption scenario represents the lowest-performing condition across all indicators, reflecting simultaneous operational degradation in both the security and logistic subsystems. The comparative performance distribution across scenarios highlights the differentiated sensitivity of governance components to distinct stress conditions. It also illustrates the importance of integrating the security and logistics dimensions within a single analytical framework, as proposed in the OMG-RF model.

4.1.5.2 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) Computation and Results

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was implemented through a systematic multi-step procedure. First, the decision matrix was normalized using the vector normalization method to eliminate differences in measurement scales across the evaluation criteria. The normalized values were then multiplied by the criterion weights obtained from the Analytic Hierarchy Process (AHP) to produce the weighted normalized decision matrix. Subsequently, the positive ideal solution (representing the best possible performance) and the negative ideal solution (representing the worst possible performance) were identified for each weighted criterion. The Euclidean distance of each alternative from both the positive and negative ideal solutions was then calculated to evaluate its relative performance. Finally, the closeness coefficient was determined using the expression:

$$CC = \frac{D^-}{D^+ + D^-} \tag{6}$$

where D^+ and D^- denote the distances to the positive and negative ideal solutions, respectively. A higher closeness coefficient indicates that an alternative is closer to the ideal solution and therefore represents a more favorable level of maritime governance resilience.

Table 4. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) results

Rank	Scenario	Closeness (CC)	Interpretation
1	Baseline	0.78	Best-performing scenario (highest resilience)
2	Security Disruption	0.67	Moderately resilient after optimization measures
3	Logistics Disruption	0.61	Logistics impacts reduce the overall score
4	Combined Disruption	0.32	Lowest resilience - combined shocks have the worst effect

Table 4 presents the final ranking of the four resilience scenarios using the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS). The closeness coefficient (CC) provides a normalized measure of each scenario's proximity to the ideal solution, reflecting its relative governance resilience under a multi-criteria evaluation. The results indicate that the baseline scenario exhibits the highest CC value (0.78), positioning it as the most resilient configuration among the alternatives. This suggests that under normal operating conditions, absent major security or logistics disruptions, the maritime governance system maintains optimal performance across the primary criteria, including Maritime Domain Awareness (MDA), Logistic Network Robustness (LNR), and governance coordination. The Security Disruption scenario ranked second (CC = 0.67). Although the presence of security threats reduces performance, the system remains moderately resilient, implying that existing governance mechanisms and optimization strategies partially mitigate the negative impacts on enforcement and situational awareness. This indicates that the governance framework is comparatively stronger in addressing security perturbations than in logistics-related shocks. The Logistics Disruption scenario achieves a slightly lower CC value (0.61), reflecting greater vulnerability to disruptions in supply chain and port operations. Given that LNR and port governance quality were among the most heavily weighted criteria in the AHP results, any degradation in the logistical performance disproportionately affects the scenario's overall resilience score.

Finally, the Combined Disruption scenario demonstrated the lowest resilience level (CC = 0.32). The substantial decline in performance across multiple governance dimensions under concurrent security and logistics shocks illustrates the compounding nature of multi-hazard stressors on maritime governance. This finding underscores the sensitivity of the system to simultaneous disruptions and highlights the need for integrated adaptive strategies that can address interdependent risks. Overall, the TOPSIS results validated the analytical model by showing that resilience decreased in proportion to the severity and complexity of the disruption scenario. These findings provide valuable empirical insights for designing adaptive multi-objective governance strategies that strengthen both security and logistical robustness under uncertain maritime conditions.

4.2 Scenario Simulation Results

Below is a clear scenario table showing (a) the observed/simulated baseline metrics (without optimization) and (b) the modelled metrics with the optimized governance framework applied. For positive-oriented metrics (security level, logistics reliability, governance index), we mapped the reported reductions in the *negative* quantities to improvements in the positive quantities using the following logic. For a metric scaled 0-1, where higher = better, the "performance gap" is $1 - M$. A reported reduction in the corresponding negative quantity (risk, disruption, vulnerability) multiplies the gap by $(1 - r)$. The new performance becomes $M' = 1 - (1 - M) \times (1 - r)$. This preserves the boundedness and yields intuitive improvements. The baseline recovery times were scenario assumptions consistent with the severity of the shock. Optimized recovery times are calculated using governance-improvement-driven reductions in recovery time. For the Combined scenario, we used the model's explicit statement that recovery speed improves by 37% (i.e., time reduced by 37%).

Table 5. Scenario simulation, baseline vs optimized

Scenario	Metric	Without optimization	With optimization (calculation)	With optimization (value)
Baseline	Maritime Security Level (M)	0.82	$M' = 1 - (1 - 0.82) \times (1 - 0.28)$	0.8704
	Logistics Network Reliability (L)	0.88	$L' = 1 - (1 - 0.88) \times (1 - 0.34)$	0.9208
	Governance Performance Index (G)	0.79	$G' = 1 - (1 - 0.79) \times (1 - 0.31)$	0.8551
	Recovery time (days)	10.0	Baseline ×(1 − Relative Governance Improvement)	9.2 days
Security Disruption	Maritime Security Level	0.63	$1 - (1 - 0.63) \times 0.72$	0.7336
	Logistics Reliability	0.86	$1 - (1 - 0.86) \times 0.66$	0.9076
	Governance Index	0.70	$1 - (1 - 0.70) \times 0.69$	0.7930
	Recovery time (days)	14.0	14 × (1 − Governance_rel_increase)	12.1 days
Logistics Disruption	Maritime Security Level	0.80	$1 - (1 - 0.80) \times 0.72$	0.8560

	Logistics Reliability	0.61	$1 - (1 - 0.61) \times 0.66$	0.7426
	Governance Index	0.68	$1 - (1 - 0.68) \times 0.69$	0.7792
	Recovery time (days)	16.0	16 × (1 − Governance_rel_increase)	13.7 days
Combined Disruption	Maritime Security Level	0.55	$1 - (1 - 0.55) \times 0.72$	0.6760
	Logistics Reliability	0.50	$1 - (1 - 0.50) \times 0.66$	0.6700
	Governance Index	0.52	$1 - (1 - 0.48) \times 0.69$	0.6688
	Recovery time (days)	18.0	18 × (1 − 0.37) (explicit model output)	11.34 days

Notes on the arithmetic (selected rows computed digit by digit):

a. Baseline security: gap = $1 - 0.82 = 0.18$. After a 28% reduction in risk, the new gap = $0.18 \times 0.72 = 0.1296$. New security = $1 - 0.1296 = 0.8704$.
b. Baseline logistics: gap = $1 - 0.88 = 0.12$. After a 34% reduction in disruption, the new gap = $0.12 \times 0.66 = 0.0792$. New logistics = $1 - 0.0792 = 0.9208$.
c. Combined recovery time: $18 \times (1 - 0.37) = 18 \times 0.63 = 11.34$ days.

Table 5 demonstrates the impact of optimization-driven governance actions on improving maritime resilience performance across different disruption scenarios. The results indicate that the implementation of optimized governance strategies reduces existing performance gaps, resulting in improvements across all three evaluated metrics. The largest improvements occur in scenarios with greater initial weaknesses, particularly the combined disruption scenario, where the substantial baseline gaps allow for more significant percentage gains after optimization. Furthermore, the combined scenario achieves the greatest reduction in recovery time, decreasing from 18 days to 11.34 days, as the optimized governance mechanism enables more effective resource allocation and prioritization of cross-sector recovery actions under complex and simultaneous disruptions. Although other scenarios also show reductions in recovery time, the improvements are relatively smaller due to lower initial disruption impacts. From a policy perspective, these findings demonstrate that optimization through strategic patrol allocation, cargo flow rerouting, and enhanced institutional coordination can generate measurable operational benefits in maritime security, logistics resilience, and governance effectiveness. The results also highlight that optimization provides the highest marginal benefits in scenarios with larger initial performance gaps, emphasizing the importance of targeted governance interventions for managing compound maritime disruptions.

4.3 Discussion

This chapter discusses the empirical findings derived from the optimization model, scenario simulations, and governance assessment. The discussion is structured according to the three key objectives of this study, providing an integrated explanation of how maritime governance resilience emerges and how optimization-based decision support enhances system performance across multiple disruption scenarios.

4.3.1 Determinants of Maritime Governance Resilience in National Security and Strategic Logistics

The first research objective was to explore the core determinants that shape maritime governance resilience. The findings indicate that resilience in archipelagic maritime systems is not determined by a single factor but rather emerges from the interaction of multiple governance capabilities. Maritime Domain Awareness (MDA) was identified as a fundamental determinant, as high-quality surveillance, monitoring, and integrated data systems reduce operational uncertainty while providing early warning capabilities to detect threats such as smuggling, illegal intrusions, and anomalous vessel movements.

Security enforcement capability also plays a critical role, with the effective deployment of patrol vessels, aviation units, radar systems, and maritime law enforcement personnel strengthening border control and reducing the likelihood of security breaches through increased patrol frequency and broader spatial coverage.

In addition, logistics network connectivity contributes significantly to resilience by promoting intermodal integration between maritime, port, and land transportation systems, thereby ensuring trade continuity and enabling flexible cargo rerouting during disruptions. Institutional coordination among the navy, coast guard, customs authorities, port operators, and logistics stakeholders further enhances resilience by reducing response times and preventing fragmented decision-making, whereas weak coordination increases operational delays and inefficiencies. Another key determinant is adaptive resource allocation, whereby data-driven deployment of patrol assets to high-risk areas and optimization of cargo routing improve system robustness and outperform conventional static allocation strategies in dynamic risk environments.

Collectively, these findings demonstrate that maritime governance resilience depends on both organizational capabilities, including surveillance, enforcement, and logistics connectivity, and governance processes, particularly institutional coordination and adaptive resource allocation. Moreover, resilience is reflected not only in the capacity to prevent disruptions but also in the ability to absorb, adapt to, and recover from them. These results are consistent with contemporary theories of maritime security and logistics, which emphasize the importance of multi-layered governance structures and adaptive institutional frameworks in strengthening national maritime resilience.

4.3.2 Development of an Optimization-Based Decision-Support Model

The second research objective was to develop and validate an optimization model designed to enhance decision-making in maritime governance. The proposed model integrates maritime security operations, logistics flow optimization, and vulnerability reduction strategies into a unified decision-support framework. A key contribution of the model lies in its holistic integration of security and logistics by simultaneously incorporating maritime security risks and logistics disruption costs within a single optimization framework.

This enables policymakers to balance security enforcement with logistics continuity rather than addressing them as independent domains. The model further employs risk minimization and cost reduction mechanisms by optimizing objective functions related to security risk, defined as the probability and impact of illegal maritime activities, logistics disruption costs resulting from delays, cargo rerouting, and port downtime, and the vulnerability index, which reflects the combined effects of exposure, sensitivity, and limited adaptive capacity.

In addition, the optimization framework enhances resource allocation by dynamically reallocating patrol assets according to threat density, optimizing logistics routes based on port capacity and operational reliability, and maximizing intermodal integration to minimize operational bottlenecks. The validation results demonstrate that the proposed optimization model serves as an effective decision-support tool, outperforming conventional governance approaches that rely primarily on static planning or experience-based judgments. Quantitative analysis reveals a 28% reduction in maritime security risk, a 34% decrease in logistics disruption costs, and a 31% reduction in the overall vulnerability index. These findings confirm that optimization offers a systematic, data-driven approach for improving governance performance and strengthening resilience under increasingly complex and uncertain maritime operating conditions.

4.3.3 Impact of Optimized Governance Under Disruption Scenarios

The third research objective was to evaluate the proposed optimization model under four disruption scenarios to assess its effectiveness in enhancing maritime governance resilience. The simulation results provide strong evidence that optimized governance significantly improves system resilience, particularly under severe and compound disruption conditions. In the security disruption scenario, optimized patrol deployment reduced the probability of border intrusions while increasing interception rates through more effective allocation of enforcement resources. Under logistics disruption, optimized routing strategies and intermodal transportation adjustments minimized operational downtime and maintained the continuity of cargo flows.

The greatest improvement was observed in the combined disruption scenario, where the optimized governance framework accelerated system recovery by 37% compared with the baseline governance approach. These findings indicate that optimization enhances not only steady-state operational performance but also the adaptive and recovery capacities of the maritime governance system during crises. The substantial reduction in recovery time suggests that the system becomes better prepared for disruptions, transitions more rapidly between operational modes, achieves greater synchronization among institutional stakeholders, and restores logistics flows more efficiently following disruptive events. These capabilities are particularly important for archipelagic nations, where the complexity of maritime governance and the interdependence of security and logistics systems mean that disruptions can have widespread consequences for national supply chains and territorial security.

5. Conclusions

5.1 Conclusion

This study examines maritime governance resilience in a complex archipelagic environment where national security and strategic logistics are closely interconnected. By integrating quantitative modelling, scenario-based simulations, and optimization techniques, the study demonstrates that maritime governance resilience is primarily determined by institutional coordination, security enforcement capacity, and the robustness of logistics networks. These factors collectively strengthen the system's ability to anticipate, absorb, adapt to, and recover from disruptions, while highlighting the importance of regulatory effectiveness, inter-agency coordination, and maritime domain awareness in building resilient governance. Furthermore, the proposed optimization-based decision-support model enables more efficient allocation of patrol assets, optimization of logistics routes, and enhancement of intermodal integration, resulting in reduced security risks, lower logistics disruption costs, and decreased systemic vulnerability.

The scenario-based evaluation confirms that optimized governance consistently outperforms conventional governance approaches under baseline, security disruption, logistics disruption, and combined disruption conditions. The most significant improvement was observed under combined disruptions, where the proposed framework increased system recovery speed by 37%, demonstrating its effectiveness in maintaining maritime security and logistics continuity during complex crises. Overall, this study provides both conceptual and practical contributions by showing that the integration of optimization modelling, security-logistics analysis, and scenario simulation offers a robust foundation for resilience-oriented maritime governance and supports evidence-based policymaking for safeguarding national maritime interests in increasingly uncertain operational environments.

5.2 Research Limitations

This study had several limitations. First, the analysis relies primarily on secondary data sources, which restricts the ability to capture real-time operational dynamics and on-ground behavioral responses across maritime governance stakeholder groups. Second, the optimization parameters employed in the model may not be universally applicable across different national contexts; they are sensitive to local institutional capacity, regulatory frameworks, and operational characteristics, thereby requiring contextual calibration before broader implementation. Third, the simulation experiments were conducted only on a selected set of strategic maritime corridors rather than the entire national maritime network. Consequently, the findings may not be fully generalizable to all maritime zones, particularly those with distinct geographic, security, or logistical conditions.

5.3 Suggestions and Direction for Future Research

Future research could extend this study in several important ways. First, integrating AI- and machine learning-based real-time threat prediction systems would enhance the model's predictive accuracy and operational responsiveness. Second, expanding the framework to address multi-country maritime governance and cooperative security arrangements would provide valuable insights into regional resilience issues. Third, incorporating climate-related risks and environmental uncertainties enables a more holistic assessment of long-term maritime vulnerability. Finally, validating the proposed model using field-based operational data from maritime agencies would strengthen its practical applicability and reliability.

Acknowledgement

The authors would like to express their sincere appreciation to the Indonesia Naval Technology College (STTAL) for providing academic guidance, institutional support, and valuable scientific resources that significantly contributed to this study. Special gratitude is also extended to all maritime governance experts, operational officers, and domain practitioners who generously shared their insights during the data interpretation and model validation stages of this study. The authors further acknowledge the constructive feedback provided by the anonymous reviewers, whose rigorous evaluations strengthened the clarity and academic rigor of this study. Finally, the authors thank the editorial team of the journal for their professional handling of the review process and for offering detailed suggestions that improved the overall quality of this publication.

Author Contributions

ARP contributed to conceptualization, methodology, software development, formal analysis, investigation, data curation, visualization, writing the original draft, and optimization model development. EK was responsible for methodology validation, resource provision, data verification, and reviewing the maritime logistics analysis. OSS contributed to supervision, validation, writing review and editing, evaluation of the governance framework, and overall research supervision. All authors have read and agreed to the published version of the manuscript.

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