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An Integrated MCDM Framework for Risk Assessment of Commercial Fishing Vessel Subsystems: Resolving Methodological Ambiguities in Maritime Safety

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ABSTRACT

Commercial fishing vessels account for 44% of global seafarer fatalities despite comprising only 2.3% of the merchant fleet, with equipment failure contributing to 31% of fatal incidents. The FMEA method critically underperforms in this context due to implicit equal weighting, non-unique Risk Priority Number (RPN) mapping, and subjective weight assignment. This study validates an integrated CRITIC-CODAS-FMEA framework, building on our prior application to composite Lenj hulls, by extending robust proof across navigation, refrigeration, and propulsion subsystems of fishing Lenj. Almost all failure modes are analyzed using expert elicitation (n=12 marine specialists). The CRITIC method derives objective weights by quantifying contrast intensity and inter-criterion conflict in S/O/D ratings, while the CODAS method employed Euclidean and Taxicab distances to resolve ranking ambiguities in the weighted space. The framework achieves 100% resolution of identical RPN clusters and elevates 89% of high-severity modes (S≥9) into top-10 rankings versus 60% for conventional FMEA. It demonstrated superior alignment with expert consensus (Spearman ρ=0.87 vs. 0.62) and 92% expert agreement versus 56% for RPN-based prioritization. This framework transforms risk assessment into a context-aware decision tool, objectively capturing marine operational realities to significantly enhance crew safety for the 34.3 million fishers operating worldwide.

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1. Introduction

Maritime safety in commercial fishing remains critically vulnerable to equipment failure within harsh operational environments. Globally, fishing vessels account for 44% of all seafarer fatalities despite comprising only 2.3% of the world's merchant fleet [1], with equipment malfunction contributing to 31% of fatal incidents[2]. These vessels operate under uniquely severe constraints: extended missions (7–21 days) far from repair facilities [3], continuous exposure to corrosive saltwater [4], [5], and dynamic mechanical stresses from wave impacts [6]. Under such conditions, systematic risk assessment of three critical subsystems navigation, refrigeration, and propulsion is essential to prevent catastrophic failures compromising vessel integrity and crew safety[7],. These constraints transform minor methodological flaws in risk assessment into critical vulnerabilities, where a failure that is a minor inconvenience on land can result in total economic or life loss at sea.

Traditional Failure Mode and Effects Analysis (FMEA) has long served as the industry standard for failure mode prioritization via the Risk Priority Number (RPN = S×O×D) [8]. However, three fundamental limitations undermine its reliability in maritime contexts. First, the equal weighting fallacy implicitly enforces equal importance on Severity (S), Occurrence (O), and Detection (D) despite empirical evidence that their significance varies by subsystem. In navigation systems, severity warrants elevated emphasis (e.g., rudder failure), whereas in refrigeration, occurrence dominates due to progressive economic losses [9], [10].

Second, non-unique RPN mapping frequently produces identical values for failure modes with distinct risk profiles. In complex maritime systems, failure modes with vastly different safety implications such as Compass Malfunction and Lack of Weather Information often yield identical RPN scores, creating ambiguity in maintenance prioritization,[11]. Third, subjective weight assignment relies on expert judgment without accounting for interdependencies between S, O, and D ratings [12], [13]. Generic weighting schemes ignore distinctive marine S–O interdependencies, such as the strong negative correlations($\rho \approx -0.68$) often found in high-severity navigation failures[14]. These limitations are problematic; a 2023 industry survey revealed that while 68% of operators rely on RPN, 41% of catastrophic failures occur in modes ranked outside the top-10 priorities [1]. A comparative breakdown of how these limitations of FMEA manifest in maritime versus land-based vehicles is provided in Table 1.

Table 1. Comparative analysis of FMEA limitations in maritime versus land-based applications

Limitation	Land-based systems	Maritime fishing vessels	Safety consequence
Equal weighting	Moderate (repair within hours)	**Severe** (7–21 day missions; 41% >200 NM from port)	Delayed critical maintenance → crew endangerment
Identical RPN values	Manageable (spare parts >30% inventory)	**Critical** (<5% spare parts inventory)	Misallocated resources → catastrophic failure
Subjective weighting	Tolerable (controlled environments)	**Unacceptable** (3.2× faster degradation)	Inconsistent risk assessment → regulatory non-compliance

The evolution of hybrid FMEA frameworks reflects a deliberate shift from subjective expert judgments to objective, data-driven weighting methods. Early hybrid approaches employed the Analytic Hierarchy Process (AHP) to replace the multiplicative RPN with weighted additive models [9], [15]. While AHP enabled explicit weighting, it reintroduced subjectivity via pairwise comparisons, with inter-expert variation exceeding 35% in marine applications [16]. To mitigate the inherent vagueness of these crisp judgments, Fuzzy AHP-FMEA integrates fuzzy set theory, modeling linguistic expert assessments through membership functions. However, while this reduces semantic ambiguity, the approach remains fundamentally anchored to subjective pairwise comparisons and fails to eliminate expert bias. Consequently, the transition toward objective weighting represents a necessary methodological paradigm shift.

Entropy-based weighting quantifies information dispersion [17], but fundamentally fails to capture inter-criterion conflicts a significant flaw for marine systems where Severity (S) and Occurrence (O) frequently exhibit strong inverse relationships[18]. The CRITIC method addresses this gap by simultaneously evaluating contrast intensity and criterion conflict [12], [19]. This dual consideration enables CRITIC to derive weights that objectively mirror operational risk dynamics. The chronological evolution of weighting paradigms within hybrid FMEA are shown in Table 2 where each approach's mathematical derivation, inherent constraints, and practical suitability for maritime reliability assessments are given. As shown, the trajectory moves from expert-dependent heuristics toward conflict-sensitive algorithms, culminating in CRITIC-based frameworks that explicitly model the S–O interdependencies characteristic of vessel operations.

Table 2. Evolution of weighting methods in hybrid FMEA frameworks

Method	Weight derivation approach	Key limitation	Maritime applicability	Representative studies
AHP-FMEA	Pairwise expert comparisons	Introduces new subjectivity; inter-expert weight variation >35%	Limited (requires stable operating context)	[15], [20]
Fuzzy AHP-FMEA	Linguistic variables + pairwise comparisons	Still dependent on subjective initial judgments; fails to capture criterion conflicts	Moderate (handles uncertainty but not interdependencies)	[13] , [21]
Entropy-FMEA	Information content quantification	Ignores inter-criterion conflicts; treats criteria as independent (fatal flaw for marine S–O inverse relationships)	Poor (fails to capture S–O inverse relationships common in marine systems)	[12], [17]
CRITIC-FMEA	Contrast intensity + inter-criterion conflict	Requires sufficient failure mode diversity for stable correlation estimates	High (explicitly models S–O interdependencies observed in marine operations)	[12], [19], [22]

Building upon these objective weighting paradigms, distance-based ranking methods constitute the final component in overcoming FMEA's scalar limitations. While TOPSIS dominated early frameworks, its reduced discrimination power when alternatives cluster near the ideal solution proves problematic for maritime FMEA [6],. The CODAS (COmbinative Distance-based ASsessment) method overcomes this via dual-distance distinction using both Euclidean and Taxicab distances from the negative-ideal solution[23], [24],[25]. Critically, the Taxicab distance captures directional differences in the weighted criterion space that Euclidean distance alone cannot resolve.

The CODAS is integrated with CRITIC-FMEA in our previous work to assess the risk priority on composite fishing Lenj hulls [26]. In that initial application, this combination demonstrated superior discrimination power by objectively weighting risk factors according to their inherent data conflicts while simultaneously resolving ranking ambiguities through dual-distance metrics. The study revealed that traditional FMEA consistently under-prioritized failure modes with high severity but moderate detectability, whereas CRITIC-CODAS-FMEA hybrid model accurately elevated these critical risks, proving robust even with sparse failure data.

Furthermore, by explicitly accounting for the inverse relationships between risk criteria, CRITIC ensures that the Taxicab distance metric can more effectively distinguish between failure modes that exhibit contrasting operational impacts, thereby translating complex correlation data into actionable maintenance priorities. The strategic positioning of the CRITIC-CODAS-FMEA model against other contemporary hybrid approaches is detailed in Table 3.

Table 3. Positioning of CRITIC-CODAS-FMEA against existing hybrid FMEA approaches

Approach	Weighting method	Ranking method	Identical RPN resolution	Marine validation	Critical limitation
Conventional FMEA	Implicit equal	Multiplicative RPN	0% (14/14 clusters unresolved)	Extensive	Three fundamental limitations unaddressed
AHP-FMEA	Subjective pairwise	Weighted additive	0% (identical RPN values persist)	Limited	Weight subjectivity reintroduces bias
CRITIC-TOPSIS	Objective (CRITIC)	Euclidean distance only	~43% (6/14 clusters resolved)	Single subsystem (navigation)	Reduced discrimination near ideal solution
Entropy-CODAS	Objective (entropy)	Dual-distance (E+T)	~71% (10/14 clusters resolved)	Non-marine contexts	Ignores S–O interdependencies critical in marine systems
CRITIC-CODAS-FMEA	Objective (CRITIC)	Dual-distance (E+Taxicab)	100% (14/14 clusters resolved)	Three subsystems (71 modes)	Computational complexity

Table 3 underscores the methodological limitations of existing approaches and highlights three interconnected gaps in current maritime risk assessment: (1) Absence of context-aware objective weighting, as existing marine FMEA studies rely on subjective weights [8], [9] and fail to capture subsystem-specific interdependencies; (2) Inadequate discrimination for identical RPN values, given that conventional RPN produces identical scores for nearly 10% of failure modes in complex marine systems[27]; and (3) Unverified CRITIC-CODAS synergy, where despite individual pairings with other methods, their combined application remains unvalidated across multi-subsystem maritime contexts. The integrated CRITIC-CODAS-FMEA framework resolves all three gaps systematically.

The developed method is applied to three subsystems, navigation and steering; refrigeration; and propulsion, of fishing Lenjes. The Lenj is a traditional wooden-hull indigenous to the Persian Gulf and Gulf of Oman, with construction techniques dating back over 400 years. The fishing Lenjes remain vital to small-scale fisheries in Iran, UAE, Oman, and Bahrain, supporting livelihoods for approximately 15,000 fishers in the region. Typical fishing Lenjes range from 12–25 m in length overall, 3.5-6 m in beam, 1.5-2.5 m in draft and 15-80 GT. These vessels carry a crew of 4–12 on 3–14 days voyages extending 50–300 nautical miles from port with a hold capacity of 5-24 tons of ice/fish. The hull material is traditionally teak or acacia wood, however, in modern variants increasingly use composite materials.

The fishing Lenjes are usually derived with a fixed pitch propeller that is run with a single diesel engine of 150-450 HP using a direct mechanical coupling. These are also equipped with a 15-40 kVA diesel generator for refrigeration and navigation equipment. The Navigation relies on GPS chart-plotters, magnetic compass, VHF radio, and basic echo sounders; advanced systems such as AIS, radar, or automated engine monitoring are rare due to cost constraints and limited electrical generation capacity. Refrigeration uses simple direct-expansion cycles with manual controls.

It is important to clarify that this study specifically targets traditional fishing Lenjes outfitted with only essential navigational and operational aids for coastal and short-sea transit. Consequently, advanced monitoring systems and specialized fishing gear characteristic of large-scale professional commercial vessels fall outside the analytical scope. This technological simplicity, combined with extended voyages in harsh marine environments, makes Lenjes particularly vulnerable to equipment failures precisely the context where systematic risk assessment proves most valuable.

Deployed across three critical fishing Lenj subsystems electronic/mechanical navigation and steering, refrigeration, and integrated propulsion assemblies the methodology encompasses a comprehensive set of 71 distinct failure modes. It is important to clarify that this research specifically targets traditional fishing Lenjes, which are typically outfitted with only the essential navigational and operational aids required for coastal and short-sea transit. Consequently, advanced monitoring systems and specialized fishing gear characteristic of large-scale professional commercial vessels fall outside the analytical scope of this study. By leveraging CRITIC to derive objective weights directly from S/O/D rating distributions and utilizing CODAS's dual-distance mechanism to resolve ranking ambiguities, we demonstrate how this combined approach neutralizes the core deficiencies of conventional FMEA. The framework's robustness is further verified through inputs from a multi-disciplinary panel of marine inspection specialists. Beyond resolving these identified gaps, three key advancements are delivered to maritime safety engineering:

- **Multi-subsystem validation and methodological generalization:** Building upon the framework's inaugural application to composite Lenj hulls, this study rigorously validates the CRITIC-CODAS-FMEA model across navigation, refrigeration, and propulsion architectures, confirming its adaptability to diverse Lenj systems.
- **Subsystem-specific objective weights validated through operational reality:** Weights are derived directly from rating distributions, eliminating expert subjectivity while capturing nuanced operational dynamics, such as the inherently low detectability of incipient propulsion failures.
- **Actionable risk prioritization with quantifiable safety improvements:** The framework achieves 100% resolution of identical RPN clusters and significantly elevates high-severity modes into top-10 rankings, directly enhancing crew protection for fishers operating in hazardous maritime environments [28].

2. Formulation of the CRITIC-CODAS-FMEA Framework

This section presents the compact mathematical formulation of the integrated risk assessment framework. The methodology comprises three sequential stages: (i) conventional FMEA for failure mode identification and S/O/D rating, (ii) CRITIC for objective criterion weighting, and (iii) CODAS for discriminative failure mode ranking.

2.1. Conventional FMEA and RPN Calculation

For a system with m failure modes evaluated against three risk criteria (Severity S, Occurrence O, and Detection D), the initial assessment yields a decision matrix $X \in \mathbb{R}_{m\times 3}$:

$$X = \begin{bmatrix} x_{11} & x_{12} & x_{13} \\ \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & x_{m3} \end{bmatrix} = \begin{bmatrix} S_1 & O_1 & D_1 \\ \vdots & \vdots & \vdots \\ S_m & O_m & D_m \end{bmatrix} \qquad (1)$$

Where $x_{ij} \in \{1, 2, ... 10\}$ represents the rating of failure mode i on criterion j. The conventional FMEA process employs standardized 10-point scales for Severity (S), Occurrence (O), and Detection (D) as defined in Table 4. These scales provide semantic anchors for expert elicitation during failure mode assessment.

Table 4. Traditional FMEA Risk Factor Evaluation Scales [29]

Level	Severity (*S*)	Occurrence (*O*)	Detection (*D*)
1	No operational impact	Almost never	Almost certain detection
2	Very low severity	Remote likelihood	Very high detectability
3	Low severity	Very low likelihood	High detectability
4	Minor functional effect	Low likelihood	Moderately high detectability
5	Moderate functional effect	Moderately low likelihood	Medium detectability
6	Significant performance loss	Medium likelihood	Low detectability
7	Major operational disruption	Moderately high likelihood	Very low detectability
8	Extreme safety hazard	High likelihood	Slight detectability
9	Critical system failure	Very high likelihood	Remote detectability
10	Catastrophic consequences	Almost certain	Almost undetectable

The traditional Risk Priority Number (RPN) is computed as:

$$\mathrm{RPN}_i = S_i \times O_i \times D_i \qquad \& \quad i = 1,2,\dots,m \qquad (2)$$

This multiplicative aggregation suffers from three critical limitations: (a) implicit equal weighting of criteria, (b) non-unique mapping (distinct (S, O, D) triples yielding identical RPN), and (c) subjective weight assignment.

2.2. CRITIC for Objective Weight Determination

The CRITIC method derives objective weights w_j by quantifying both contrast intensity and inter-criterion conflict. It consists the following steps:

Step 1 – Standardization: Convert X to normalized matrix $R \in [0,1]_{m\times 3}$ using linear scaling (benefit criteria):

$$r_{ij} = \frac{x_{ij} - \min_i (x_{ij})}{\max_i (x_{ij}) - \min_i (x_{ij})} \qquad (3)$$

Step 2 – Correlation analysis: Compute Pearson correlation coefficients ρ_{jk} between criteria j and k:

$$\rho_{jk} = \frac{\sum_{i=1}^{m} (r_{ij} - \bar{r}_j)(r_{ik} - \bar{r}_k)}{\sqrt{\sum_{i=1}^{m} (r_{ij} - \bar{r}_j)^2 \sum_{i=1}^{m} (r_{ik} - \bar{r}_k)^2}} \qquad (4)$$

Step 3 – Criterion contrast and conflict: Calculate contrast intensity (standard deviation σ_j) and conflict measure C_j:

$$\sigma_j = \sqrt{\frac{1}{m-1} \sum_{i=1}^{m} (r_{ij} - \bar{r}_j)^2} \qquad (5)$$

$$C_j = \sigma_j \sum_{k=1}^{3} (1 - |\rho_{jk}|) \qquad (6)$$

Step 4 – Objective weight derivation

$$w_j = \frac{C_j}{\sum_{k=1}^{3} C_k}, \quad where \quad \sum_{j=1}^{3} w_j = 1 \ \& \ w_j \geq 0 \qquad (7)$$

This yields system-specific weights $w = [w_S, w_O, w_D]^T$ reflecting marine operational realities (e.g., elevated w_S for navigation subsystems). From a practical implementation standpoint, the CRITIC framework inherently self-calibrates to distinct marine operating conditions, ensuring that weight distributions emerge directly from observed failure data rather than relying on subjective expert assumptions. The CRITIC weights for the navigation, refrigeration and propulsion subsystems of fishing Lenj are given in table 5. These weights are obtained from 71 failure mode dataset.

Table 5. CRITIC-derived weights for fishing Lenj subsystems

Subsystem	w_S	w_O	w_D	Interpretation
Navigation and Steering	0.359	0.421	0.220	Occurrence dominates due to frequent operational failures (e.g., GPS signal loss) with moderate severity and poor detectability of incipient faults
Refrigeration	0.357	0.333	0.310	Near-uniform weights reflect equal criticality of severity (catch spoilage), occurrence (extended voyages), and detection (basic sensor coverage)
Propulsion	0.351	0.479	0.170	Occurrence-severity dominance with minimal detection influence due to poor observability of incipient failures (oil consumption, corrosion) on resource-constrained Lenjes

2.3. CODAS for Failure Mode Ranking

CODAS ranks alternatives using Euclidean (E) and Taxicab (T) distances from the negative-ideal solution (NIS). It consists of the following steps:

Step 1 – Compute Weighted normalized matrix;

$$V = [v_{ij}] \quad \text{where} \quad v_{ij} = r_{ij} \times w_j \tag{8}$$

Step 2 – Determine Negative-ideal solution (NIS) vector;

$$n = [n_1, n_2, n_3]^T \quad \text{with} \quad n_j = \min_i (v_{ij}) \tag{9}$$

Step 3 – Calculate the Euclidean (E) and Taxicab (T) distances;

$$E_i = \sqrt{\sum_{j=1}^{3} (v_{ij} - n_j)^2} \tag{10}$$

$$T_i = \sum_{j=1}^{3} | v_{ij} - n_j | \tag{11}$$

Step 4 – Construct relative assessment matrix;

$$H = [h_{ik}] \quad \text{where} \quad h_{ik} = (E_i - E_k) + \tau(E_i - E_k) \times (T_i - T_k) \tag{12}$$

With threshold parameter τ = 0.02 (empirically validated for FMEA applications).

Step 5 – Determine the final score and ranking

$$\text{CODAS}_i = \sum_{k=1}^{m} h_{ik}, \quad \text{Rank}_i = \text{descending order of CODAS}_i \tag{13}$$

The dual-distance approach resolves RPN ambiguities (e.g., identical RPN modes receive distinct CODAS scores via T_i differentiation). The integrated framework algorithm of the complete CRITIC-CODAS-FMEA procedure are shown in Table 6.

Table 6. Integrated framework algorithm of the complete CRITIC-CODAS-FMEA method

Step	Input	Operation	Output	Resolves FMEA Limitation
1	Expert ratings	Construct $\mathbf{X} \in \mathbb{R}_{m\times 3}$	S/O/D matrix	—
2	**X**	CRITIC weight derivation (Part 3.2)	$\mathbf{w} = [w_S, w_O, w_D]^T$	Equal weighting & subjectivity
3	**X**, **w**	Normalization + weighting → **V**	Weighted decision matrix	—
4	**V**	CODAS distance computation (Part 3.3)	E_i, T_i for all i	Identical RPN ambiguity
5	E_i, T_i	Relative assessment → ranking	Final priority order	Scalar aggregation limitation

3. Expert Elicitation Methodology and Data Collection

To minimize subjectivity in risk assessment, Severity (S), Occurrence (O), and Detection (D) ratings were evaluated independently by twelve marine inspection specialists organized into three domain-specific panels corresponding to the subsystems under study: navigation, refrigeration, and propulsion. Each panel possessed ≥10 years' field experience inspecting commercial fishing Lenjes in Persian Gulf operations and rated only their assigned subsystem to ensure deep domain expertise:

- **Navigation and steering panel:** Experts specializing in electronic/mechanical navigation systems.

- **Refrigeration panel:** Experts specializing in marine refrigeration and cold-chain systems.
- **Propulsion panel:** Experts specializing in diesel propulsion and auxiliary machinery.

This panel-based approach ensured consistent evaluation rigor across all 71 failure modes (Navigation: 17 modes, Refrigeration: 21 modes, Propulsion: 33 modes). Within each panel, experts independently rated all failure modes of their subsystem using the standardized 10-point scales in Table 4. Ratings were collected via anonymous digital forms with randomized failure mode presentation to minimize anchoring bias and groupthink.

Unlike conventional studies that employ the arithmetic mean, final scores for each failure mode were derived using the median method combined with a round-up (ceiling) function. This approach enhances robustness against outliers and adheres to the precautionary principle in maritime safety by conservatively rounding fractional risk scores to the next highest integer. The aggregation formula is defined as:

$$Score_{final} = Ceil(median(Score_1, Score_2, \dots, Score_n)) \quad (14)$$

Where $Score_i$ represents the rating assigned by the i-th expert within the subsystem panel, n is the number of experts in the panel, and Ceil() denotes the rounding up function (to the nearest integer) (rounding up to the nearest integer). For example, if the expert ratings for a failure mode were {5, 6, 7, 8}, the median is 6.5, which is rounded up to 7 to ensure a conservative risk estimation. Discrepancies exceeding 2 rating points triggered moderated discussion until ≥90% consensus was achieved. Inter-rater reliability analysis confirmed substantial agreement within panels for Severity ($\kappa = 0.78 \pm 0.04$) and Occurrence ($\kappa = 0.72 \pm 0.05$), and moderate agreement for Detection ($\kappa = 0.65 \pm 0.06$) using Fleiss' kappa coefficient (mean ± standard deviation across three panels). The resulting decision matrix X∈R71×3 provided empirically grounded, domain-validated input for CRITIC weight derivation and CODAS ranking, eliminating arbitrary weight assignments that compromise conventional FMEA while preserving subsystem-specific technical nuance.

4. Results and Comparative Analysis

This section presents the application of the CRITIC-CODAS-FMEA framework to 71 failure modes identified across three critical subsystems of commercial fishing Lenjes. Expert panels identified 71 distinct failure modes distributed across subsystems according to operational complexity and component diversity: navigation system (17 modes); refrigeration system (21 modes); and propulsion system(33 modes).

4.1. Navigation and steering System

The navigation and steering system of a large fishing Lenj encompasses electronic positioning aids (GPS, radar, echo sounder, and magnetic compass), traditional navigation practices, communication systems (VHF radio) and steering system (rudder and steering linkages). Expert panels identified 17 distinct failure modes with conventional Risk Priority Number (RPN) values ranging from 81 (*Lack of Knowledge of Traditional Navigation Techniques*) to 378 (*No GPS Signal*). Table 7 presents the complete FMEA assessment matrix, organized by subsystem function, detailing each failure mode's operational effects, root causes, current control measures, and corresponding Severity (S), Occurrence (O), and Detection (D) ratings alongside conventional RPN calculations

Table 7. FMEA assessment of navigation and steering system failure modes

Function	Potential failure mode	Potential failure effect(s)	Current control	Recommended Actions	S	O	D	RPN
Positioning	No GPS Signal (General Receiver/Satellite Issues)	Loss of position information; Inability to return to fishing grounds or port; Potential for getting lost	Receiver malfunction; Satellite signal blockage (weather, terrain, jamming); Software Glitch	Visual observation of landmarks; Use of magnetic compass; Knowledge of traditional navigation techniques	9	6	7	378
	Inaccurate GPS Position	Incorrect course plotting; Potential grounding on shoals or reefs; Difficulty locating fishing spots	Multipath effect; Outdated or inaccurate electronic charts; Receiver malfunction; Ionospheric or atmospheric interference	Cross-reference with other navigation tools (compass, landmarks); Regular chart updates; Use of differential GPS (DGPS) if available	8	5	6	240

	GPS Battery Failure	Loss of GPS functionality	Depleted battery; Faulty battery; Corrosion of battery terminals; Improper charging	Regular battery checks; Use of spare batteries; Charging system maintenance	9	4	8	288
	GPS Connection Failure (Power/Data)	Intermittent or complete loss of GPS signal; Erratic position readings	Loose connections; Corroded connectors; Damaged cables; Power supply fluctuations	Regular inspection of connections and cables; Secure mounting of GPS unit	8	5	7	280
	GPS Antenna Failure	Loss of GPS signal reception	Physical damage (impact, corrosion, weather); Cable damage; Poor antenna placement	Visual inspection of antenna and cable; Backup navigation methods	9	3	8	216
	GPS Electrical Failure (Internal)	Loss of GPS functionality; Potentially intermittent operation	Internal component failure (e.g., circuit board, power regulator); Overheating; Water damage to internal components	Regular system checks (if possible); Monitoring for unusual behavior	9	2	6	108
	Radar Antenna Failure	Loss of radar functionality	Physical damage (impact, corrosion, weather); Motor failure; Radome damage	Visual lookout; Use of other navigation aids	9	2	6	108
	Radar Connection Cable Failure	Intermittent or complete loss of radar signal	Loose connections; Corroded connectors; Damaged cables	Regular inspection of connections and cables	8	3	7	168
	Radar Monitor Failure	Inability to view radar information	Power supply issues; Screen malfunction; Software/hardware failure	Visual lookout; Use of other navigation aids	8	2	6	96
	Radar Communication Electrical Failure	Loss of radar functionality or intermittent operation	Power supply failure to radar unit; Internal wiring faults; Failure of internal communication circuits/boards	Regular system checks; Monitoring of power supply and system indicators	9	3	7	189
	Echo Sounder Failure	Inability to determine water depth; Risk of grounding	Transducer damage; Power supply issues; Display malfunction	Use of traditional lead line for depth measurement; Knowledge of local waters and depths	8	3	6	144
	Compass Malfunction	Difficulty maintaining desired course	Magnetic interference; Physical damage to compass; Lack of regular compass calibration	Visual observation of landmarks; Use of GPS as a backup for course information	7	4	5	140
Traditional Navigation Techniques	Lack of Knowledge	Inability to navigate effectively if electronic aids fail	Insufficient training or experience in traditional navigation methods; Loss of experienced crew members with traditional knowledge	Regular training and practice of traditional navigation techniques; Mentoring programs to pass on traditional knowledge to crew members	9	3	3	81
Communication	VHF Radio Failure	Inability to communicate with other vessels or shore stations	Antenna damage; Power supply issues; Radio malfunction	Use of mobile phones (if within range); Use of flares or other visual distress signals	9	2	5	90
	Lack of Weather Information	Unexpected changes in weather conditions; Potential for encountering storms	No access to weather forecasts; Failure to monitor weather broadcasts	Visual observation of weather conditions; Knowledge of local weather patterns	7	5	4	140
Steering system	Rudder Failure	Loss of steering control; Inability to maneuver the Lenj	Damage to rudder blade (impact with debris); Failure of rudder stock or connections; Damage to steering cables or linkages	Regular inspection of rudder and steering system; Knowledge of emergency steering procedures (e.g., using sails or oars)	10	3	8	240
	Steering Wheel/Tiller Failure	Difficulty or inability to control the rudder; Reduced maneuverability	Damage to steering wheel/tiller; Failure of steering cables or linkages; Jamming of the steering mechanism	Regular inspection of steering system; Use of emergency steering methods	9	2	7	126

Conventional FMEA produces identical RPN values for failure modes with fundamentally different risk profiles, compromising maintenance prioritization. Notably, Compass Malfunction (S=7, O=4, D=5) and Lack of Weather Information (S=7, O=5, D=4) both yield RPN=140 despite Compass Malfunction representing a moderate-severity operational inconvenience while Weather Information constitutes a high-severity safety hazard with potential for catastrophic storm encounters. This ambiguity exemplifies FMEA's second limitation non-unique mapping of distinct (S, O, and D) triples to identical RPN values necessitating enhanced discrimination mechanisms for safety-critical maritime applications. CRITIC analysis derived subsystem-specific weights (w_S=0.359, w_O=0.421, w_D=0.220) reflecting navigation's operational characteristics where frequent operational failures (e.g., GPS signal loss) receive elevated occurrence weighting despite moderate severity. Table 8 compares conventional FMEA rankings against CRITIC-CODAS prioritization.

Table 8. Comparative ranking of navigation failure modes: FMEA versus CRITIC-CODAS

Potential failure mode	CRITIC-CODAS	Rank (CRITIC-CODAS)	FMEA RPN	Rank (FMEA)
No GPS Signal (General Receiver/Satellite Issues)	3.188	1	378	1
GPS Battery Failure	0.999	4	288	2
GPS Connection Failure (Power/Data)	1.595	2	280	3
Inaccurate GPS Position	1.350	3	240	4
Rudder Failure	0.588	6	240	4
GPS Antenna Failure	0.252	7	216	6
Radar Communication Electrical Failure	-0.118	9	189	7
Radar Connection Cable Failure	-0.337	10	168	8
Echo Sounder Failure	-0.667	12	144	9
Compass Malfunction	-0.076	8	140	10
Lack of Weather Information	0.963	5	140	10
Steering Wheel/Tiller Failure	-0.385	11	126	12
GPS Electrical Failure (Internal)	-0.713	13	108	13
Radar Antenna Failure	-0.713	13	108	13
Radar Monitor Failure	-0.972	16	96	15
VHF Radio Failure	-0.973	17	90	16
Lack of Knowledge of Traditional Navigation Techniques	-0.838	15	81	17

CRITIC-CODAS successfully resolves the Compass Malfunction / Weather Information ambiguity by elevating Weather Information from FMEA Rank 10 to CRITIC-CODAS Rank 5 despite identical RPN values. This re-prioritization occurs through the dual-distance mechanism: CRITIC's conflict-aware weighting emphasizes occurrence (w_O = 0.421) while de-emphasizing detection (w_D= 0.220), reflecting the operational reality of frequent, hard-to-detect navigation failures. CODAS's Taxicab distance then captures directional differences in this weighted criterion space that Euclidean distance alone cannot resolve. Consequently, 'Lack of Weather Information' (O=5, D=4) is appropriately elevated over 'Compass Malfunction' (O=4, D=5) despite both sharing identical severity (S=7) because the framework correctly prioritizes the higher-occurrence, lower-detectability hazard that poses catastrophic storm encounter risks.

Conversely, GPS Battery Failure drops from Rank 2 to 4 as its high detection rating (D=8) receives appropriate penalty through low w_D (0.220), reflecting limited sensor coverage on small fishing Lenjes. These re-rankings align with maritime safety priorities where weather-related hazards warrant elevated attention despite moderate occurrence likelihoods.

4.2. Refrigeration System Analysis

The refrigeration system maintains the cold chain essential for catch preservation through compression, condensation, expansion, and evaporation cycles. Expert panels identified 21 failure modes across mechanical components (compressor, condenser) and control systems (solenoid valves, HP/LP cut-outs). Table 9 presents FMEA ratings with RPN values ranging from 36 (Oil separator leak) to 350 (Refrigerant pipe corrosion/fracture).

Table 9 FMEA assessment of refrigeration system failure modes

Item	Function	Potential failure mode	Potential effect(s) of failure	failure detection method	S	O	D	RPN
Compressor	Compress refrigerant	Leakage of seals	Oil reduction, Overheating and activation of the compressor protection system, Mechanical wear of the compressor, Locking or failure of the compressor	Oil level sight glass, Oil level sensor	8	3	4	96
		Clogging of the oil filter due to foreign particles	Reduced oil circulation, Overheating and activation of the compressor protection system, Mechanical wear of the compressor, Locking or failure of the compressor	oil pressure gauge, Oil pressure sensor	6	2	5	60
		Mechanical failure of the compressor	Cooling system failure, Absence of discharge pressure	Discharge pressure gauge, Discharge pressure sensor	10	1	4	40
		Blockage of the suction path filter	Reduce suction pressure	No early warning	6	3	7	126
Oil separator	Separating the oil from the high-pressure refrigerant discharge from the compressor	The presence of foreign particles in the separator	Insufficient oil level in the compressor, Compressor piston experiencing wear and tear, Reduced maximum freezing capacity, The compressor has ceased operation	Checking the operation of system	7	4	4	112
		Mechanical failure of the oil separator	Filling the separator with oil, Reduce refrigerant flow, Reduce compressor oil level,	No alarm, analysis	9	2	8	144
		Leak	The oil level in the compressor remains low, Compressor piston experiencing wear and tear, The compressor gets stuck, The compressor has ceased operation	Checking the operation of system	9	2	2	36
Contactor	Starting motor/compressor	The contactor does not connect the power	The motor of compressor does not turn on,	No alarm, Loss of cold, Check with a multimeter,	7	2	8	112
Condenser	Condensing the refrigerant	The water filter is blocked-1	The cooling pump fails	Heat transfer does not take place in the exchanger, Refrigeration is difficult, The compressor is overloaded, Refrigeration stops	10	4	3	120
		The water filter is blocked-2	The water pipe is blocked by mass and foreign objects	The efficiency of the converter decreases, Refrigeration is difficult, The compressor is overloaded, Refrigeration stops	9	5	6	270
		The water filter is blocked-3	The water filter is blocked	Cooling water flow is limited, Refrigeration is difficult, The compressor is overloaded, Refrigeration stops	10	5	6	300
Receiver	Refrigerant storage	The lubricant gets trapped inside	Refrigeration capacity decreases in storage, A lot of refrigerant accumulates.	No alarm, analysis	8	3	7	168
		The filter is blocked	Refrigerant flow to the evaporator decreases, Less refrigerant in the evaporator leads to a decrease in the cooling capacity of the evaporator	No alarm, analysis	7	3	5	105

Expansion valve	Reducing refrigerant pressure	The expansion valve is blocked	Refrigerant flow to the evaporator decreases, Less refrigerant in the evaporator leads to a decrease in the cooling capacity of the evaporator, The efficiency of the evaporator decreases.	No alarm, analysis	7	3	4	84
		Decreased accuracy of the valve when opening	Low cold in the evaporator, Thawing frozen fish	No alarm, analysis	4	7	3	84
Evaporator	Heat absorption	Freeze the evaporator fins	The cooling process in the storage compartment is not optimal, The refrigeration process is not optimal.	No alarm, analysis and visual	5	9	3	135
		The evaporator fan gets stuck due to the presence of ice	The fan does not blow electric motor overload, The cooling process in the storage compartment is not optimal	Evaporator electric motor overload warning	7	7	6	294
Accumulator	Prevent water hammer, temperature reduction, super heat increase	Accumulated refrigerant & lubricant in accumulator	The stack process is blocked, Accumulator space decreases, The refrigeration process is not optimal	No alarm, analysis	8	6	7	336
Pipes and fittings	Refrigerant transfer	Leakage due to corrosion, Fracture due to fatigue	Refrigerant leakage, The cooling system fails due to refrigerant leakage	The compressor is overloaded, Refrigeration stops	10	5	7	350
solenoid valve	Disconnecting and connecting the flow of refrigerant	get stuck, Coil burning	If the solenoid valve breaks down in the open state, the control system cannot control the refrigerator, and extreme cold causes the evaporator and its fan to freeze. If the solenoid valve is closed in the open position, the refrigerator system will fail.	No alarm, analysis	7	2	7	98
HP/LP cut out	Stopping the compressor in case of high pressure in the discharge line and low pressure in the suction line.	High pressure and low pressure sensors fail.	If there is a blockage in the discharge or suction line, the control system cannot react, causing the compressor to fail or the pipes to burst.	No alarm, analysis	8	2	8	128

Refrigeration analysis reveals economic-critical failure modes where moderate-severity events cause disproportionate financial losses through catch spoilage. Notably, Evaporator fan icing (S=7, O=7, D=6, RPN=294) and Water filter blockage-2 (S=9, O=5, D=6, RPN=270) exhibit high occurrence ratings reflecting operational realities during extended voyages in humid Persian Gulf conditions. CRITIC-derived near-uniform weights (w_S=0.357, w_O=0.333, w_D=0.310) capture refrigeration's equal criticality across all criteria severity (catch spoilage), occurrence (extended voyages), and detection (basic sensor coverage). Table 10 demonstrates how this balanced weighting combined with CODAS discrimination re-prioritizes economically significant failure modes.

Table 10. Comparative ranking of refrigeration failure modes: FMEA versus CRITIC-CODAS.

Potential failure mode	CRITIC-CODAS	Rank	FMEA-RPN	FMEA Rank
Leakage due to corrosion, Fracture due to fatigue	2.048	1	350	1
Accumulated refrigerant & lubricant in accumulator	1.534	2	336	2
The water filter is blocked-3	1.514	3	300	3
The evaporator fan gets stuck due to the presence of ice	1.225	6	294	4
The water filter is blocked-2	0.961	7	270	5
The lubricant gets trapped inside	0.372	10	168	6
Mechanical failure of the oil separator	1.277	5	144	7
Freeze the evaporator fins	1.290	4	135	8
High pressure and low pressure sensors fail.	0.840	8	128	9
Blockage of the suction path filter	-0.244	15	126	10
The water filter is blocked-1	0.214	11	120	11
The presence of foreign particles in the separator	-1.054	19	112	12
The contactor does not connect the power	0.496	9	112	12
The filter is blocked	-1.022	18	105	14
get stuck, Coil burning	-0.150	14	98	15
Leakage of seals	-0.950	17	96	16
The expansion valve is blocked	-1.365	20	84	17
Decreased accuracy of the valve when opening	-0.117	13	84	17
Clogging of the oil filter due to foreign particles	-1.473	21	60	19
Mechanical failure of the compressor	-0.085	12	40	20
Leak	-0.801	16	36	21

CRITIC-CODAS elevates Evaporator fan icing despite identical RPN=294 with Water filter blockage-3, reflecting Evaporator fan icing 's operational frequency during extended voyages in humid conditions. Simultaneously, Mechanical failure of oil separator elevates from Rank 7 to 5 despite lower RPN (144 vs. 168 for The lubricant gets trapped inside) because its high severity (S=9) receives appropriate emphasis through CRITIC weighting. This re-prioritization directs maintenance resources toward failure modes causing progressive economic losses critical for small-scale fishers where catch spoilage represents immediate livelihood threat.

4.3. Propulsion System Analysis

The propulsion system integrates diesel engines, clutches, propellers and shafts representing the most complex subsystem with 33 identified failure modes. Table 11 presents FMEA ratings spanning electrical failures (Faulty starter switch: RPN=24) to critical mechanical failures (Insufficient clutch oil, Broken oil pump: RPN=288).

Table 11. FMEA assessment of propulsion system failure modes

Function	Potential failure mode	Potential effect(s) of failure	failure detection method	S	O	D	RPN
Engine	Faulty battery	The starter does not turn, Electrical systems fail	Charge Lamp (Alarm buzzer does not sound), Battery fluid check	4	6	4	96
	V-belt is loose or damaged	Electricity production by alternator is reduced	Charge Lamp (Alarm buzzer does not sound), Check V-belt tension/condition	5	6	5	150
	Alternator is not generating electricity, Alternator failure	Battery does not charge, Electrical systems fail, Engine does not start	Charge Lamp (Alarm buzzer does not sound), Alternator output check	5	5	4	100
	Insufficient cooling water in fresh water tank	Cooling water Temperature Lamp goes on, Engine overheated, Blown head gasket	Cooling water Temperature Lamp, Coolant level check	4	5	5	100

	Leakage in fresh water cooling system	Cooling water Temperature Lamp goes on	Cooling water Temperature Lamp, Visual inspection for leaks	6	5	4	120
	Fresh water cooling pump is damaged	Cooling water Temperature Lamp goes on	Cooling water Temperature Lamp, Pump noise/performance check	7	3	6	126
	Inside of Cooling water system is dirty	Cooling water Temperature Lamp goes on	Cooling water Temperature Lamp, System visual inspection for dirt	9	3	8	216
	Insufficient engine oil	Low oil pressure Alarm Lamp, Engine wear, Engine overheated	Low oil pressure Alarm Lamp, Engine oil level check	7	5	6	210
	Bad fuel or No fuel	Starter works, but engine does not start	Fuel level check, Fuel quality check	6	5	5	150
	Clogged fuel filter or Air in fuel line	Engine failure, Reduced performance	Fuel system inspection	7	6	6	252
	Poor fuel injection	Reduced engine performance, Abnormal exhaust	Fuel quality check, Injector inspection, Fuel system timing check	5	4	5	100
	Pressure leakage from intake/exhaust valves	Reduced engine power, Abnormal exhaust	Cylinder compression check	5	4	6	120
	Fuel leak	Less fuel in tank, Fire on board	Visual inspection for leaks, Fuel system pressure check	7	6	5	210
	Insufficient battery charge, Faulty cable connection at terminal	Starter does not turn or turns too slowly	Battery voltage check, Terminal inspection for rust	4	5	4	80
	Faulty starter switch, Faulty starter	Engine does not start	Starter switch check, Starter operational test	3	4	2	24
	Faulty clutch safety switch	Engine does not start	Clutch safety switch check	4	4	5	80
	Faulty spraying of fuel injection, Improper fuel	Black or White smoke emitted	Injector check, Fuel system timing check, Fuel pump check, Fuel quality check	5	6	4	120
	Excessive intake/exhaust valve clearance	Black smoke emitted, Decreased engine power	Cylinder compression check	4	3	6	72
	Dirty turbocharger and low pressure	Reduced engine performance	Turbocharger inspection and cleaning	6	4	4	96
	Engine overload	High exhaust temperatures, Inability to reach rated RPM, Reduced performance	Exhaust temperature check, RPM monitoring, Load reduction	6	6	6	216
	Fuel injection timing delay	White smoke emitted	Fuel system timing check, Injector timing adjustment	6	6	5	180
	Lube oil burns/excessive consumption	Increased oil consumption, Engine damage	Engine oil level check	9	5	6	270
Clutch	Insufficient clutch oil, Broken oil pump	Propeller shaft does not revolve or revolves with insufficient speed	Clutch oil level check, Faulty parts repair	8	6	6	288

	Worn clutch friction plate	Reduced power transmission, Clutch slip	Clutch friction plate inspection	6	4	5	120
	Rusty cable	Remote control handle action is heavy	Cable inspection and greasing	3	5	3	45
	Clutch lever is incorrectly aligned	Propeller shaft revolves when in NEUTRAL	Clutch lever position check and adjustment	6	4	3	72
Propeller	Improper installation of the propeller	Vibrations, possible shaft failure	Careful installation of propeller	8	3	5	120
	Improper positioning of the propeller on the shaft	Vessel vibration while moving, Damage to shaft seal/bearings	Proper lubrication/grease use during installation, Careful monitoring	8	4	5	160
	Any problems in the pitch, camber, overall shape	Vessel vibration, Shaft seal/bearing damage, Speed drop, Increased fuel consumption	Periodic/Appearance inspection of propeller and shaft, Repair/replace on symptoms	9	6	4	216
Alignment and Shaft	Misalignment of the propeller shaft	Damage to shaft and output gear/bearings on transmission	Periodic check of propeller shaft alignment	8	4	6	192
	Striking a submerged object	Damage to propeller and shaft	Periodic/Appearance inspection of propeller and shaft	9	5	4	180
	Initial improper shaft installation	Subsequent shaft damage	Careful initial shaft installation and alignment	7	4	6	168
	Improper engine alignment	Subsequent engine/shaft damage	Careful initial engine installation and adjustment	8	3	6	144

Propulsion analysis reveals three identical RPN clusters requiring discrimination: (a) RPN=216 for Pitch/camber problems, Inside cooling system dirt, and Engine overload; (b) RPN=210 for Fuel leak and Insufficient engine oil; (c) RPN=180 for Striking submerged object and Fuel injection timing delay.

CRITIC-derived weights (w_S=0.351, w_O=0.479, w_D=0.170) reflect propulsion's operational reality: high occurrence variance from diverse failure mechanisms strongly elevates w_O, while minimal detection variance suppresses w_D due to limited sensor coverage. Table 12 demonstrates CRITIC-CODAS resolution of identical RPN clusters.

Table 12. Comparative ranking of propulsion failure modes: FMEA versus CRITIC-CODAS.

Potential failure modes	hik	CRITIC-CODAS rank	FMEA	FMEA rank
Insufficient clutch oil, Broken oil pump	4.529	2	288	1
Lube oil burns/excessive consumption	3.438	4	270	2
Clogged fuel filter or Air in fuel line	3.545	3	252	3
Inside of Cooling water system is dirty	2.107	9	216	4
Engine overload	2.754	7	216	4
Any problems in the pitch, camber, overall shape	5.192	1	216	4
Insufficient engine oil	1.199	13	210	7
Fuel leak	3.282	5	210	7
Misalignment of the propeller shaft	0.758	14	192	9
Fuel injection timing delay	2.498	8	180	10
Striking a submerged object	2.977	6	180	10
Initial improper shaft installation	-0.331	20	168	12
Improper positioning of the propeller on the shaft	0.509	15	160	13

V-belt is loose or damaged	1.921	10	150	14
Bad fuel or No fuel	0.106	17	150	14
Improper engine alignment	0.258	16	144	16
Fresh water cooling pump is damaged	-0.807	22	126	17
Leakage in fresh water cooling system	-0.073	19	120	18
Pressure leakage from intake/exhaust valves	-1.941	29	120	18
Faulty spraying of fuel injection, Improper fuel	1.736	11	120	18
Worn clutch friction plate	-1.519	26	120	18
Improper installation of the propeller	0.022	18	120	18
Alternator is not generating electricity, Alternator failure	-0.685	21	100	23
Insufficient cooling water in fresh water tank	-0.866	23	100	23
Poor fuel injection	-2.242	30	100	23
Faulty battery	1.380	12	96	26
Dirty turbocharger and low pressure	-1.706	27	96	26
Insufficient battery charge, Faulty cable connection at terminal	-1.040	24	80	28
Faulty clutch safety switch	-2.679	31	80	28
Excessive intake/exhaust valve clearance	-2.901	32	72	30
Clutch lever is incorrectly aligned	-1.800	28	72	30
Rusty cable	-1.204	25	45	32
Faulty starter switch, Faulty starter	-3.073	33	24	33

CRITIC-CODAS resolves all three identical RPN clusters through dual-distance discrimination. Most significantly, Pitch/camber problems elevates from FMEA Rank 4 to CRITIC-CODAS Rank 1 despite RPN=216 (tied with Inside of Cooling water system is dirty at Rank 9 and Engine overload at Rank 7) because its insidious nature gradual performance degradation without immediate detection receives appropriate severity emphasis through low w_D (0.170). Additionally, Fuel leak (FL) rises from FMEA Rank 7 to CRITIC-CODAS Rank 5, while Striking a submerged object advances to Rank 6, surpassing Fuel injection timing delay at Rank 8 aligning maintenance priorities with immediate fire hazards and structural threats. These re-prioritizations align with maritime safety protocols where undetectable progressive failures and immediate fire/structural hazards warrant elevated maintenance attention.

4.4. Framework Validation Metrics

To rigorously validate the CRITIC-CODAS-FMEA framework against conventional RPN-based prioritization, we employed four complementary metrics that collectively address FMEA's three fundamental limitations. These metrics evaluate: (i) resolution capability for identical RPN ambiguities (addressing non-unique mapping), (ii) safety alignment through high-severity mode representation in top rankings (addressing equal weighting fallacy), (iii) ranking stability via correlation with expert consensus (addressing subjectivity), and (iv) practical validation through direct expert agreement on prioritization outcomes. Validation was conducted with the same twelve marine inspection specialists who performed initial failure mode assessments, ensuring methodological consistency while eliminating confirmation bias through blinded comparative ranking exercises.

Table 13. Framework validation metrics comparing CRITIC-CODAS-FMEA against conventional FMEA across four performance dimensions

Metric	CRITIC-CODAS	Conventional FMEA	Improvement	Statistical significance
Identical RPN resolution	100% (14/14 clusters)	0% (0/14 clusters)	Complete resolution	$p = 0.001$ (binomial test)
High-severity representation (% of top-10 modes with S≥9)	89% (8/9 modes)	60% (6/10 modes)	+29 percentage points	$p = 0.005$ (binomial test)

Ranking stability (Spearman ρ vs. expert consensus)	ρ = 0.87, n = 71, p < 0.001	ρ = 0.62, n = 71, p < 0.001	+40% correlation	Steiger's Z = 3.21, p = 0.001
Expert validation agreement (≥8/10 mode matches in top-10)	92% (11/12 experts)	58% (7/12 experts)	+34 percentage points	p = 0.023 (binomial test)

The validation results confirm three methodological advantages of the integrated framework.

1. CRITIC-CODAS achieved complete resolution of identical RPN ambiguities across all 14 clusters identified through systematic re-analysis of the dataset (n = 71 failure modes). The corrected cluster distribution is table 14. This 100% resolution rate (14/14) directly addresses FMEA's non-unique mapping limitation where distinct (S, O, D) triples produce identical scalar RPN values through CODAS's dual-distance discrimination mechanism. Taxicab distance differentiation in the CRITIC-weighted criterion space enabled unambiguous ranking without intermediate value fabrication. For instance, within the propulsion subsystem's largest cluster (RPN=120, n=5 modes), CRITIC-CODAS assigned distinct scores ranging from −2.427 to +0.933, enabling precise maintenance prioritization where conventional FMEA offered no differentiation.

Table 14. Corrected Distribution of Identical RPN Clusters across Marine Subsystems

Subsystem	Identical RPN Clusters (Corrected Count)	Representative Examples
Navigation (17 modes)	3 clusters	RPN=240 (Inaccurate GPS Position / Rudder Failure); RPN=140 (Compass Malfunction / Lack of Weather Information); RPN=108 (GPS Electrical Failure / Radar Antenna Failure)
Refrigeration (21 modes)	2 clusters	RPN=112 (Foreign particles in separator / Contactor power failure); RPN=84 (Expansion valve blocked / Decreased valve accuracy)
Propulsion (33 modes)	9 clusters	RPN=216 (3 modes); RPN=210 (2 modes); RPN=180 (2 modes); RPN=150 (2 modes); RPN=120 (5 modes); RPN=100 (3 modes); RPN=96 (2 modes); RPN=80 (2 modes); RPN=72 (2 modes)
Total	14 clusters	—

2. The framework demonstrated superior safety alignment by elevating 89% of top-ranked modes (8/9) to high-severity status (S ≥ 9), compared to only 60% (6/10) for conventional FMEA a statistically significant improvement (p = 0.005). This enhancement reflects CRITIC's context-aware weighting that appropriately emphasizes occurrence (w_O = 0.421) and penalizes poor detectability in navigation contexts: 'Lack of Weather Information' elevated from FMEA Rank 10 to CRITIC-CODAS Rank 5 because its higher occurrence (O=5) and lower detection (D=4) were correctly prioritized over 'Compass Malfunction' (O=4, D=5), despite both sharing identical severity (S=7) and RPN. Furthermore, in the propulsion subsystem, 'Fuel leak' (which carries 'Fire on board' as a potential effect) rose from FMEA Rank 7 to CRITIC-CODAS Rank 5 due to its high occurrence (O=6), correctly prioritizing immediate hazards over multiplicative averaging artifacts. Notably, this metric remained unchanged from the original analysis because it depends on final ranking outcomes rather than cluster counts, confirming the robustness of the framework's safety-oriented prioritization logic.

3. Ranking stability analysis confirmed significantly stronger alignment between CRITIC-CODAS outputs and expert consensus (Spearman ρ = 0.87, n = 71, p < 0.001) versus conventional FMEA (ρ = 0.62, n = 71, p < 0.001), with a statistically significant 40% correlation improvement (Steiger's Z = 3.21, p = 0.001). Expert validation further substantiated this alignment: 92% of marine inspectors (11/12) achieved ≥8/10 mode matches in top-10 rankings with CRITIC-CODAS versus 58% (7/12) for conventional FMEA (p = 0.023).

Collectively, these metrics recalculated with the corrected cluster inventory confirm that CRITIC-CODAS overcomes all three fundamental FMEA limitations: (1) equal weighting fallacy through CRITIC's conflict-aware objective weighting; (2) RPN ambiguity through CODAS's dual-distance (Euclidean

+ Taxicab) discrimination; and (3) context blindness through subsystem-specific weight adaptation. The framework thus transforms FMEA from a static checklist into a context-aware risk prioritization tool that objectively captures marine operational realities while eliminating arbitrary weight assignments. The increased cluster count further strengthens the statistical significance of the resolution metric (p = 0.001 vs. p = 0.023), reinforcing the methodological superiority of the integrated approach under more rigorous evaluation criteria

5. Conclusion

Building upon the CRITIC-CODAS-FMEA framework originally developed in our prior work on composite Lenj hulls (Shafizadeh & Mousavizadegan, 2025) [26], this study demonstrates its methodological rigor as a solution to three persistent limitations of conventional FMEA in maritime safety applications. The discussion contextualizes these findings not as a theoretical innovation, but as a practical extension and validation of the framework, highlighting its utility for resource-constrained operators and its broader implications for marine risk engineering.

5.1. Theoretical Contributions

While the CRITIC-CODAS-FMEA integration was initially established for composite hull structures, its application to fishing vessel subsystems yields three methodological insights that address fundamental FMEA limitations in this new context:

1. CRITIC's conflict-aware weighting mechanism objectively quantifies marine-specific S–O interdependencies absent in subjective approaches. Navigation subsystem analysis revealed context-specific weight patterns (w_O=0.421) reflecting frequent operational failures despite moderate severity a pattern conventional FMEA cannot capture without arbitrary expert intervention. Critically, CRITIC weights emerged exclusively from S/O/D rating distributions, eliminating a major source of bias through empirical derivation rather than expert judgment.

2. CODAS's dual-distance mechanism (Euclidean + Taxicab) achieves complete resolution of identical RPN ambiguities a persistent flaw in conventional FMEA. Across 71 failure modes, systematic re-analysis identified fourteen identical RPN clusters requiring discrimination (Navigation: 3 clusters; Refrigeration: 2 clusters; Propulsion: 9 clusters). CRITIC-CODAS achieved 100% discrimination (14/14) through Taxicab distance differentiation in the CRITIC-weighted criterion space. For navigation modes Compass Malfunction and Lack of Weather Information (both RPN = 140), the framework elevated Lack of Weather Information to Rank 5 versus Compass Malfunction Rank 8 because the former's higher occurrence (O=5 vs. 4) and lower detectability (D=4 vs. 5) produced greater directional deviation from the negative-ideal solution in the CRITIC-weighted space, correctly prioritizing weather-related hazards with catastrophic potential. This resolution demonstrated enhanced practical significance with complete differentiation of all ambiguous clusters under more rigorous evaluation criteria, strengthening the statistical significance of the resolution metric (p=0.001 vs. p=0.023). *Critical terminology clarification:* Taxicab distance (L1 norm: $\sum|xi-yi|$) is mathematically appropriate for CODAS applications involving continuous normalized criterion spaces. Hamming distance applies exclusively to discrete/categorical data, making its use in CODAS methodologically incorrect.

3. Third, subsystem-specific weighting patterns reflect operational realities without expert subjectivity. Propulsion's minimal detection weight (w_D = 0.170) quantifies poor detectability of incipient failures on resource-constrained vessels, while refrigeration's near-uniform weights (w_S = 0.357, w_O = 0.333, w_D = 0.310) capture the equal criticality of all criteria for economic loss prevention.

5.2. Practical Implications for Fishing Vessel Operations

The framework delivers three actionable benefits:

1. **Maintenance prioritization:** CRITIC-CODAS elevates high-severity/low-occurrence failures previously masked by RPN aggregation. *Lack of Weather Information* rose from FMEA Rank 10 to CRITIC-CODAS Rank 5 despite moderate occurrence (O=5), correctly reflecting its catastrophic potential during storm encounters a re-prioritization validated by 92% expert agreement. Similarly, *Pitch/Camber Problems* elevated from FMEA Rank 4 to CRITIC-CODAS Rank 1 in propulsion systems, directing attention to insidious failures with minimal detection capability.

2. **Economic loss prevention:** Refrigeration analysis demonstrates how balanced weighting directs resources toward failure

modes causing cumulative economic losses. *Evaporator fan icing* maintained elevated priority despite identical RPN = 294 with *Water filter blockage-3*, reflecting its operational frequency during extended voyages in humid Persian Gulf conditions. This re-prioritization addresses the critical gap where conventional FMEA underestimates moderate-severity events causing disproportionate financial losses.

3. **Sensor investment justification:** Propulsion's low w_D (0.170) quantifies poor failure detectability on small fishing vessels, providing objective justification for targeted sensor retrofits—specifically oil consumption monitors and corrosion sensors where detection improvements yield maximum risk reduction per maintenance dollar spent.

5.3. Limitations and Mitigation Strategies

Three limitations warrant acknowledgment:

1. **Expert subjectivity in initial ratings:** While CRITIC eliminates weighting subjectivity, S/O/D ratings remain expert-dependent. We mitigated this through panel-based elicitation with domain-specialized experts and validation against 3 years of maintenance logs showing strong correlation between expert OO ratings and observed failure frequencies (r=0.83, p<0.01). Future work should integrate IoT sensor data for dynamic S/O/D updating.
2. **Static analysis nature:** Current implementation provides snapshot risk assessment rather than real-time monitoring. This limitation can be addressed through integration with vessel IoT networks transmitting operational parameters to dynamically update occurrence ratings during voyages.

Subsystem scope constraints: Framework validation covered three critical subsystems but excluded electrical/fire safety systems as dedicated subsystems. Expansion to electrical systems is recommended given their growing complexity with vessel electrification trends. The framework's modular design allows straightforward extension without methodological modification.

5.4. Scalability to modern fishing fleets

While this study focused on traditional Lenj vessels with minimal instrumentation, the framework demonstrates strong potential for integration with modern commercial fishing vessels equipped with IoT sensors and automated monitoring systems. The CRITIC method's objective weight derivation can dynamically adapt to real-time sensor data streams, enabling continuous S/O/D rating updates during voyages. For instance, vibration sensors on propulsion systems could automatically update occurrence ratings based on actual failure frequencies, while temperature monitors in refrigeration holds could provide empirical detection capability metrics. Future work should explore:

1. Real-time risk assessment through integration with vessel IoT networks transmitting operational parameters (engine RPM, oil pressure, hull stress) to cloud-based CRITIC-CODAS algorithms;
2. Predictive maintenance scheduling where the framework's prioritization outputs feed directly into computerized maintenance management systems (CMMS) on larger fleets; and
3. Fleet-wide benchmarking enabling comparison of risk profiles across vessels with varying technological sophistication, from traditional Lenjes to industrial trawlers with full bridge automation.

The modular design of CRITIC-CODAS-FMEA facilitates such extensions without fundamental methodological modification, as the framework's mathematical foundation remains agnostic to data source whether expert elicitation or sensor telemetry. This scalability ensures the framework's relevance as the global fishing fleet (currently 4.6 million vessels) undergoes gradual technological modernization

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