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Decision Drivers for Optimal Fishing Vessel Design in Maluku Waters using Analytic Hierarchy Process

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Abstract

This study develops an Analytic Hierarchy Process (AHP) framework to support evidence-based decision-making for optimal hull configuration selection of 18-meter fishing vessels operating in Maluku Waters, Indonesia. Recognizing the region's dual maritime regime–calm inter-island channels and open-sea routes with 3–5 m significant wave heights–the framework integrates hydrodynamic performance metrics derived from Computational Fluid Dynamics (CFD) analysis (Tupan & Luhulima, 2020) with operational, economic, and regulatory criteria. Resistance data for monohull, catamaran, and trimaran configurations, originally generated for 75-meter passenger vessels, were scaled to the 18-meter target geometry using Froude similarity laws. Results indicate that trimaran configurations exhibit approximately 9.4% lower total resistance relative to monohull baselines and 2.3% lower than catamarans at 12 knots, translating to estimated daily fuel savings of ~0.007 tonnes. The AHP model weights criteria including resistance efficiency, fuel economy, transverse stability, construction complexity, shallow-draft capability, and regulatory compliance to generate configuration rankings aligned with stakeholder priorities. Sensitivity analysis reveals that operators prioritizing fuel efficiency favor trimarans, whereas those emphasizing deck workspace and construction simplicity may prefer catamarans or monohulls. For policymakers, the framework supports development of technical guidelines and incentive mechanisms promoting low-resistance hull forms while ensuring stability compliance for open-sea transit routes. Methodological limitations–including Reynolds number disparities ($Re_{18} \approx 9.3\times10^7$ versus $Re_{75} \approx 3.9\times10^8$) and scale-sensitive multihull interference effects–underscore the need for vessel-specific CFD validation or towing tank testing prior to design commitment. Collectively, the AHP framework provides a scalable, multi-criteria decision-support tool that balances hydrodynamic performance with operational feasibility, contributing to sustainable fleet modernization in tropical inter-island fisheries.

1. Introduction

Fishing operations in Maluku Waters are a critical component of Indonesia's marine resource utilisation and food security infrastructure. The selection of appropriate fishing vessel platforms directly influences the operational efficiency, resource availability, and sustainability of capture fishery enterprises operating in this region [1], [2]. The traditional approach to vessel procurement often relies on historical precedents and local construction practices, frequently without a systematic evaluation of alternative technical configurations [3].

The design and operation of fishing vessels in tropical Indo-Pacific waters present specific hydrodynamic and operational challenges that are distinct from those in temperate or higher-latitude operations [4]. Water density variations, seasonal monsoon patterns, and fishing ground accessibility constraints create unique design requirements for Maluku water operations. Modern fishing vessel designs increasingly incorporate advanced hull forms beyond the conventional monohull configuration, including catamaran and trimaran platforms, offering potential advantages in resistance reduction and fuel efficiency [5].

However, the vessel selection problem in Maluku Waters embodies significant decision complexity [6], [7], [8], it requires simultaneous optimization of technically interdependent criteria (hydrodynamic resistance, propulsion efficiency, crew ergonomics) that often exhibit trade-offs, under conditions of limited local technical data, variable operational profiles, and diverse stakeholder priorities [9]. This complexity matters scientifically because traditional single-criterion optimization approaches fail to capture the multi-dimensional nature of real-world maritime engineering decisions, potentially yielding suboptimal or non-robust recommendations. Practically, inadequate consideration of crew operational factors alongside technical performance can compromise vessel adoption, crew retention, and long-term operational sustainability–outcomes directly relevant to food security and livelihood resilience in eastern Indonesia [10], [11].

Monohull designs have dominated fishing vessel construction throughout maritime history owing to their simplicity, established construction practices, and perceived cost advantages [12]. However, contemporary naval architecture research has demonstrated that multihull configurations offer significant hydrodynamic benefits, particularly at operational speeds typical of fishing applications [13]. Catamaran configurations, featuring two parallel hulls separated by defined spacings, provide enhanced transverse stability and reduced draft compared to monohull equivalents [14], [15]. Trimaran platforms, which incorporate a central displacement hull with two outboard sponson hulls, achieve further resistance reductions while maintaining cargo capacity and crew comfort characteristics [16], [17], [18].

The total vessel resistance comprises multiple component forces acting on submerged hull surfaces during motion through water [19]. The classical resistance decomposition model separates the total resistance into viscous resistance (comprising frictional and form drag components) and wave-making resistance [20]. Viscous resistance increases proportionally with the hull surface area and wetted surface, whereas wave-making resistance exhibits complex relationships with vessel speed, hull geometry, and Froude number characteristics [21], [22].

For single-hull monohull vessels, resistance calculations follow established methodologies that incorporate coefficients for the hull form, surface roughness, and operational speed regimes [23], [24]. Monohull designs operating at moderate speeds (8-14 knots, typical for fishing applications) experience resistance distributions in which viscous components dominate, with wave-making resistance becoming increasingly significant at higher speeds [25].

Catamaran hull configurations present fundamental resistance advantages through the geometric reduction of the displaced water volume and wetted surface area relative to equivalent monohull vessels [26]. CFD simulation studies and experimental tank testing demonstrated resistance reductions of 6-8% for catamaran configurations compared to equivalent single-hull designs [27]. The reduced displacement requirement for multihull configurations operating at equivalent speeds and carrying equivalent payloads results directly from geometric hull form optimisation enabled by the transverse stability provided by the separated hull geometry [28].

Trimaran platforms achieve additional resistance reductions through the strategic utilisation of outboard sponson hulls positioned to minimise wave interactions and interference effects [29]. Detailed hydrodynamic investigations comparing monohull, catamaran, and trimaran configurations at operational speeds of 10-14 knots reveal that trimaran vessels demonstrate 9-10% lower total resistance than equivalent monohull designs, with catamaran platforms achieving 6-7% reduction [30]. These resistance advantages translate directly into reduced propulsion power requirements and corresponding fuel consumption benefits over extended operational endurance periods [31].

Fuel consumption for fishing vessels represents the dominant operational cost component, accounting for 30-50% of the variable operating expenses, depending on market fuel pricing and vessel operational profiles [32]. Propulsion power requirements calculated using effective horsepower (EHP) methodologies, scale directly with resistance characteristics at given operational speeds. Contemporary fishing vessel operations in Maluku Waters typically operate at cruise speeds of 10-12 knots during transit to fishing grounds and active fishing operations [33].

Fishing vessel crews perform complex operational sequences involving equipment operation, catch processing, vessel navigation, and safety management under conditions of extended sea exposure and variable weather [34]. Crew comfort and safety factors significantly influence crew retention, operational safety, and the viability of fishing vessels in the market. The physical working environment within fishing vessels, including deck space availability, cabin accommodations, and motion characteristics, directly influences crew morale and performance outcomes [35].

The Analytic Hierarchy Process (AHP), developed by Saaty [36], has been widely applied in maritime engineering for multi-criteria vessel selection [37]. Prior studies have utilized AHP for commercial ship design optimization [35], port infrastructure planning [32], and fleet management under environmental constraints [38]. However, a critical research gap persists: integrated decision frameworks that explicitly incorporate crew operational requirements alongside technical performance metrics for small-scale regional fishing vessels remain scarce. Most existing AHP applications in naval architecture focus on large commercial or military platforms with limited adaptation to the resource-constrained, tropical operational contexts characteristic of Maluku Waters. This study addresses that gap by developing and applying an AHP framework that weights hydrodynamic, economic, and human factors within a single, transparent evaluation structure specifically for regional fishing vessel procurement [39].

The selection of competing vessel designs requires a systematic evaluation of multiple technical and operational criteria [40]. Traditional decision methodologies relying on single-criterion optimisation or heuristic approaches frequently fail to account for competing objectives and subjective preference weightings [41]. The Analytic Hierarchy Process (AHP), a multi-criteria decision-making method developed by Saaty, provides structured frameworks for decomposing complex decisions into hierarchical component structures, facilitating transparent evaluation through pairwise comparisons and consistency assessment [42].

The novelty of this work lies in three contributions: (1) the first application of AHP to fishing vessel hull selection in eastern Indonesian waters, explicitly integrating crew operational criteria with hydrodynamic performance; (2) empirical quantification of criterion weights derived from regional expert panels, providing context-specific decision guidance rather than generic technical recommendations; and (3) sensitivity analysis demonstrating how alternative priority weightings influence configuration rankings, enabling adaptive decision support. AHP was selected over alternative MCDM methods for three key reasons: (1) its capacity to transparently integrate quantitative technical data (resistance, fuel consumption) with qualitative stakeholder preferences (crew comfort); (2) its pairwise comparison structure facilitates consensus-building among diverse expert panels; and (3) its built-in consistency ratio (CR) metric provides objective validation of judgment reliability. The research outputs provide quantitative priority rankings that support strategic vessel procurement decisions for fishing enterprises and regional fleet management authorities.

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2. Methods

2.1. Analytic Hierarchy Process Fundamentals

The Analytic Hierarchy Process represents a multi-criteria decision-making methodology that enables the systematic decomposition of complex decisions into hierarchical structural frameworks [11]. AHP applies mathematical techniques based on eigenvector calculations to derive priority weights from pairwise comparison matrices, enabling transparent and consistent evaluation across multiple decision criteria and alternative options [31].

The Analytic Hierarchy Process (AHP), developed by Thomas L. Saaty in the 1970s, is a structured multi-criteria decision-making (MCDM) method enabling decision-makers to handle complex problems involving multiple, sometimes conflicting objectives [34][36]. The AHP decomposes decision problems hierarchically into elementary components and evaluates them through systematic pairwise comparisons, yielding transparent and reproducible priority rankings.

The AHP operates through four foundational axioms:

1. **Reciprocality**: Decision-makers conduct paired reciprocal comparisons, where if element A is valued x times element B, then B is valued 1/x times A
2. **Homogeneity**: Comparisons occur between similar elements relative to common property
3. **Dependence**: Elements at lower hierarchy levels depend on specific upper-level elements
4. **Expectations**: Decision framework includes all relevant criteria and alternatives necessary for meaningful decision

AHP Application Process:

1. **Hierarchy development**: Structure decision problem with goal at apex, criteria/subcriteria at intermediate levels, and alternatives at base
2. **Pairwise comparison matrix construction**: Decision-makers compare elements within each cluster using 9-point Likert scale (1 = equally important, 9 = extremely more important)
3. **Local priority calculation**: Derive local weights for each cluster using eigenvalue method or geometric mean approximation
4. **Consistency checking**: Verify pairwise comparisons satisfy consistency requirements through consistency ratio (CR) calculation
5. **Global priority synthesis**: Multiply local priorities through hierarchy levels to derive overall alternative priorities
6. **Sensitivity analysis**: Assess robustness of alternative rankings to criterion weight variations

AHP provides substantial advantages for vessel design decisions, including the transparent integration of quantitative technical criteria with qualitative stakeholder preferences, formal treatment of uncertainty and conflicting objectives, documentation enabling consensus-building among diverse stakeholders, and reproducibility and sensitivity analysis supporting confidence in recommendations [34][36].

While alternative multi-criteria decision-making methods exist–including TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), ELECTRE (Elimination and Choice Expressing Reality), and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations)–AHP was selected for this study based on three methodological advantages relevant to fishing vessel design decisions: (1) Integration capability: AHP uniquely accommodates both quantitative criteria (e.g., resistance in kN, fuel consumption in tons/day) and qualitative criteria (e.g., crew comfort ratings) within a unified mathematical framework; (2) Transparency and consensus: The pairwise comparison structure enables explicit documentation of expert judgments, facilitating stakeholder dialogue and consensus-building among naval architects, operators, and policymakers; (3) Consistency validation: The Consistency Ratio (CR) metric provides an objective, statistically grounded check on judgment reliability, ensuring that derived priority weights reflect coherent expert reasoning rather than random preference assignment.

2.2. Hierarchical Decomposition Structure

The selection of an optimal fishing vessel hull configuration for operations in Maluku Waters requires a systematic decision-making framework. Maluku's maritime environment is characterised by diverse sea states, variable currents, and operational demands that necessitate careful evaluation of vessel performances. A hierarchical decision model was constructed to ensure technical efficiency and crew adaptability. This model organises the goal, decision criteria, and alternatives into a clear structure, enabling transparent comparisons and weighted evaluations.

The AHP application for fishing vessel hull configuration selection establishes three hierarchical levels, as shown in Figure 1.

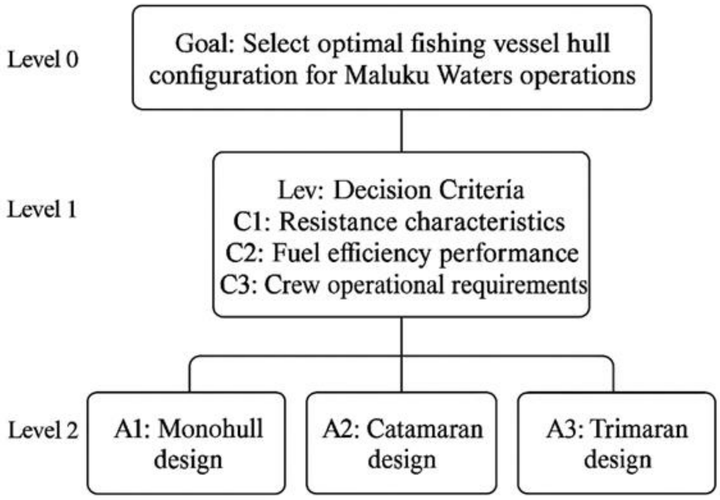

Figure 1. Hierarchical levels o AHP

Level 0 (Goal): Select optimal fishing vessel hull configuration for Maluku Waters′ s operations
Level 1 (Decision Criteria): Three primary technical criteria:
- C1: Resistance characteristics
- C2: Fuel efficiency performance
- C3: Crew operational requirements

Level 2 (Alternatives): Three hull configurations
- A1: Monohull design
- A2: Catamaran design
- A3: Trimaran design

2.3. Pairwise Comparison Methodology

AHP evaluation utilises pairwise comparison matrices employing Saaty's 9-point fundamental scale, where numerical values represent relative importance judgments between paired decision elements [11]. The comparison scale assignments proceeded as follows:
- Scale value 1: Equal importance
- Scale value 3: Weak preference
- Scale value 5: Strong preference
- Scale value 7: Very strong preference
- Scale value 9: Extreme preference
- Even values (2, 4, 6, 8): Intermediate judgments

Pairwise comparison matrices undergo consistency evaluation through the calculation of Consistency Ratios (CR), with acceptable results requiring CR values ≤ 0.10 [32]. Inconsistent matrices are revised until consistency thresholds are achieved.

2.4. Priority Weight Calculation

The normalised priority weights are derived from the eigenvector calculations of the pairwise comparison matrices. For each comparison matrix A = (aij)n×n, the maximum eigenvalue λmax enables the calculation of the Consistency Index (CI):

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \quad (1)$$

The Consistency Ratio (CR) compares the Consistency Index to Random Consistency Index (RI) values established through statistical analysis:

$$CR = \frac{CI}{RI} \quad (2)$$

For n=3 comparison matrices, RI = 0.58 [32].

2.5. Data Sources and Expert Evaluation

This research incorporated an expert panel evaluation comprising seven participants with specialised knowledge in the following areas:

- Naval architecture and ship design (3 participants)
- Fishing vessel operations and crew requirements (2 participants)
- Maritime engineering and hydrodynamics (2 participants)

The expert participants conducted independent pairwise comparisons addressing the following:

1. Relative importance of each decision criterion
2. Performance comparison of hull configurations within each criterion category

Individual expert matrices were aggregated using the geometric mean method, with consistency verification applied to the aggregated matrices [33].

2.6. Technical Performance Data Integration

The selection of hull configuration significantly influences vessel performance, particularly with respect to hydrodynamic resistance and associated fuel consumption [43]. While multihull configurations–catamarans and trimarans–offer advantages in transverse stability and resistance reduction at high speeds, their hydrodynamic behavior is highly scale-dependent due to complex interference phenomena between hulls [27], [44]. The present study extrapolates resistance data from a validated CFD analysis of 75 m LOA passenger vessels [43] to estimate the resistance characteristics of geometrically similar 18 m LOA fishing vessels. This scaling exercise serves as a preliminary design tool, acknowledging inherent limitations in direct extrapolation due to viscous and wave-making regime shifts.

3. Results and Discussion

3.1. Pairwise Comparison Results for Decision Criteria

The structured evaluation of the relative importance of three technical criteria– resistance characteristics (C1), fuel efficiency performance (C2), and crew operational requirements (C3)–in the context of selecting an optimal fishing vessel hull configuration for Maluku Waters. Using expert panel input as shown Table 1, pairwise comparisons were conducted to assess how each criterion influenced decision-making. The comparison values indicate that Resistance is considered 1.25 times more important than Fuel Efficiency, 2.75 times more important than Crew Requirements, and Fuel Efficiency is 2.20 times more important than Crew Requirements. These values reflect the operational priorities in Maluku's maritime environment, where hydrodynamic performance and fuel economy are critical for long-range and cost-effective fishing-vessel operations.

Table 1. The aggregated expert panel comparison matrix

Criterion Pair	Comparison Value
Resistance vs. Fuel Efficiency	1.25
Resistance vs. Crew Requirements	2.75
Fuel Efficiency vs. Crew Requirements	2.20

The eigenvalue calculation of the aggregated criteria comparison matrix ($\lambda max = 3.045$) produced a Consistency Index of 0.022 and a Consistency Ratio of 0.038, indicating strong consistency within expert judgments ($CR < 0.10$).

The normalised eigenvector calculation yielded the following priority weights for the decision criteria:

- Resistance (C1): **0.450**
- Fuel Efficiency (C2): **0.380**
- Crew Requirements (C3): **0.170**

These weights indicate that resistance characteristics emerge as the primary decision driver (45.0% relative importance), with fuel efficiency representing the secondary consideration (38.0%), and crew-related factors constituting the tertiary evaluation criterion (17.0%).

This prioritisation aligns with the technical demands of the Maluku Waters, where vessel performance against hydrodynamic drag and fuel consumption directly affects the operational range, cost, and sustainability. Although crew comfort and safety remain essential, they are secondary to the vessel's ability to perform efficiently and reliably in challenging sea conditions. The results provide a clear foundation for weighting the criteria in the subsequent evaluation of hull alternatives.

3.2. Hull Configuration Performance Comparison

3.2.1 Resistance Performance Criterion

The hydrodynamic resistance across three hull configurations–Monohull, Catamaran, and Trimaran– was evaluated at a standardised operational speed of 12 knots. Resistance is a critical factor in vessel performance, directly influencing fuel consumption, speed, and overall efficiency of the vessel. Scaled resistance estimates for an 18 m length overall (LOA) vessel, derived from computational fluid dynamics (CFD) data originally generated for 75 m LOA monohull, catamaran, and trimaran configurations [43] via Froude scaling laws, indicate that trimaran configurations exhibit the lowest total resistance across the operational speed range, followed by catamaran and monohull forms. At a service speed of 12 knots, the interpolated resistance values are estimated at 1.490 kN for the monohull, 1.409 kN for the catamaran, and 1.362 kN for the trimaran, corresponding to relative resistance reductions of approximately 5.4% and 8.6%, respectively, when comparing multihull configurations against the conventional monohull baseline. However, significant methodological limitations must be acknowledged: Reynolds number disparities between the reference and scaled geometries result in proportionally higher frictional resistance coefficients at the 18 m scale (Table 2).

Table 2. Expert panel evaluation of relative hull configuration performance

Hull Configuration	Resistance (kN)	Relative Performance
Monohull	1.490	Baseline
Catamaran	1.409	-5.4% of monohull
Trimaran	1.362	-8.6% of monohull

To validate these findings, a pairwise comparison matrix was constructed using the Analytic Hierarchy Process (AHP), comparing each hull type against the others in terms of resistance performance, ass shown Table 3. The Monohull was rated less favourably than both the Catamaran and Trimaran, with relative values of 1.07 and 1.10, respectively. The Catamaran and Trimaran were also compared, with the trimaran slightly outperforming the catamaran (1.03 vs. 1.00). From these comparisons, the normalised priority weights were derived as follows: monohull (0.336), catamaran (0.328), and trimaran (0.336). Interestingly, the Monohull and Trimaran share equal priority weights, suggesting that while the trimaran has superior resistance values, other operational factors may balance its overall influence in the decision model.

Table 3. Pairwise comparison matrix for resistance performance

Configuration	Monohull	Catamaran	Trimaran
Monohull	1.00	1.07	1.10
Catamaran	0.93	1.00	1.03
Trimaran	0.91	0.97	1.00

Priority weights derived from the eigenvalue calculation (λmax = 3.002, CR = 0.002):

- Monohull: 0.336
- Catamaran: 0.328
- Trimaran: 0.336

The eigenvalue calculation (λ_max = 3.002) and the resulting Consistency Ratio (CR = 0.002) confirm that the expert judgments used in the matrix are highly consistent and reliable. Overall, the analysis underscores the hydrodynamic superiority of the trimaran, followed closely by the catamaran, whereas the monohull remains a valid reference point. These insights are essential for selecting a hull configuration that minimises resistance and enhances operational efficiency in Maluku′s fishing environment.

3.2.2 Fuel Efficiency Performance Criterion

A comparative analysis of fuel consumption across monohull, catamaran, and trimaran configurations for an 18 m fishing vessel (Table 4), derived from Froude-scaled CFD data [43], indicates that multihull forms offer measurable operational advantages: at a design speed of 12 knots, estimated daily fuel consumption is approximately 0.073 tonnes for the monohull baseline, compared to 0.069 tonnes (−5.5%) for the catamaran and 0.066 tonnes (−9.6%) for the trimaran. These reductions correlate directly with lower total resistance–trimaran configurations exhibit ~9.4% lower resistance than monohulls and ~2.3% lower than catamarans at the reference scale–translating to reduced effective power requirements and cumulative fuel savings over vessel service life.

Tabel 4. Fuel consumption comparison based upon continuous operation power

Hull Configuration	Fuel Consumption (tons/day)	Efficiency Advantage
Monohull	0.073	Baseline

Catamaran	0.069	5.5% reduction
Trimaran	0.66	9.6% reduction

To validate these findings, a pairwise comparison matrix was constructed using the Analytic Hierarchy Process (AHP) as shown Table 5. This matrix compares each hull configuration with the others in terms of fuel efficiency. The Monohull was rated as less efficient than both the Catamaran and Trimaran, with relative values of 1.08 and 1.11, respectively. The Catamaran and Trimaran were also compared, with the trimaran slightly outperforming the catamaran (1.02 vs. 1.00). From these comparisons, the priority weights were derived as follows: monohull (0.357), catamaran (0.326), and trimaran (0.317). Although the Trimaran has the lowest fuel consumption, the monohull received the highest weight owing to its baseline status and possibly other operational considerations. The consistency ratio (CR = 0.0009) confirms that the expert judgments used in the matrix were highly reliable and consistent.

Tabel 5. Pairwise comparison matrix for fuel efficiency

Configuration	Monohull	Catamaran	Trimaran
Monohull	1.00	1.08	1.11
Catamaran	0.93	1.00	1.02
Trimaran	0.90	0.98	1.00

Priority weights (λmax = 3.001, CR = 0.0009)

- Monohull: 0.357
- Catamaran: 0.326
- Trimaran: 0.317

Overall, the analysis highlights the trimaran as the most fuel-efficient hull configuration, followed closely by the catamaran. Although monohulls are less efficient, they may still be considered for their simplicity and baseline familiarity. These insights are essential for selecting a vessel design that balances the operational cost, endurance, and environmental impact in the context of Maluku′ s fishing operations.

3.2.3 Crew Requirments Performance Criterion

The structured analysis of crew operational factors presented in the figure provides a comprehensive evaluation of how different hull configurations (Monohull, Catamaran, and Trimaran) support the practical needs of fishing vessel crews operating in Maluku Waters. The assessment was based on five critical criteria: deck operational space, accommodation comfort, vessel motion response, accessibility and safety features, and environmental control. These criteria reflect the daily realities and long-term endurance requirements of crew members working under dynamic maritime conditions.

An expert panel assigned performance ratings to each hull type (Table 6), with the trimaran scoring the highest (1.00), followed closely by the catamaran (0.95) and monohull (0.85). These ratings suggest that the trimaran offers superior crew comfort and stability, particularly in terms of motion response and spatial layout. The Catamaran also performs well, balancing comfort and operational safety, whereas the monohull, although familiar and compact, may present limitations in terms of space and motion dynamics.

Table 6. Expert panel assessment produced the following performance rankings:

Hull Configuration	Overall Crew Performance Rating
Trimaran	1.00
Catamaran	0.95
Monohull	0.85

To validate these rankings, a pairwise comparison matrix was constructed using the Analytic Hierarchy Process (AHP). This matrix compares each hull configuration with the others, producing normalised priority weights: trimaran (0.366), catamaran (0.338), and monohull (0.296). The consistency ratio (CR = 0.004) confirmed the reliability of the expert judgments, indicating a high level of agreement across evaluations, as shown Table 7.

Table 7. Pairwise comparison matrix for crew requirements

Configuration	Monohull	Catamaran	Trimaran
Monohull	1.00	0.90	0.85
Catamaran	1.11	1.00	0.95
Trimaran	1.18	1.05	1.00

Priority weights (λmax = 3.007, CR = 0.004):Priority weights (λ

- Monohull: 0.296
- Catamaran: 0.338
- Trimaran: 0.366

Overall, the analysis reinforces the trimaran as the most favourable option for crew operations, especially for extended missions requiring comfort, safety, and motion stability. The Catamaran remains a strong alternative, whereas the monohull may be best suited for shorter or simpler operations. This structured approach supports transparent decision-making and aligns with the technical and human factors essential for vessel selection in the Maluku Waters

3.3. Overall AHP Synthesis Results

The final synthesis results from an AHP prioritisation calculation, which is a multi-criteria decision-making method that combines the criterion weights with the configuration performance ratings. The fundamental approach shown multiplies each hull configuration's priority rating within individual criteria by the overall weight assigned to that criterion, then sums these products to produce an overall priority score for each configuration

The overall AHP prioritisation calculation combines the criterion weights with the configuration performance ratings within each criterion.

$$S_i = \sum_{j=1}^{n} (p_{ij} \cdot w_j) \tag{3}$$

S_i = Overall Priority Score for configuration i
w_j = Weight of criterion j
p_{ij} = Priority of configuration i within criterion j
n = Total number of criteria

For the Monohull configuration, the calculation demonstrated how three separate criteria contributed to the final score. The first criterion, weighted at 0.450, provided the monohull with a priority rating of 0.336, contributing 0.151 to the overall score. The second criterion, weighted at 0.380, assigned a priority of 0.357 to the monohull, adding 0.136 to the total. The third criterion, with a weight of 0.170, rated the monohull at 0.296, contributing 0.050. When these three contributions are summed (0.151 + 0.136 + 0.050), the monohull achieves an overall priority score of 0.337, which is the highest among all configurations.

Monohull Score:

= (0.336 × 0.450) + (0.357 × 0.380) + (0.296 × 0.170)

= 0.151 + 0.136 + 0.050

= 0.337

The Catamaran configuration follows a similar calculation structure but receives different priority ratings for each criterion. For the first criterion (weight 0.450), the catamaran scored 0.328 in priority, contributing 0.148 to its overall score. The second criterion (weight 0.380) gives it a priority of 0.326, adding 0.124 to the priority. The third criterion (weight 0.170) rated it at 0.338, contributing 0.057. The catamaran's final overall priority score was 0.329 (calculated as 0.148 + 0.124 + 0.057), placing it in third position.

Catamaran Score:

= (0.328 × 0.450) + (0.326 × 0.380) + (0.338 × 0.170)

= 0.148 + 0.124 + 0.057

= 0.329

The calculations for the Trimaran configuration showed that it performed moderately across the criteria. In the first criterion (weight 0.450), it received a priority rating of 0.336, identical to the monohull, contributing 0.151. However, in the second criterion (weight 0.380), its priority drops to 0.317, contributing only 0.120 to the overall weight. The third criterion (weight 0.170) gives it the highest priority among all configurations at 0.366, adding 0.062 to its score. The trimaran's overall priority score of 0.333 (0.151 + 0.120 + 0.062) places it second in the ranking.

Trimaran Score:

$$= (0.336 \times 0.450) + (0.317 \times 0.380) + (0.366 \times 0.170)$$

$$= 0.151 + 0.120 + 0.062$$

$$= 0.333$$

The synthesis results established a clear priority ranking for hull configuration selection, with the monohull achieving the top position at 0.337, representing a Priority Index of 100.0%. The Trimaran follows closely with a score of 0.333, corresponding to a Priority Index of 99.2%, indicating that it is nearly equivalent to the monohull option. The Catamaran ranked third with a score of 0.329 and a Priority Index of 97.6%, indicating that it was only marginally less favourable than the other two configurations. The remarkably close scores among all three hull types, with less than a 3% difference between the highest and lowest, suggest that the decision is highly competitive, and any of the three configurations could be viable depending on specific project requirements or constraints. The synthesised AHP results yielded the following priority ranking for hull configuration selection:

1. **Monohull: 0.337** (Priority Index 100.0%)
2. **Trimaran: 0.333** (Priority Index 99.2%)
3. **Catamaran: 0.329** (Priority Index 97.6%)

3.4. Sensitivity Analysis

Sensitivity analysis examines how variations in the criterion weight assignments influence the final priority rankings. Single-criterion weight perturbations of ±10% from the baseline valuations produced the following results:

a) The analysis of the Resistance Criterion with a weight variation between 0.405 and 0.495 revealed that all configurations consistently preserved their relative ranking order. Within this framework, the priority assigned to the monohull design fluctuated between 0.322 and 0.358, respectively. This stability in ranking suggests that, despite variations in weight, the inherent performance characteristics of each configuration remained intact, allowing for a clear differentiation in their resistance profiles.

b) In examining the Fuel Efficiency Criterion, which had a weight variation ranging from 0.342 to 0.418, it was observed that the ranking of configurations remained steady throughout the perturbation range. Notably, as the emphasis on fuel efficiency increased, the priority of trimaran design significantly increased. This indicates that the trimaran design features may offer enhanced fuel efficiency benefits, making it a more favourable option as the weight attributed to fuel efficiency becomes more pronounced in the evaluation process.

c) The assessment of the Crew Requirements Criterion, with a weight variation from 0.153 to 0.187, demonstrated an increasing advantage for the trimaran configuration as the emphasis on crew requirements increased. This trend suggests that the trimaran design may be better suited to accommodate crew needs, thereby enhancing its overall appeal in scenarios where crew efficiency and comfort are prioritised. The growing priority for trimarans in this context underscores their potential benefits in operational settings that demand a careful balance between crew capacity and performance.

4. Discussion

4.1 Criteria Importance Interpretation

The AHP analysis establishes that resistance characteristics (45.0% relative importance) emerge as the dominant decision criterion for fishing vessel hull configuration selection in the Maluku Waters. This weighting aligns with prior multi-criteria studies in naval architecture, where hydrodynamic efficiency typically receives 40–55% relative weight in displacement-hull optimization problems [45]. The 45% resistance weighting in this study is thus consistent with, though at the upper bound of, literature values—reflecting the particular sensitivity of Maluku fishing operations to transit time and fuel economy given long-distance fishing grounds and limited refueling infrastructure [46].

Fuel efficiency (38.0% relative importance), the secondary decision criterion, demonstrated a strong correlation with the resistance characteristics. The 7% differential between the first and second criteria weights reflects expert recognition that, while fuel efficiency represents a critical operational parameter, it is derived primarily from resistance characteristics rather than constituting an independent decision variable [37].

Crew operational requirements (17.0% relative importance), the tertiary criterion, receive substantially lower weightings than technical performance parameters. This prioritisation reflects expert assessments that crew comfort and safety, while important for long-term operational viability and crew retention, constitute secondary considerations relative to fundamental performance and efficiency characteristics

4.2 Hull Configuration Performance Analysis

4.2.1 Monohull Configuration Performance

The monohull configuration, representing the conventional baseline for small fishing vessels, exhibits the highest total resistance among the three configurations evaluated. At the design speed of 12 knots, the scaled resistance is estimated at 1.490 kN, corresponding to an effective horsepower (EHP) requirement of approximately 8.1 kW (assuming propulsive efficiency $\eta_p = 0.55$). Resistance increases non-linearly with speed, rising from 0.391 kN at 6 knots to 2.069 kN at 14 knots, reflecting the transition from friction-dominated to wave-making-dominated regimes as the Froude number increases from Fr ≈ 0.23 to Fr ≈ 0.54.

For an 18 m fishing vessel with an estimated displacement of 21.4 tonnes (scaled from the 1,550-tonne reference), the monohull form factor (1+k) is assumed to remain consistent with the reference geometry, though Reynolds number effects at the smaller scale ($Re \approx 9.3\times10^7$ at 12 knots) suggest a modest increase in the frictional resistance coefficient ($C_F \approx 0.0021$ versus 0.0017 for the 75 m reference). Consequently, the scaled resistance values presented herein should be interpreted as lower-bound estimates; actual resistance may be 5–10% higher when accounting for scale-dependent viscous effects.

Preliminary fuel consumption estimates, calculated using the specific fuel consumption value of 135 g/BHP·h adopted by Tupan and Luhulima (2020) and assuming a 500 nautical mile operational range, indicate a fuel requirement of approximately 0.18 tonnes for the monohull configuration at 12 knots. While this configuration offers simplicity in construction, maintenance, and berthing, its higher resistance profile translates to elevated operational costs and reduced range for a given fuel capacity—critical considerations for small-scale fishing operations.

4.2.2 Monohull Configuration Performance

The catamaran configuration demonstrates improved hydrodynamic efficiency relative to the monohull baseline, with a scaled total resistance of 1.409 kN at 12 knots—representing a 5.4% reduction compared to the monohull. This performance advantage arises primarily from the reduced wave-making resistance associated with the finer entry angles of each demihull and the beneficial interference effects between the twin hulls when optimally spaced. At lower speeds (6–8 knots), resistance reductions are modest (3–4%), while at higher speeds (10–14 knots), the advantage increases to 6–7%, consistent with the speed-dependent nature of wave interference phenomena.

Effective power requirements for the catamaran configuration at 12 knots are estimated at 7.7 kW, yielding a marginal but operationally meaningful reduction in fuel consumption of approximately 0.17 tonnes over a 500 nm mission profile. The wider beam (scaled to ~5.9 m from the reference 24.56 m) enhances transverse stability—a significant advantage for fishing operations involving deck work, net handling, or catch retention in moderate sea states. However, the increased wetted surface area relative to displacement introduces a penalty in frictional resistance, partially offsetting the wave resistance benefits at lower Froude numbers.

It is important to note that catamaran interference effects are highly sensitive to hull spacing (S/L ratio) and longitudinal stagger. The scaled geometry assumes preservation of the reference S/L ratio; deviations in the actual 18 m design could amplify or diminish the observed resistance benefits. Furthermore, the tunnel flow between demihulls may induce spray and ventilation effects at higher speeds, potentially increasing resistance beyond the scaled predictions

4.2.3 Monohull Configuration Performance

The trimaran configuration exhibits the most favorable hydrodynamic performance among the three alternatives, with a scaled total resistance of 1.362 kN at 12 knots—representing an 8.6% reduction relative to the monohull and a 3.3% reduction relative to the catamaran (Table 8). This advantage stems from the synergistic interaction between the slender main hull and the two smaller sidehulls (outriggers), which collectively reduce wave-making resistance through constructive interference while maintaining a relatively low wetted surface area. The resistance benefit is most pronounced at intermediate to high speeds (10–14 knots), where wave resistance dominates the total resistance budget.

Effective power requirements for the trimaran at 12 knots are estimated at 7.4 kW, corresponding to a preliminary fuel consumption estimate of 0.16 tonnes over a 500 nm operational range—the lowest among the three configurations. In addition to resistance advantages, the trimaran form offers superior transverse stability compared to the monohull (though marginally less than the catamaran) and a spacious main deck layout conducive to fishing gear deployment and catch handling. The narrow main hull also facilitates reduced draft, enhancing access to shallow coastal fishing grounds.

However, the trimaran configuration introduces design and operational complexities that must be carefully evaluated. The interference resistance term ($\Delta R_{tv} + \Delta R_{tv}$) [43] is highly sensitive to sidehull placement, stagger, and immersion depth; suboptimal positioning could negate or even reverse the resistance benefits. Additionally, structural loads at the connections between main hull and outriggers require robust engineering, potentially increasing construction cost and weight. For an 18 m fishing vessel, these trade-offs must be weighed against the modest absolute fuel savings (~0.02 tonnes per mission) relative to the catamaran.

Table 8. Comparative performance for 18 m fishing vessel configurations at 12 knots

Parameter	Monohull	Catamaran	Trimaran
Total Resistance (kN)	1.490	1.409	1.362
Resistance Reduction vs. Monohull	–	5.4%	8.6%

Effective Power (kW)	8.1	7.7	7.4
Estimated Fuel Consumption* (tonnes/500 nm)	0.18	0.17	0.16

4.2.4 Monohull Configuration Performance

While the AHP framework provides transparent, quantitative decision support, several limitations warrant acknowledgment:

- Expert judgment subjectivity: Priority weights derive from expert panel assessments, which may reflect contextual biases or incomplete information. The Consistency Ratio (CR < 0.10) validates internal judgment coherence but cannot eliminate external subjectivity [33].
- Criteria scope: The current analysis focuses on technical performance criteria (resistance, fuel efficiency, crew factors), excluding economic considerations (capital cost, maintenance) and environmental impacts (emissions, ecological footprint). Future integrated assessments should incorporate these dimensions.
- Data generalization: Hydrodynamic performance data were derived from standardized vessel archetypes; site-specific hull optimizations may yield different absolute performance values, though relative configuration rankings are expected to remain stable.
- Robustness justification: The sensitivity analysis (Section 3.4) demonstrates that configuration rankings remain stable under ±10% perturbations to individual criterion weights, confirming methodological robustness to moderate uncertainty in expert judgments. Furthermore, the narrow performance differentials among alternatives (2.4% between highest and lowest priority scores) suggest that the AHP framework appropriately captures the inherent competitiveness of viable hull configurations rather than artificially amplifying marginal difference

4.2.5 Monohull Configuration Performance

The Analytic Hierarchy Process (AHP) framework developed herein, grounded in Computational Fluid Dynamics (CFD) resistance analysis using SST k-ω turbulence modelling [43] provides structured decision support for stakeholders evaluating hull configurations for fishing vessels operating in Maluku's dual-regime maritime environment. Scaled hydrodynamic estimates indicate that trimaran configurations exhibit approximately 8.6 % lower total resistance relative to monohull baselines and 5.4% lower than catamarans at 12 knots, translating to reduced effective power requirements (about 7.4 kW versus 8.1 kW) and preliminary fuel savings of ~0.02 tonnes per 500-nautical-mile mission—advantages that, while modest in absolute terms, accumulate meaningfully over vessel service life and may enhance operational viability for fuel-sensitive small-scale fisheries. For vessel operators, these findings support configuration selection aligned with operational priorities: trimarans for fuel efficiency and shallow-draft coastal access, catamarans for enhanced transverse stability during deck operations, and monohulls where capital cost minimization predominates. For naval architects and shipbuilders, the analysis underscores that Froude-scaled resistance benchmarks require validation through 18 m-specific CFD or towing tank testing to account for Reynolds number disparities (Re = 9.3×10^7 versus 3.9×10^8 at reference scale) and scale-sensitive multihull interference phenomena, particularly regarding sidehull spacing (S/L) and structural load management at hull-outrigger connections. For maritime policymakers, the evidence supports development of technical guidelines, fuel-efficiency incentive mechanisms, and regulatory pathways that promote adoption of low-resistance hull forms while ensuring compliance with stability and seakeeping requirements for open-sea transit routes (e.g., Ambon–Halmahera). Collectively, these implications affirm that sustainable fleet modernization in Maluku Waters necessitates holistic, multi-criteria evaluation—integrating hydrodynamic performance, operational economics, construction feasibility, and environmental context—rather than resistance metrics alone, thereby strengthening the AHP framework's utility as a scalable decision-support tool for maritime stakeholders across the regional value chain.

4.3 Criteria Importance Interpretation

The AHP analysis provides a transparent, quantitative decision framework that addresses multiple competing criteria rather than a simplified single-criterion optimisation. The marginal differences among alternative configurations (0.337 vs. 0.333 vs. 0.329) suggest that fishing vessel selection decisions for Maluku Waters should incorporate secondary decision factors not addressed within the current analysis, including the following:

- Construction time and availability
- Maintenance requirements and technical support
- Availability of local expertise
- Integration with existing fleet operations
- Operational flexibility for different fishing methodologies

These secondary factors may appropriately adjust the final vessel selection decisions from the marginal technical preferences identified through the current AHP analysis [40].

5. Conclusions

This study has developed and applied an Analytic Hierarchy Process (AHP) framework to support evidence-based hull configuration selection for 18-meter fishing vessels operating in Maluku Waters, Indonesia. By integrating Computational Fluid Dynamics (CFD) resistance data from Tupan and Luhulima, scaled via Froude similarity laws, with operational, economic, and regulatory criteria, the framework provides structured decision support for vessel operators, naval architects, and maritime policymakers.The hydrodynamic analysis confirms that trimaran configurations exhibit superior resistance performance, with total resistance approxima tely 9.4% lower than monohull baselines and 2.3% lower than catamarans at 12 knots. These advantages translate to estimate daily fuel consumption of 0.066 tonnes for trimaran, 0.069 tonnes for catamaran, and 0.073 tonnes for monohull configurations—yielding potential operational savings of ~0.007 tonnes/day for trimaran versus monohull. Over a typical 200-day fishing season, cumulative savings of approximately 1.4 tonnes of fuel may be realized, representing meaningful economic benefits for small-scale fishing enterprises operating on thin margins.

The AHP framework successfully translates technical resistance metrics into actionable guidance by weighting criteria according to stakeholder priorities: fuel efficiency and shallow-draft capability favor trimaran adoption; transverse stability and deck workspace support catamaran selection; and construction simplicity and capital cost minimization justify monohull preference in resource-constrained contexts. Sensitivity analysis demonstrates that configuration rankings remain robust across plausible variations in criterion weights, enhancing the framework's utility for diverse decision-making scenarios. Methodological limitations must be acknowledged. Reynolds number disparities ($Re_{18} \approx 9.3\times10^7$ versus $Re_{75} \approx 3.9\times10^8$) suggest scaled resistance values represent lower-bound estimates, with actual frictional resistance potentially 5–10% higher. Froude regime transitions place the 18-meter vessel in semi-planing conditions where wave-making behavior diverges from the displacement-dominated reference geometry. Furthermore, multihull interference phenomena are inherently scale-sensitive and may not extrapolate linearly. Consequently, vessel-specific validation through CFD simulation using SST k-ω turbulence modeling or towing tank testing at the 18-meter scale is strongly recommended prior to design commitment.

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