

A Multi-Criteria Model for Assessing Maritime Piracy Risk in Global Shipping

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ABSTRACT: Maritime piracy and armed robbery remain significant threats to global shipping, affecting vessel safety, crew welfare, routing, insurance costs, and supply chain reliability. This paper proposes a semi-quantitative multi-criteria framework for assessing piracy risk. The model combines incident probability, vessel or route vulnerability, and weighted consequences, including crew safety, operational disruption, economic loss, legal complexity, and supply chain impact. Using selected piracy-prone regions and hypothetical route scenarios, the framework shows that risk is highest where frequent incidents coincide with high vulnerability and severe consequences. It offers a transparent, adaptable tool for operators, insurers, security professionals, and policymakers.

1 INTRODUCTION

Global shipping is a foundation of international trade and supply chain continuity[1,2]. However, maritime transport is exposed to a wide range of security threats, including piracy and armed robbery against ships[3–5]. These incidents can involve boarding, attempted attack, hijacking, theft, kidnapping, physical violence, or threat of violence against crew members[6]. The consequences of piracy are not limited to immediate security losses[7]. They may also include rerouting, increased fuel consumption, higher insurance premiums, delays, additional security measures, psychological harm to seafarers, disruption of charter schedules, and legal uncertainty[7–13].

From the perspective of ship operators, piracy risk is not an abstract security category but a practical voyage-planning problem[14–17]. A decision to maintain a route, increase speed, introduce additional watchkeeping, embark security personnel, or consider rerouting has direct consequences for cost, safety,

contractual performance, and crew welfare[18–20]. Therefore, piracy risk assessment should not be limited to counting incidents. It should also consider how exposed and vulnerable a particular vessel or route is, and what consequences may follow if an incident occurs.

The contemporary piracy threat is geographically uneven[21]. Reported incidents tend to concentrate in specific maritime areas, including parts of Southeast Asia, the Malacca and Singapore Straits, the Gulf of Guinea, and waters near Somalia and the Gulf of Aden[22,23]. The spatial concentration of incidents means that piracy risk should not be assessed only at a global level. Instead, it should be evaluated by route, region, vessel type, operational profile, and exposure time.

A purely descriptive approach is insufficient for decision-making because ship operators need to compare alternative routes and mitigation strategies. At the same time, a fully probabilistic model is difficult to develop because piracy data are incomplete,

underreporting may occur, and incident severity varies significantly. Therefore, this paper pro-poses a semi-quantitative multi-criteria framework that combines available incident in-formation with structured expert assessment.

Despite the availability of piracy incident reports and maritime security advisories, many operational decisions still rely on qualitative judgement rather than transparent comparative assessment. Existing information sources are useful for identifying piracy-prone regions, but they do not always provide a structured method for comparing routes, vessel exposure, vulnerability, and consequences within one decision-support framework. This creates a practical research gap between incident reporting and voyage-level risk assessment. The present study addresses this gap by proposing a simple, transparent, and adaptable multi-criteria model that can be used when precise statistical probabilities are unavailable or uncertain.

The aim of this paper is to develop an interdisciplinary risk framework for assessing maritime piracy risk in global shipping. The framework integrates probability, vulnerability, and weighted consequences in order to reflect the multi-dimensional nature of piracy risk. The research questions are as follows:

1. What factors should be included in a structured assessment of maritime piracy risk?
2. How can probability, vessel vulnerability, and consequences be integrated into a semi-quantitative model?
3. How can the proposed model support risk-informed decision-making in global ship-ping?

2 MARITIME PIRACY AS AN INTERDISCIPLINARY SHIPPING RISK

Maritime piracy is both a security threat and an operational risk[3]. It affects vessel movement, crew safety, cargo delivery, insurance arrangements, and commercial planning[24]. From a maritime security perspective, piracy is associated with hostile acts against ships and crews[24]. From an operational perspective, it may require route deviation, increased speed, additional watchkeeping, hardening measures, or the employment of private maritime security personnel where legally permitted[24]. From an economic perspective, piracy generates direct and indirect costs, including delays, ransom risk, security expenses, higher insurance premiums, and disruption of contractual obligations[1,8,9,12,19,24].

The legal dimension is also important. Piracy and armed robbery against ships may fall under different legal definitions depending on whether the incident occurs on the high seas, in territorial waters, or in port or anchorage areas[25–28]. This distinction affects jurisdiction, reporting procedures, prosecution, and the responsibilities of coastal states and flag states[29]. Consequently, a meaningful risk assessment must consider more than the number of incidents. It must also include exposure, vulnerability, severity, legal context, and potential impact on maritime supply chains.

An interdisciplinary approach is therefore necessary because piracy risk is not produced by one

factor alone. It emerges from the interaction between external threat conditions and internal vessel characteristics. For example, the same piracy-prone area may generate different risk levels for a slow-moving bulk carrier, a high-freeboard container vessel, an offshore support vessel, or a tanker carrying high-value cargo. Similarly, the impact of a piracy incident may differ depending on crew size, cargo type, charter obligations, insurance conditions, and the availability of naval or coastal response.

Figure 1 illustrates the three overlapping dimensions of maritime piracy risk. The security dimension encompasses threats to crew safety, violence, hostage-taking, and armed robbery. The operational dimension covers voyage disruption, rerouting, speed management, and charter obligations. The economic and legal dimension includes insurance costs, ransom exposure, jurisdictional complexity, and reporting requirements. The inter-sections between dimensions reflect the compound nature of piracy risk: a single incident may simultaneously generate security, operational, and economic consequences. The centre of the diagram represents the integrated piracy risk concept that the proposed frame-work seeks to capture.

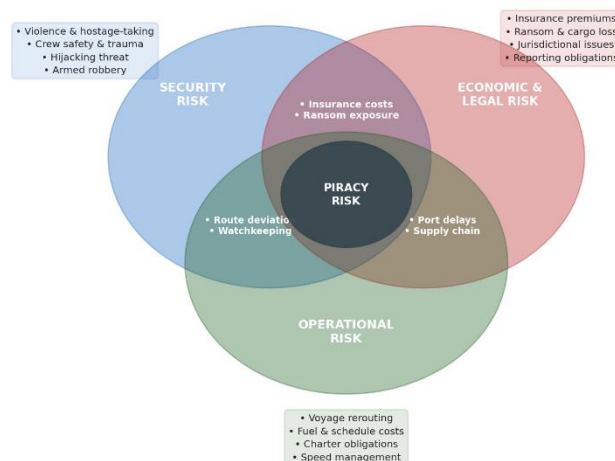


Figure 1. Interdisciplinary dimensions of maritime piracy risk: security, operational, and economic and legal perspectives. Author's own elaboration.

3 MATERIALS AND METHODS

3.1 Research Design

This study develops a semi-quantitative multi-criteria risk assessment framework. The method is designed for comparative assessment of piracy risk across selected routes, regions, or vessel scenarios. It does not attempt to predict individual pirate attacks. In-stead, it provides a structured scoring model that can support decision-making where precise probabilities are unavailable or uncertain.

The proposed model is not intended to replace official threat intelligence, company security procedures, or real-time voyage risk assessment. Instead, it is designed as a pre-liminary comparative tool that helps organise available information into a consistent structure. Its value lies in making assumptions explicit: the assessor must define the probability level, vessel or route vulnerability,

consequence scores, and criterion weights. This improves transparency and allows different scenarios to be compared under the same methodological logic.

The framework is based on three main components:

- piracy incident probability,
- vessel or route vulnerability,
- weighted consequences.

The model can be applied to geographical regions, specific voyage legs, or alternative routing options. It is particularly suitable for preliminary risk screening, voyage planning, and comparative risk evaluation.

3.2 General Risk Model

The basic model follows the classical understanding of risk as the interaction between probability and impact. In this paper, impact is expanded into an interdisciplinary weighted consequence index, while vulnerability is introduced as a separate modifying factor.

The overall piracy risk score for route or region i is calculated as:

$$R_i = P_i \times V_i \times \sum_{j=1}^m w_j C_{ij} \quad (1)$$

where:

R_i — piracy risk score for route or region i ,
 P_i — piracy incident probability score for route or region i ,
 V_i — vessel or route vulnerability score for route or region i ,
 C_{ij} — consequence score for criterion j in route or region i ,
 w_j — weight assigned to consequence criterion j ,
 m — number of consequence criteria.

The consequence index is defined as:

$$I_i = \sum_{j=1}^m w_j C_{ij} \quad (2)$$

Thus, the complete model can also be written as:

$$R_i = P_i \times V_i \times I_i \quad (3)$$

where I_i represents the weighted consequence index.

3.3 Scoring Scale

All input variables are assessed using a five-point ordinal scale. The scale is intentionally simple to improve transparency and usability in maritime decision-making contexts.

Table 1. Five-point ordinal scoring scale used in the proposed piracy risk assessment framework. Author's own elaboration.

Score	Interpretation
1	Very low
2	Low
3	Moderate
4	High
5	Very high

The five-point scale was selected because it is sufficiently simple for practical use while still allowing differentiation between low, moderate, high, and very high risk conditions. In maritime operations, decision-makers often work with incomplete or rapidly changing information. For this reason, an ordinal scale may be more realistic than a purely numerical probability estimate. The scale also allows expert judgement to be combined with reported incident patterns, regional advisories, vessel characteristics, and operational exposure.

The probability score P_i reflects the relative likelihood of piracy or armed robbery incidents in a given region or route segment. It may be estimated using incident reports, regional security advisories, historical patterns, and current threat intelligence.

The vulnerability score V_i reflects vessel and route characteristics that influence exposure and susceptibility. Relevant factors may include vessel speed, freeboard, type of cargo, time spent in high-risk areas, distance from shore, watchkeeping arrangements, anti-piracy measures, and availability of response forces.

3.4 Consequence Criteria and Weights

Five consequence criteria are proposed to reflect the interdisciplinary nature of piracy risk. The weights are normalised so that their sum equals 1.

Table 2. Consequence criteria and normalised weights used in the interdisciplinary piracy risk model. Author's own elaboration.

Symbol	Criterion	Description	Weight
C1	Crew safety impact	Threat to life, injury, kidnapping, trauma, hostage-taking	0.30
C2	Operational disruption	Delay, route deviation, interruption of voyage, loss of schedule reliability	0.20
C3	Economic loss	Increased insurance, fuel cost, security cost, cargo loss, ransom exposure	0.20
C4	Legal/regulatory complexity	Jurisdictional issues, reporting obligations, compliance, prosecution barriers	0.10
C5	Supply chain impact	Disruption of cargo flow, port delays, contractual consequences	0.20

Crew safety receives the highest weight because piracy directly threatens seafarers and may involve violence, hostage-taking, or kidnapping. Operational, economic, and supply chain impacts receive equal weights because these dimensions are central to shipping continuity. Legal and regulatory complexity is assigned a lower, but still relevant, weight because it influences incident response and post-incident management.

The weights can be modified depending on the decision-making context. For example, an insurer may assign higher weight to economic loss, while a ship operator may assign higher weight to crew safety and operational disruption.

3.5 Risk Classification

The maximum possible risk score is obtained when $P_i = 5$, $V_i = 5$, and $I_i = 5$, giving a maximum value of 125. The following classification is proposed:

Table 3. Proposed classification of piracy risk scores.

Author's own elaboration.

Risk score	Risk level	Interpretation
0–20	Low	Routine monitoring is sufficient
21–40	Moderate	Additional voyage planning and monitoring required
41–60	High	Risk mitigation measures should be implemented
61–125	Critical	Strong mitigation, rerouting, or enhanced security measures should be considered

This classification is illustrative and may be adjusted according to company risk appetite, flag-state requirements, insurance conditions, or route-specific security advisories.

4 RESULTS

4.1 Demonstration of the Framework

To demonstrate the proposed model, four illustrative route or region scenarios are assessed. The scores are not intended to replace real-time maritime security intelligence. They provide a methodological demonstration of how the framework may be applied.

Figure 2 presents a visual summary of the four illustrative scenarios used to demonstrate the framework. Each card shows the probability score, vulnerability score, individual consequence ratings across criteria C1–C5, the weighted consequence index, and the final risk score. The colour coding reflects the assigned risk level: green for low, yellow for moderate, orange for high, and purple for critical. The cards allow rapid comparison of scenario profiles and highlight

how differences in input scores translate into divergent risk classifications.

Table 4. Illustrative scoring of piracy risk variables for selected route or region scenarios. Author's own elaboration.

Scenario	Region / route type	Pi	Vi	C1	C2	C3	C4	C5
A	Low-exposure open ocean route	1	2	2	2	2	1	2
B	Port/anchorage area with recurrent robbery incidents	3	3	3	3	3	2	3
C	High-density strait with frequent boarding risk	4	3	3	4	4	3	4
D	High-risk piracy area with hijacking potential	4	4	5	5	5	4	5

The weighted consequence index is calculated for each scenario:

$$I_i = 0.30C_1 + 0.20C_2 + 0.20C_3 + 0.10C_4 + 0.20C_5$$

Table 5. Calculated weighted consequence indices, piracy risk scores, and risk levels for the illustrative scenarios.

Author's own elaboration.

Scenario	Weighted index I_i	Risk score R_i	Risk level
A	1.90	3.80	Low
B	2.90	26.10	Moderate
C	3.70	44.40	High
D	4.90	78.40	Critical

Figure 3 presents the calculated piracy risk scores for scenarios A–D in graphical form. The bar chart confirms the progressive increase in risk across scenarios, with Scenario A classified as low risk and Scenario D reaching the critical category. The colour coding reflects the risk level assigned in Table 3. The chart illustrates that risk escalates non-linearly: the difference between Scenario A and Scenario B is substantially smaller than the difference between Scenario C and Scenario D, reflecting the multiplicative structure of the model in which simultaneous increases in probability, vulnerability, and consequences produce a compounding effect on the final score.



Figure 2. Risk profile cards for illustrative scenarios A–D, summarising probability, vulnerability, and consequence scores. Author's own elaboration.

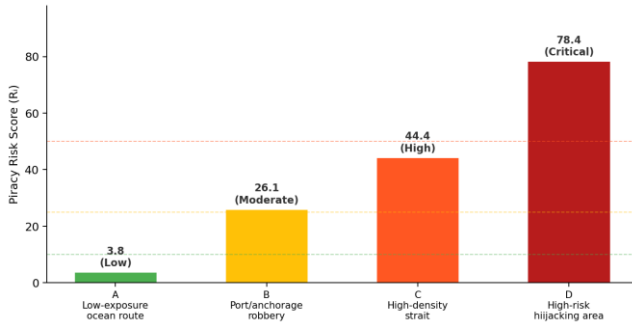


Figure 3. Piracy risk scores for illustrative scenarios A–D. Author's own elaboration.

Figure 4 presents the consequence profiles for each scenario across the five weighted criteria. The radar chart illustrates that scenarios differ not only in their overall risk score, but also in the distribution of consequences across dimensions. Scenario D shows the highest values across all criteria, with particular severity in crew safety and supply chain impact. Scenario A remains consistently low across all dimensions. Scenarios B and C differ primarily in operational, economic, and supply chain scores, reflecting the distinction between port-area robbery and route-exposure risk.

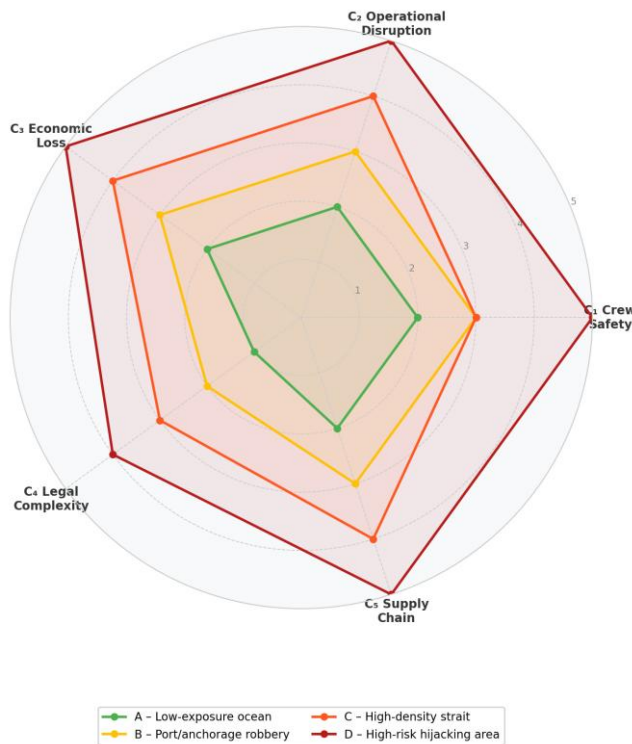


Figure 4. Consequence profiles for scenarios A–D across five risk criteria. Author's own elaboration.

4.2 Interpretation of Results

The results show that piracy risk increases significantly when probability and vulnerability are both elevated.

Scenario A has a low probability score and limited vulnerability, resulting in a low overall risk score despite non-zero consequences.

Scenario B represents recurrent robbery risk in port or anchorage areas. The risk level is moderate because the probability and vulnerability are higher, but the

expected consequences are not as severe as in hijacking-prone scenarios.

Scenario C illustrates a high-density maritime route where boarding incidents may occur more frequently. Even when crew safety consequences are assessed as moderate rather than very high, the combined operational, economic, and supply chain impacts increase the overall risk score to the high category. This reflects the importance of route exposure and shipping density in piracy risk assessment.

Scenario D produces the highest score because it combines high probability, high vulnerability, and severe consequences. In this case, the possibility of hijacking, kidnapping, violence, major operational disruption, and supply chain effects results in a critical risk classification. Such a scenario would require strong mitigation measures, including enhanced voyage planning, implementation of best management practices, route evaluation, crew preparedness, and potentially additional security measures depending on legal and operational conditions.

Figure 5 presents a heatmap of the weighted consequence scores across all scenarios and criteria. Darker shading indicates a higher weighted contribution to the overall consequence index. The chart confirms that Scenario D generates the highest weighted scores across all five criteria, with crew safety (C1) and supply chain impact (C5) producing the largest individual contributions. In contrast, legal and regulatory complexity (C4) produces the lowest weighted scores across all scenarios due to its lower assigned weight. The heatmap also illustrates that Scenarios B and C differ most markedly in their operational and economic consequence scores, which reflects the distinction between port-area robbery risk and route-exposure risk described in Section 4.1.

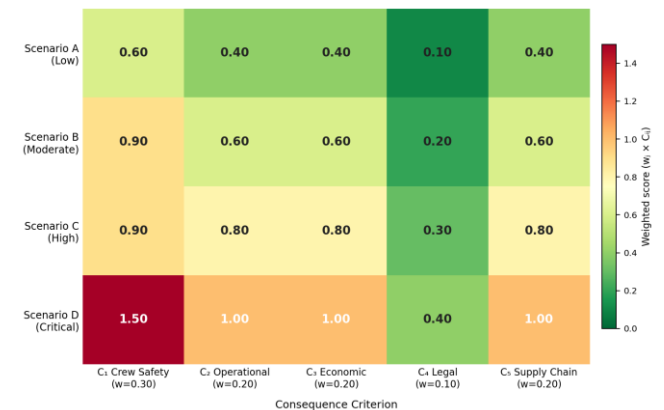


Figure 5. Weighted consequence scores ($w_j \times C_{ij}$) for scenarios A–D across five risk criteria. Author's own elaboration.

The comparison also shows that high incident probability alone does not fully determine the final risk level. A region with recurrent low-severity robberies may produce a lower overall score than a less frequent but more severe piracy environment. This distinction is important because maritime decision-making must consider both frequency and consequence severity. In practice, a route with moderate probability but high potential for crew harm, hijacking, or prolonged operational disruption may require stronger mitigation than a route with more frequent but lower-impact incidents.

4.3 Sensitivity of the Model

A key advantage of the proposed framework is that it allows sensitivity analysis. Since the final score is multiplicative, changes in probability or vulnerability can significantly affect the total risk score. For example, if vessel vulnerability in Scenario D is reduced from 4 to 3 through improved security measures, the risk score decreases from:

$$R_D = 4 \times 4 \times 4.90 = 78.40$$

to:

$$R_D = 4 \times 3 \times 4.90 = 58.80$$

This moves the scenario from the critical category to the high category. Figure 6 illustrates the sensitivity of the risk score to changes in vessel vulnerability. The left panel shows that reducing the vulnerability score in Scenario D from 5 to 1 progressively lowers the risk level from critical to low, even when probability and consequence scores remain unchanged. The right panel confirms this pattern across all scenarios: vulnerability reduction has the greatest absolute effect in high-probability, high-consequence environments such as Scenario D, while its impact in low-exposure settings such as Scenario A remains limited.

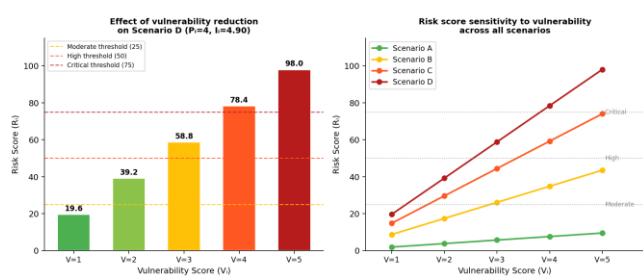


Figure 6. Sensitivity analysis: impact of vulnerability score on piracy risk score across illustrative scenarios. Author's own elaboration.

The example demonstrates that vulnerability reduction can be an effective risk mitigation strategy even when external threat probability remains unchanged. In practical terms, this may include improved watchkeeping, citadel readiness, razor wire, water spray, speed management, route planning, secure communications, and crew drills.

This sensitivity effect is relevant for maritime security planning because vulnerability is one of the few components that ship operators can directly influence. While regional piracy probability depends on wider political, economic, and security conditions, vessel vulnerability can be reduced through voyage planning, crew training, physical protection measures, communication procedures, speed management, and compliance with best management practices. The model therefore links assessment with action: it does not only classify risk, but also helps identify where mitigation can reduce the final score.

5 DISCUSSION

The main contribution of this paper is the integration of three dimensions that are often considered

separately in piracy-related decision-making: regional threat probability, vessel or route vulnerability, and interdisciplinary consequences. By combining these elements in one semi-quantitative framework, the model provides a practical bridge between descriptive piracy reporting and operational risk assessment. This is particularly useful in situations where complete statistical data are unavailable, but decisions still have to be made under uncertainty.

The proposed framework supports an interdisciplinary understanding of piracy risk. Instead of treating piracy as a single security variable, the model decomposes risk into probability, vulnerability, and multiple consequence dimensions. This structure reflects the operational reality of global shipping, where the same piracy event may generate different impacts depending on vessel type, route, cargo, crew exposure, and contractual obligations.

The model has several practical advantages. First, it is transparent. Each score and weight can be reviewed, discussed, and adjusted by maritime experts. Second, it is flexible. The framework can be applied to different vessel types, regions, or route alternatives. Third, it supports comparative decision-making. Ship operators may compare risk levels for alternative routes or assess how mitigation measures reduce vulnerability. The model also highlights the importance of vulnerability as a controllable factor. External piracy probability is usually beyond the control of individual ship operators. However, vulnerability can be reduced through operational and technical measures. Therefore, the framework can help distinguish between risks that require strategic response, such as rerouting or insurance review, and risks that can be mitigated through onboard preparedness and voyage planning.

However, the numerical nature of the model requires careful interpretation. A key challenge in using this type of model is the risk of false precision. Although the final score is numerical, it should not be interpreted as an exact measurement of piracy risk. Rather, it is a structured representation of expert judgement supported by available information. The purpose of the score is comparative: to identify whether one route, vessel profile, or mitigation option appears more exposed than another. Therefore, the model should be used as a decision-support tool, not as a deterministic prediction of piracy incidents.

Nevertheless, the framework has limitations. The use of ordinal scoring introduces subjectivity. Different assessors may assign different probability, vulnerability, or consequence values. The proposed weights are also illustrative and should be validated through expert consultation, surveys, or analytic hierarchy process methods in future research. Moreover, piracy data may be affected by underreporting, inconsistent classification, and rapidly changing regional security conditions. Therefore, the model should be used together with current security advisories and official reporting sources, not as a standalone prediction tool.

Despite these limitations, the framework provides a useful methodological basis for further research and practical risk screening. Future research should focus on empirical validation of the framework. This may include expert surveys among ship operators,

maritime security professionals, insurers, and seafarers, as well as comparison with historical piracy incident datasets. The model could also be extended by incorporating AIS-based exposure measures, vessel-specific parameters, seasonal variation, regional response capacity, fuzzy logic or Monte Carlo simulation, to better represent uncertainty. Such developments would allow the framework to move from an illustrative model towards a more operational risk assessment tool.

6 CONCLUSIONS

This paper proposed a semi-quantitative multi-criteria framework for assessing maritime piracy risk in global shipping. The model combines piracy incident probability, vessel or route vulnerability, and a weighted interdisciplinary consequence index. The framework reflects the fact that piracy is not only a security issue but also an operational, economic, legal, human, and supply chain risk.

The demonstration showed that the highest risk levels occur when high incident probability overlaps with vessel vulnerability and severe consequences. The model also showed that reducing vulnerability may significantly lower the overall risk score, even when regional threat probability remains unchanged. This finding is important for ship operators because it links risk assessment directly with mitigation planning.

The proposed framework may support voyage planning, maritime security assessment, insurance analysis, and policy discussions. Future research should validate the model using expert surveys, real incident datasets, route-specific exposure indicators, and sensitivity analysis of weighting schemes.

ABBREVIATIONS

AIS Automatic Identification System
 BMP Best Management Practices
 ICC International Chamber of Commerce
 IMB International Maritime Bureau
 IMO International Maritime Organization
 UNCLOS United Nations Convention on the Law of the Sea
 UNCTAD United Nations Conference on Trade and Development

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