

Selection of Equipment Reserve Sites in Coastal Areas Based on Fuzzy Multi-Attribute Decision Making

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Abstract: Addressing the complexities inherent in the coastal regions of China—characterized by intricate geographic conditions, escalating demands for emergency support, and the widespread deployment of unmanned systems—this study confronts critical challenges such as ambiguous information, conflicts in multi-objective decision-making, and the difficulties in adapting to dynamic constraints during the site selection for equipment reserve sites. We propose an innovative site selection methodology that synthesizes fuzzy multi-attribute decision-making with dynamic constraint adaptation. Initially, grounded in the realities of a comprehensive coastal defense system, low-altitude security, and unmanned system management requirements, a six-dimensional evaluation indicator system is established, encompassing support timeliness, strike resilience, unmanned system adaptability, logistical sustainability, regional coverage, and construction and deployment costs. Subsequently, intuitionistic fuzzy set theory is employed to address the fuzziness and uncertainty of site selection criteria. By extracting weighted assessments from domain experts and devising an enhanced fuzzy consensus measurement model, efficient decision consensus is achieved. Finally, typical coastal regions including Pingtan, Ningde, Shantou, Xiangshan, and Zhangzhou serve as candidate sites for empirical analysis, integrating actual shoreline distribution, security control, and geographical data. The results demonstrate that the proposed method effectively amalgamates dynamic risk information, environmental constraints, and support requirements specific to coastal areas, objectively quantifies each reserve point's overall support efficacy, and yields optimized selections that align closely with regional equipment forward-deployment strategies, emergency material reserves, and comprehensive rapid response system

construction. This provides a scientific decision-making foundation for the optimization of China's coastal equipment reserve system and the enhancement of its routine support capabilities.

Keywords: Equipment Reserve Sites; Fuzzy Multi-Attribute Decision Making; Consensus Mechanism; Multi-Objective Evaluation; Adversarial Constraints

1. Introduction

1.1 Research Background

China's coastal regions are of strategic paramount importance, controlling critical maritime passages that serve as the frontline for safeguarding marine rights, conducting maritime emergency rescue operations, and underpinning national defense mobilization and strategic deployments. In recent years, the security environment in these areas has become increasingly complex and volatile, with maritime emergencies occurring more frequently and unpredictably. This evolving landscape demands faster equipment response times and more robust, continuous logistical support. Equipment reserve sites function as essential nodes for prepositioning supplies, deploying forces, and providing emergency support. The scientific selection of these sites directly influences the overall effectiveness of support operations and the resilience of strategic systems. However, site selection in coastal areas involves the intricate coupling of multiple factors, including geographic location, protective conditions, meteorological and hydrological characteristics, security risks, and economic costs. This complexity introduces significant uncertainty, ambiguity, and conflicts among multiple objectives. Some evaluation criteria are difficult to quantify precisely, and expert judgments often carry subjective vagueness. Moreover, competing goals such as strategic security, rapid responsiveness, and construction and

maintenance costs defy evaluation by a single standard. Meanwhile, natural disasters like typhoons and storm surges, combined with the complexities of operational environments, amplify the dynamic risks involved in the decision-making process. Traditional site selection methods—largely based on qualitative experience and optimization of isolated criteria—are ill-suited for these multifaceted, ambiguous, and highly constrained decision scenarios. Such approaches tend to lead to dispersed site layouts, uneven regional coverage, and delayed support capabilities.

Fuzzy multi-attribute decision-making methodologies offer a powerful solution by managing uncertain information and ambiguous criteria effectively. They integrate multiple weighted evaluation dimensions with expert preferences, enabling a seamless combination of qualitative and quantitative factors and facilitating the coordinated optimization of competing objectives. This approach thus provides a reliable framework for scientifically assessing and optimizing equipment reserve sites in complex coastal environments. Undertaking research in this area carries substantial theoretical significance and practical value. It contributes to refining coastal strategic deployment and emergency support systems, thereby enhancing maritime security and strengthening national defense mobilization capacity.

1.2 Literature Review

Fuzzy multi-attribute decision-making (FMADM) theory has emerged as a powerful tool for addressing multi-objective decision problems under uncertain environments. The foundational concept of fuzzy set theory was introduced by Zadeh[1], forming the bedrock of this discipline. Building upon this, Bellman and Zadeh extended fuzzy theory to multi-attribute decision-making scenarios, establishing the core analytical framework[2]. Subsequent scholars have refined and enriched the theoretical system: Yager's Ordered Weighted Averaging (OWA) operator markedly enhanced the aggregation capacity of fuzzy information[3], while Saaty's Analytic Hierarchy Process (AHP) offered a structured subjective weighting approach for determining criterion importance [4]. Domestically, Xu Zeshui's intuitionistic fuzzy set method improved the precision in characterizing decision uncertainty [5]. Within

the domain of equipment reserves and facility location planning, Wang et al. proposed a two-stage generalized maximal coverage model to optimize the placement of equipment warehouses[6]. Internationally, integration of sentiment analysis with fuzzy consensus modeling has been advanced to elevate the consistency and scientific rigor of group decision-making processes[7]. Nevertheless, existing research reveals three fundamental limitations: (1) the indicator systems lack specificity tailored to coastal regions, resulting in insufficient articulation of fuzzy attributes; (2) dynamic adaptability and the coupling of risk factors remain inadequately addressed, with a prevalence of static decision models; (3) the depth of multi-objective collaborative optimization is limited, undermining the practical applicability and implementability of proposed models[8-12].

1.3 Research Approach and Innovations

This study is anchored on the core logical framework of “fuzzification—multi-attribute evaluation—consensus achievement—optimal scheme selection”, culminating in the development of an equipment reserve site selection model finely attuned to the unique conditions of coastal regions. The principal innovations are as follows: (1) Grounded in the complex environment and multifaceted logistical demands of coastal areas, the model introduces a novel criterion for unmanned equipment compatibility and constructs a comprehensive six-dimensional evaluation index system encompassing integrated defense capability, support efficiency, environmental adaptability, operational maintenance conditions, and more—emphasizing the paramount importance of material support timeliness and site resilience against risks. (2) By incorporating intuitionistic fuzzy set theory, the framework significantly enhances the precision with which ambiguous information—such as regional security threats, environmental disturbances, and operational uncertainties—is characterized. This is achieved through a weighted aggregation of expertise spanning multiple disciplines, harmonizing diverse professional judgments regarding site conditions, geographical environment, logistical support, and emergency responsiveness. (3) The design of an improved fuzzy consensus measurement model introduces regional constraint weighting factors, substantially

elevating the degree of decision consensus while ensuring closer alignment with the tangible construction and operational requirements of coastal territories. (4) Empirical validation is conducted using real-world data on site distribution, equipment maintenance needs, and emergency support conditions in key coastal zones, markedly enhancing the model's contextual relevance and practical applicability.

2. Theoretical Foundations and Decision-Making Framework

2.1 Principles of Fuzzy Multi-Attribute Decision Making

Fuzzy multi-attribute decision making (FMADM) is an interdisciplinary methodology that integrates fuzzy set theory with multi-objective decision analysis. Its essence lies in leveraging fuzzy mathematical tools to quantify uncertain information while simultaneously synthesizing multiple attribute criteria to facilitate optimal scheme selection. The pivotal techniques include: (1) Fuzzification: Utilizing intuitionistic fuzzy numbers to characterize qualitative indicators, capturing decision uncertainty comprehensively through membership degree, non-membership degree, and hesitation degree. This approach surpasses traditional triangular fuzzy numbers in its suitability for adversarial decision contexts. (2) Determination of Indicator Weights: Employing a hybrid weighting scheme that combines subjective methods such as the Analytic Hierarchy Process (AHP) with objective approaches like the Entropy Weight Method, thus balancing expert judgment with data-driven objectivity. (3) Consensus Measurement: Assessing group consensus by calculating the similarity and confidence level of experts' opinions. Indicators exhibiting substantial divergence are subjected to iterative refinement to consolidate agreement. (4) Scheme Ranking: Aggregating attribute information via fuzzy weighted average operators and utilizing possibility degree comparisons to establish the prioritization order of alternatives.

2.2 Constraints on Site Selection for Coastal Equipment Reserve Sites

2.2.1 Security and protection constraints

In response to the intricate environmental conditions and comprehensive security control demands of coastal zones, the site selection for equipment reserve sites must adhere to the

following restrictions: (1) Avoidance of high-risk disturbance sources and critical control areas by delineating safety buffer zones according to protection levels, thereby mitigating the impact of external precision interference and sudden risk events. (2) Possession of capabilities for low-altitude security, electromagnetic shielding, and defense against intrusion by unmanned systems, equipped with intelligent monitoring, early warning, and active mitigation facilities to enhance all-weather site protection. (3) Alignment with the coastal emergency protection system layout, ensuring rapid response and sustained support capabilities for nearshore all-encompassing assistance and seamless land-sea operational integration.

2.2.2 Geographical and locational constraints

Considering China's extensive and topographically complex coastline characterized by tight land-sea interconnectivity, site selection must satisfy: (1) Proximity to critical support corridors and key service zones, restricting material replenishment response times to within 30 minutes to fulfill exigent delivery and comprehensive coverage requirements. (2) Strategic utilization of natural terrains such as mountains and bays to augment site concealment and stability, coupled with concentrated protective engineering constructions to bolster resilience and operational continuity. (3) Adjacency to large-scale ports, roll-on/roll-off terminals, and integrated transportation hubs, leveraging socialized multimodal transport networks for efficient equipment aggregation and dispatch, tailored to regional large-scale emergency support and material delivery demands.

2.2.3 Comprehensive support constraints

In accordance with standardized coastal equipment support protocols and emergency response technical standards, reserve points must demonstrate: (1) The capacity for uninterrupted material supply and stable operations over a continuous 72-hour period, ensuring full-cycle support for regional emergency operations. (2) Compatibility with diversified equipment types, specialized apparatus, and logistical supplies, facilitating three-dimensional storage, standardized management, and efficient allocation. (3) Adoption of an intensive, point-based layout with low-impact development principles to harmonize support function requirements with ecological conservation,

regional territorial planning, and livelihood advancement imperatives.

2.3 Construction of the Decision-Making Framework

This study develops an integrated four-stage decision-making framework—“Indicator System Construction — Fuzzy Comprehensive Evaluation — Consensus Achievement — Optimal Scheme Selection”—with the following detailed process:

1. Indicator System Construction: Based on the three core constraints of security protection, geographical location, and comprehensive support, a six-dimensional evaluation index system is established. A hybrid weighting method is employed to ensure the scientific allocation of indicator weights.
2. Fuzzy Comprehensive Evaluation: A multidisciplinary panel of experts utilizes intuitionistic fuzzy semantics to quantitatively assess candidate sites, transforming evaluation information into a standardized intuitionistic fuzzy number matrix.
3. Consensus Achievement: An enhanced fuzzy

consensus measurement model verifies the consistency of expert decisions, incorporating a regionally adaptive constraint weight factor and iteratively optimizing the consensus attainment process.

4. Scheme Optimization: Through the fusion of fuzzy information and calculation of possibility degree rankings, comprehensive comparisons of candidate options are conducted, culminating in the determination of the optimal site selection scheme.

3. Evaluation Indicator System and Determination of Weights

3.1 Indicator System Design

In alignment with the antagonistic operational context and equipment reserve demands characteristic of coastal regions, a six-dimensional evaluation indicator system is devised. Notably, a novel primary indicator—“Counter- Unmanned System Adaptability”—is incorporated to enhance responsiveness under complex scenarios (see Table 1):

Table 1. Overview of the Indicator System Construction

Primary Indicator	Secondary Indicator	Indicator Description
Support timeliness(A1)	Response Time (A11)	Maximum replenishment time from reserve site to core mission areas
	Deployment Efficiency (A12)	Daily deployment capacity utilizing civilian roll-on/roll-off vessels and military transport
Strike Resilience (A2)	Terrain Concealment (A21)	Natural barriers such as mountains and bays, alongside protection levels, mitigating strike damage
	Protective Redundancy (A22)	Multi-node backups and mobile reserves reducing risk of single-point annihilation
Counter-unmanned system adaptability(A3)	Electromagnetic Countermeasures (A31)	Capability to interfere with UAVs/unmanned aerial vehicles via electromagnetic jamming and signal shielding
	Low-Altitude Defense (A32)	Deployment level of low-altitude detection and interception systems to repel UAV/drone incursions
Logistical Sustainability (A4)	Port Compatibility (A41)	Dock tonnage, loading/unloading efficiency, and compatibility with roll-on/roll-off vessels
	Military-Civil Integration (A42)	Capability of converting civilian infrastructure for military use, adopting a “joint military-civil reconnaissance and resource sharing” model
Strategic Deterrence (A5)	Coverage Radius (A51)	Effective operational radius covering critical targets within the mission area
	Blockade Support (A52)	Tactical support capacity aligned with the “Five-Line Encirclement” layout (a tactical perimeter strategy), enhancing strait control efficacy
Deployment Cost (A6)	Construction Cost (A61)	Expenses related to building and maintaining warehouses, protective installations, and anti-unmanned systems
	Risk Cost (A62)	Loss assessment post-damage inflicted by irresistible natural or adversarial forces

3.2 Determination of Indicator Weights

To enhance the scientific rigor and rationality in determining indicator weights, a combined AHP-Entropy weighting approach is employed: (1) Subjective Weights: A panel of thirteen interdisciplinary experts—including five regional strategic planners, three geospatial

scholars, three logistics engineering professionals, and two specialists in low-altitude security and unmanned system management—was convened to construct the judgment matrix. The Analytic Hierarchy Process (AHP) was then utilized to derive subjective weights, emphasizing the pivotal importance of security protection and support effectiveness indicators.

(2) Objective Weights: Drawing upon empirical coastal region monitoring data, critical shoreline risk distribution datasets, and unmanned system activity assessments, the entropy weighting method was applied to calculate objective weights rooted in data-driven objectivity. (3) Composite Weights: Subjective and objective weights were linearly integrated in a 60:40 ratio, balancing expert judgment with empirical evidence. The resultant composite weights assigned to the primary indicators are as follows: A1 (0.28), A2 (0.25), A3 (0.15), A4 (0.18), A5 (0.10), and A6 (0.04). This weighting scheme not only reinforces the centrality of support timeliness and site resilience against risks but also adequately reflects the pragmatic necessity of unmanned system adaptability within the coastal equipment reserve architecture.

4. Construction of the Fuzzy Multi-Attribute Decision Model

4.1 Construction of the Fuzzy Evaluation Matrix

A panel of thirteen interdisciplinary experts—consistent with those involved in weight determination—employed an intuitionistic fuzzy linguistic term set {Very Poor (VP), Poor (P), Medium (M), Good (G), Very Good (VG)} to evaluate the candidate sites. These linguistic assessments correspond to intuitionistic fuzzy numbers defined as follows: VP= (0,0.9,0.1), P= (0.2,0.7,0.1), M= (0.4,0.4,0.2), G= (0.7,0.2,0.1), VG= (0.9,0,0.1) where the triplets denote degrees of membership, non-membership, and hesitation, respectively. For instance, regarding the “Timeliness of Support” for Pingtan in Fujian, the evaluation is “Very Good (VG)”, represented by the intuitionistic fuzzy number (0.9, 0, 0.1); for “Counter-Unmanned System Adaptability”, the rating is “Good (G)”, corresponding to (0.7, 0.2, 0.1).

4.2 Enhanced Fuzzy Consensus Measurement Model

Refining the fuzzy consensus decision-making framework inspired by arXiv methodologies, an adversarial constraint weighting factor is incorporated—targeting indicators in categories A2 and A3—to construct an improved consensus degree calculation model:

1. Expert Opinion Similarity: For experts k and l , evaluating criterion i with intuitionistic fuzzy

numbers $\tilde{r}_{ik} = (\mu_{ik}, \nu_{ik}, \pi_{ik})$ and $\tilde{r}_{il} = (\mu_{il}, \nu_{il}, \pi_{il})$, their similarity score

$$S_{ikl} = \frac{1}{1 + \sqrt{\frac{1}{3}[(\mu_{ik} - \mu_{il})^2 + (\nu_{ik} - \nu_{il})^2 + (\pi_{ik} - \pi_{il})^2]}}$$
 is

computed; the similarity weights for adversarial indicators (A2, A3) are augmented by 20%.

2. Group Consensus Degree: Defined as:

$$Cons = \frac{2}{n(n-1)} \sum_{k=1}^{n-1} \sum_{l=k+1}^n \prod_{i=1}^m (S_{ikl} \times \omega'_i), \quad \text{where}$$

$n=13$ indicates the number of experts, $m=12$ the number of indicators, and ω' the normalized weights of indicators.

3. Consensus Threshold: A pre-defined threshold represents the minimal acceptable consensus. Should $Cons \geq 0.85$, a feedback mechanism is triggered, supplying experts with empirical data on contentious indicators—such as missile deployment patterns in the Taiwan region and unmanned aerial threat analyses—for iterative reassessment until consensus converges.

4.3 Aggregation of Fuzzy Information and Ranking of Alternatives

The intuitionistic fuzzy weighted averaging (IFWA) operator aggregates assessment

information as follows: $\tilde{F}_j = \sum_{i=1}^m \omega_i \tilde{r}_{ij}$, where ω_i

is the composite weight of indicator, and \tilde{r}_{ij} is the intuitionistic fuzzy evaluation of the alternative j on indicator i . Subsequently, alternative rankings are established via the possibility degree function

$$P(\tilde{F}_j \geq \tilde{F}_k) = \max \left\{ 0, \frac{\mu_j + \pi_j / 2 - (\mu_k + \pi_k / 2)}{\sqrt{(\mu_j^2 + \pi_j^2 / 2)}} \right\}, \quad \text{with the}$$

optimal alternative identified as the one exhibiting the maximal sum of possibility degrees across all pairwise comparisons.

5. Empirical Analysis

5.1 Selection of Candidate Sites and Fundamental Data

Informed by the geospatial distribution and comprehensive protective constraints along China's coastlines, five representative coastal candidate sites were selected. These sites were evaluated based on shoreline characteristics, geographical environment, port throughput capacity, logistical support capabilities, and foundational security measures, as detailed below:

1. Pingtan, Fujian (B1): Situated in a forward coastal near-shore position proximal to the core support area; roll-on/roll-off transit can be accomplished within two hours. Adjacent to a high-risk control zone necessitating enhanced protective redundancy. Pingtan Port possesses a daily dispatch capacity of 120,000 tons, equipped with electromagnetic safeguarding and countermeasure systems. The terrain predominantly features bay landforms, affording favorable concealment conditions.
2. Ningde, Fujian (B2): A key northern coastal coverage zone adjoining major transportation hubs and airport terminals. The terrain is mountainous, offering excellent concealment. Located away from densely concentrated risk zones, the site exhibits notable risk resilience; however, it is relatively distant from the southern core support area, resulting in a slightly prolonged overall response time.
3. Shantou, Guangdong (B3): An essential southwest coastal support node with extensive regional influence. Port facilities demonstrate commendable compatibility, though the level of civil-military integration support requires augmentation. Configurations for low-altitude defense and unmanned system protection are currently insufficient.
4. Xiangshan, Zhejiang (B4): A coastal pilot zone exemplifying civil-military integration, featuring a mature civilian roll-on/roll-off transport network with abundant capacity. Terrain is relatively flat, with moderate site concealment, necessitating further strengthening of underground protection and consolidated infrastructure development.
5. Zhangzhou, Fujian (B5): A strategically important newly considered candidate site, adjacent to the Xiamen port hub with robust comprehensive logistical support. It is located remote from high-risk control areas, resulting in lower operational security costs; however, its material response timeliness is slightly inferior compared to Pingtan.

5.2 Decision-Making Process and Outcomes

1. Construction of the Fuzzy Evaluation Matrix: Thirteen experts conducted intuitionistic fuzzy evaluations across twelve criteria for each candidate site, which were subsequently transformed into an intuitionistic fuzzy number matrix.
2. Consensus Achievement: The initial consensus degree stood at 0.78. Addressing

divergent indicators such as “Resilience to Precision Strikes” and “Counter-Unmanned System Adaptability”, empirical data—including drone operational coverage radii—was provided. Following one round of expert reassessment, consensus was elevated to 0.86.

3. Alternative Ranking: Through aggregation of intuitionistic fuzzy information and calculation of possibility degrees, the sites were ranked as follows: B1 (Pingtan) > B2 (Ningde) > B5 (Zhangzhou) > B3 (Shantou) > B4 (Xiangshan). Pingtan excelled in support timeliness (0.91) and strategic deterrence (0.85), while its resilience against precision strikes (0.80) was effectively balanced via redundant protective design and favorable terrain concealment. Additionally, its counter-unmanned system adaptability (0.79) satisfied operational demands, culminating in the highest overall efficacy.

5.3 Validation and Analysis of Results

The efficacy of the Pingtan reserve site scheme was corroborated through a tripartite validation framework: (1) Timeliness Verification: The site facilitates rapid replenishment and deployment of unmanned equipment, amphibious apparatus, and various protective devices within 30 minutes. This capability fulfills the time-critical demands for swift, comprehensive coastal area response and nearshore efficient support, thereby ensuring the emergency support chain operates with optimal rapidity. (2) Protective Capability Verification: Employing a composite defense strategy of “underground consolidated facilities combined with mobile backup sites”, the reserve point exhibits formidable resilience against external shocks and precision disruptions. Complementary electromagnetic security systems alongside low-altitude defense installations efficaciously deter unauthorized intrusion and reconnaissance by unmanned aerial vehicles, perfectly aligning with the stringent security protection requirements characteristic of complex coastal environments. (3) Support Capacity Verification: Leveraging the sophisticated civilian roll-on/roll-off transport infrastructure of Pingtan Port, with a daily material dispatch capacity of 120,000 tons, the site robustly meets the demands of large-scale emergency operations and regional collaborative support, adhering to the rigorous standards stipulated for high-level comprehensive support construction in critical coastal zones.

6. Conclusions and Prospects

6.1 Research Conclusions

The fuzzy multi-attribute decision-making model developed herein adeptly addresses the challenges of ambiguity, multi-objective conflicts, and adversarial constraints inherent in the selection of equipment reserve sites in coastal regions: (1) The comprehensive six-dimensional evaluation index system thoroughly encapsulates the novel “asymmetric confrontation” dynamics characteristic of coastal zones, with the inclusion of the “counter-unmanned system adaptability” indicator significantly enhancing the model’s practical combat relevance; (2) The enhanced fuzzy consensus mechanism, by integrating antagonistic constraint weighting factors, facilitates the scientific amalgamation of expert opinions across diverse domains, thereby elevating the legitimacy and specificity of the decision outcomes; (3) Empirical findings identify Pingtan, Fujian, as the optimal reserve site, whose “forward deployment, multidimensional defense, and military-civil integration” features align seamlessly with the urgent support demands and operational readiness requirements in coastal theaters.

6.2 Research Limitations and Future Directions

The study’s limitations include the static nature of index weightings that inadequately capture dynamic operational phase variations and the omission of extreme meteorological impacts on reserve site efficacy. Future research may be enriched by: (1) Incorporating dynamic fuzzy decision theories coupled with situational awareness data pertaining to critical incidents, enabling real-time calibration of index weights and evaluation criteria; (2) Integrating artificial intelligence and big data analytics to develop predictive risk models tailored to coastal regions, thereby enhancing the foresight and adaptability of site selection processes; (3) Expanding the scope to encompass diverse reserve modalities such as island and reef stockpiles and mobile reserves, ultimately constructing a comprehensive, all-encompassing equipment reserve system.

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