

Article

Optimisation of Nautical Anchorages: A Six-Method Hybrid Approach

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Abstract

The increasing complexity of marine spatial management and the rapid growth of nautical tourism require the use of formal and transparent decision-making models. Identifying optimal locations for nautical anchorages is a multi-criteria decision problem (MCDP) in which navigation safety, spatial constraints, and environmental protection often conflict. This study presents an integrated framework combining Geographic Information Systems (GIS) and multi-criteria decision-making (MCDM) methods for the systematic evaluation and ranking of nautical anchorages. As a case study, 86 potential locations in Split-Dalmatia County, Croatia, were analysed based on 18 criteria encompassing hydrological, meteorological, and spatial factors, as well as risk factors relevant to navigation safety. The methodological approach applies six MCDM methods implemented in the R programming language: Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), ViseKriterijska Optimizacija I Kompromisno Rjesenje (VIKOR), Multi-Objective Optimisation on the Basis of Ratio Analysis (MOORA), Complex Proportional Assessment (COPRAS), Measurement of Alternatives and Ranking according to Compromise Solution (MARCOS), and Evaluation Based on Distance from Average Solution (EDAS). To reduce methodological bias, a final Consensus rank was calculated to synthesise the results of all applied methods. The stability of the obtained ranking was examined through an analysis of rank agreement between methods, using a diagonal matrix of rank overlaps and the corresponding heatmap visualisation. The results indicate a high level of consistency among individual MCDM methods and strong stability of the final consensus ranking. The proposed model ranks locations from best to worst based on how well they meet the established criteria, while ensuring strict navigational safety and compliance with environmental constraints. These findings confirm that the integrated GIS–MCDM approach is a reliable, repeatable, and scientifically grounded tool for supporting spatial planning and concession allocation in the development of nautical infrastructure.



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1. Introduction

In contemporary maritime transport, marine spatial management faces challenges of increasing complexity, requiring a departure from traditional, often fragmented approaches toward the application of rigorous, mathematically grounded models. The central problem addressed in this study is the absence of a unified and scientifically validated methodology for the spatial positioning of nautical anchorages, which frequently results in suboptimal

solutions in terms of navigational safety and environmental protection. From this problem emerges the research focus: a comprehensive evaluation of 86 potential anchorage sites within the maritime area of Split-Dalmatia County (SDC), Croatia, where each location is treated as an alternative within a multidimensional system defined by 18 key nautical, hydrometeorological, economic, and environmental criteria.

The primary objective of the research is the development and validation of a decision-support framework that enables transparent and objective ranking of anchorage areas. The motivation for this approach lies in the necessity to reconcile conflicting interests: the demand of mariners for maximum safety, the concessionaires' pursuit of economic efficiency, and the requirements of local communities for the preservation of marine ecosystems and protected areas such as the Natura 2000 network [1]. In the context of substantial investments and responsibility for human lives, mathematical optimization emerges as the only approach capable of ensuring the safest—not merely the most economically favorable—solution.

Methodologically, the study relies on advanced geoinformatics (GIS) tools and the rigorous application of six complementary multi-criteria decision-making (MCDM) methods implemented in the R programming environment [2]: the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Multi-Criteria Optimization and Compromise Solution (VIKOR), Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA), Complex Proportional Assessment (COPRAS), Measurement of Alternatives and Ranking according to the COMpromise Solution (MARCOS), and Evaluation based on Distance from Average Solution (EDAS). This methodological diversification enables the derivation of a final *Consensus* rank—a synthetic ranking that provides a high level of reliability through validation using Spearman's rank correlation.

The stability of the obtained ranking was examined by explicitly quantifying the degree of agreement among all applied methods. For this purpose, a diagonal rank-overlap matrix was constructed to measure the number of identical rank positions shared by each pair of methods, including the final consensus ranking. The corresponding heatmap visualisation offers a clear and intuitive representation of consistency patterns, where larger and more intensely coloured elements indicate higher levels of agreement. The analysis reveals a high degree of concordance among individual MCDM methods and confirms the robustness and stability of the final consensus ranking with respect to methodological variations.

All locations are ranked according to how well they meet the established criteria, providing a comprehensive overview of the overall ranking. In the final section of the results, a detailed analysis is presented for the ten most favourable locations, which best satisfy navigational safety and environmental requirements. By integrating spatial analyses with multiple decision-making perspectives, subjectivity in the site selection process is reduced, while transparency and repeatability of the decision-making procedure are increased. The results confirm that the integrated GIS–MCDM approach is a scientifically grounded and practically applicable tool to support maritime spatial planning and the allocation of concessions for the development of nautical infrastructure.

The structure of the paper follows the logical sequence of the scientific process, beginning with the introduction, a review of related research, and a general overview of MCDM methods, followed by a Materials and Methods section detailing the weighting coefficients and algorithms. The Results section presents descriptive statistics and interactive Leaflet maps visualizing the top ten optimal locations. The final sections comprise a discussion with expert validation of the proposed solutions and a conclusion offering concrete recommendations for improving the legal framework and spatial planning of anchorages as a common maritime good.

1.1. Previous Research on Anchorage Methodology and Spatial Planning

Research in maritime spatial planning and anchorage site optimisation has advanced significantly over the past decade. Particular emphasis has been placed on the application of MCDM methods and the integration of GIS tools, enabling accurate site evaluation under complex spatial and environmental constraints [3–9]. Hybrid models combining the Analytical Hierarchy Process (AHP), Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE), fuzzy TOPSIS, International Safety Management (ISM), MARCOS, and EDAS methods have proved robust for ranking alternatives and reducing uncertainty in decision-making [10–14]. Analyses of maritime traffic and nautical infrastructure indicate the need to optimise anchorage locations to reduce navigational risks and enhance safety [3,4,15–17].

1.2. Sustainable Development and Environmental Aspects

Anchorage planning today must consider environmental and regulatory guidelines. Protected areas, the Natura 2000 network, and The World Association for Waterborne Transport Infrastructure (PIANC) technical guidelines ensure the protection of benthic communities and habitats from the impacts of anchoring activities [1,5,18–20]. Decision support systems (DSS) and assessment models assist in the sustainable management of nautical tourism, concession allocation, and the planning of environmentally acceptable anchorage sites [21–25]. GIS and advanced MCDM algorithms are also applied in planning offshore projects, ports, and mariculture, enabling balanced development of maritime resources [7–9,13].

1.3. DSS, MCDM, and the Application of Analytical Tools

The transformation of theoretical concepts into practical tools is evident in the development of DSS and multi-method MCDM models, which enable the ranking of regional transport programmes, optimisation of container terminals and feeder services, and evaluation of operational efficiency [26–34]. The robustness of methods such as MARCOS, EDAS, and TOPSIS enables reliable decision-making under uncertainty [10–12,35]. The use of the R programming language further facilitates statistical data processing and the integration of spatial and environmental information [2]. Ultimately, hybrid GIS–MCDM approaches support intelligent and sustainable development of maritime resources, including anchorages, ports, and offshore projects [1,5,18–20].

Despite significant progress in applying MCDM techniques to maritime spatial planning, most previous studies rely on a single decision-making algorithm or, at most, compare several methods without integrating their results into a unified decision framework. Consequently, the final ranking often depends on the mathematical properties and weighting mechanisms of the selected algorithm, which may lead to variations in the prioritisation of alternatives. Furthermore, relatively little attention has been paid to systematically evaluating the consistency of rankings across different MCDM methods, leaving the robustness and reliability of the final decision insufficiently addressed. To address these limitations, this study proposes a comprehensive six-method hybrid framework that combines TOPSIS, VIKOR, MOORA, COPRAS, MARCOS, and EDAS within a consensus-based decision-support model. Rather than identifying the best individual algorithm, the proposed approach focuses on deriving stable rankings consistently supported by multiple complementary MCDM methods. The integration of consensus ranking with statistical validation of inter-method agreement provides an additional level of methodological robustness and objectivity, offering a more reliable basis for nautical anchorage evaluation and maritime spatial planning than conventional single-algorithm approaches.

1.4. Specifics of the Proposed Approach

Compared with existing studies in nautical anchorage planning and optimisation, this research introduces an original and methodologically advanced approach that integrates spatial analytics, multi-criteria decision-making, and statistical validation into a unified decision-support framework.

The principal distinction from previous studies is that the selection of optimal anchorage locations is not based on the results of a single method or a limited set of criteria but on the integration of six state-of-the-art MCDM methods (TOPSIS, VIKOR, MOORA, COPRAS, MARCOS, and EDAS), applied to a dataset of 86 potential locations evaluated against 18 interrelated criteria encompassing navigational safety, spatial characteristics, hydrometeorological conditions, environmental constraints, and economic considerations. This comprehensive framework enables the simultaneous assessment of all relevant dimensions of the problem and represents a substantial advancement over studies that address only selected aspects of the decision-making process.

A key scientific contribution of the study is the development and implementation of a Consensus Rank model, through which the results of all applied methods are integrated into a single, stable, and robust ranking system. This approach reduces the dependence of the final decision on the specific characteristics of individual algorithms and provides a higher level of objectivity. Rather than addressing which method produces the “best” result, the proposed framework identifies locations that consistently achieve superior rankings regardless of the method applied, thereby providing a more reliable basis for strategic decision-making.

Unlike most previous studies, which typically conclude with the presentation of a final ranking of alternatives, this research introduces an additional layer of validation through the assessment of inter-method agreement. By applying Spearman rank correlation analysis and rank-overlap matrices, the stability and robustness of the results are systematically quantified. Consequently, the study demonstrates not only which locations are ranked most favourably but also the extent to which these rankings remain consistent across different methodological approaches, thereby significantly enhancing the scientific credibility of the findings.

One of the most significant contributions of the study is its spatially explicit analytical framework. While most existing studies present results solely through tabular outputs and numerical rankings, the proposed approach integrates the ranking process within a GIS environment and visualises the results through detailed spatial representations. This enables the identification of geographical patterns, spatial clusters, and relationships between the highest-ranked locations, navigation routes, coastal infrastructure, protected areas, and other elements of the maritime environment. Of particular importance is the detailed spatial analysis and cartographic presentation of the best-performing locations, which substantially enhances the practical applicability of the results for maritime spatial planning and decision-making processes.

The contribution of the study extends beyond methodological innovation. The proposed framework constitutes an operational decision-support tool that enables transparent, reproducible, and scientifically grounded evaluation of anchorage locations. By reducing subjectivity in concession allocation and nautical infrastructure planning, the model facilitates balanced consideration of the three fundamental objectives of contemporary maritime spatial management: navigational safety, economic viability, and environmental protection.

Ultimately, the originality of this research lies in its position as one of the first studies in nautical anchorage planning to integrate multi-method ranking, consensus-based decision-making, robustness assessment, GIS-driven spatial analytics, and detailed evaluation of a large set of potential locations within a single analytical framework. By moving beyond

conventional approaches based on individual methods, the proposed methodology provides a comprehensive and scientifically rigorous model for maritime spatial planning and anchorage optimisation, offering substantial academic, professional, and practical value.

2. Materials and Methods

2.1. Data

The primary data for this research are sourced from the “Study of Anchorages in the Split-Dalmatia County—Phases I and II” [36] and include detailed specifications for 56 nautical anchorage locations. As multiple fields are recorded per location, these are treated as 86 alternatives in the MCDM analysis.

All technical, nautical, and environmental parameters used in the MCDM models (18 criteria in total) were derived, systematised, and analysed based on the original case study data. Each anchorage location is defined by basic identifiers (“Id”, “name”, “Island”, and “field”), where the variable “Island” has four values across the 86 fields: 1. BRAC 14; 2. CIOVO, DRVENIK, SOLTA AND MAINLAND 20; 3. HVAR 34; and 4. VIS 18. Spatial characteristics include “surfaceF” (field area in m²), “surfaceB” (bay area in m²), and “percentage” (share of the field area relative to the total bay area).

Safety and operational criteria include “protection” (degree of protection), “distance” (distance from the coast), “numberF” (number of fields at the location), “traffic” (proximity to main shipping routes), “anchorage” (existence of an official anchorage), “cables” (proximity to underwater cables and pipelines), “danger” (collision risk), “depth” (water depth), “tide” (tidal currents), “proximityP” (proximity to public ports), and “existingB” (proximity to existing moorings). Ecological and cultural variables include “environment” (Natura 2000 ecological network), “harmfulness” (damage from anchoring to the seabed), and “site” (archaeological site). The spatial coordinates of the locations are defined by “latitude” and “longitude”, enabling precise spatial analysis.

Specifically, “spatial_dist”, the 18th criterion in the model, expresses the spatial centrality of each location and is calculated as the mean distance to all other anchorages using the Haversine formula, which accounts for the Earth’s curvature. This criterion ensures even spatial coverage when selecting the best locations and optimises the strategic placement of anchorages according to spatial requirements. The values of “longitude” range from 16.002 to 16.888, while “latitude” ranges from 42.982 to 43.507, covering the entire area of Split-Dalmatia County and enabling precise spatial analysis of locations. The unit of measurement for each anchorage point is the degree (°).

Note: “Spatial_dist”, the 18th criterion in the analysis, represents the spatial centrality of a location, expressed as the mean distance to all other analysed anchorages. Distances were calculated using the Haversine formula (Equation (1)) based on the geographic coordinates (latitude (ϕ) (Equation (2)) and longitude (λ) (Equation (3)) of two points), taking the Earth’s curvature into account. Distances along the sea were not used; instead, straight-line (“as-the-crow-flies”) distances between coordinates were considered. As some of the 56 analysed locations contain multiple fields, a total of 86 fields were considered, each treated as a separate alternative in the MCDM methods. This approach ensures even spatial coverage when selecting the top 10 locations and optimises the strategic distribution of anchorages according to spatial criteria.

$$d = 2 \cdot R \cdot \arcsin \left(\sqrt{\sin^2 \left(\frac{\Delta \phi}{2} \right) + \cos(\phi_1) \cos(\phi_2) \sin^2 \left(\frac{\Delta \lambda}{2} \right)} \right) \quad (1)$$

$$\Delta \phi = \phi_2 - \phi_1 \quad (2)$$

and

$$\Delta\lambda = \lambda_2 - \lambda_1 \quad (3)$$

where R represents the radius of the Earth (6371 km).

Table 1 presents all 18 criteria used in the MCDM models for evaluating anchorages (N = 86). The columns show the criterion number (No.), the criterion name (Variable), the description of the criterion and its impact on the anchorage (Description), the unit or scale of the value (Unit/Scale), an additional note on the function of the criterion (Note), classification as “Benefit” or “Cost” (Category), and the rationale for assigning the criterion to the corresponding category (Rationale).

Table 1. Benefit and cost classification of criteria for MCDM analysis of anchorage locations (N = 86).

No	Variable	Description	Unit/Scale	Note	Category	Rationale
1	surfaceF	Area of the individual field of the anchorage	m ²	Operational and capacity criterion	Benefit	Larger area increases usability of the anchorage
2	surfaceB	Area of the bay in which the field is located	m ²	For proportional allocation of space	Benefit	Larger bay area allows more flexible anchoring
3	percentage	Share of the field area relative to total bay area	%	Normalisation for comparative evaluation	Benefit	Higher share indicates better efficiency in space usage
4	protection	Degree of sheltering from wind and waves	1–Protected; 5–Partially protected; 9–Unprotected	Safety and operational criterion	Cost	Higher values indicate less protection, increasing risk
5	distance	Distance from the shore	meters	Accessibility criterion	Benefit	Greater distance may reduce congestion and risk
6	numberF	Number of fields at the location including the analysed field	numeric	Influences overall capacity and flexibility	Cost	More fields can indicate crowding and management complexity
7	traffic	Presence of maritime traffic (proximity to main shipping lanes)	1–Yes; 5–No	Operational safety consideration	Cost	Closer traffic increases collision risk
8	anchorage	Presence of official anchorage	1–Yes; 5–No	Regulatory criterion	Cost	Presence may impose regulatory or management restrictions
9	cables	Proximity to underwater cables and pipelines (<500 m)	1–Yes; 5–No	Technical and safety limitation	Cost	Close proximity increases operational risk
10	danger	Collision risk with other vessels	1–Negligible; 2–Low; 3–Medium; 4–High; 5–Very high	Navigation safety criterion	Cost	Higher risk reduces safety and usability
11	depth	Water depth at the anchorage	1–Inadequate; 5–Adequate	Determines accessibility and vessel size	Benefit	Adequate water depth allows safe anchoring and access for vessels
12	tide	Influence of tide and sea currents	1–Low; 3–Medium; 5–High	Hydrometeorological operational factor	Cost	Higher influence increases operational difficulty
13	proximityP	Proximity to public ports or maritime infrastructure	1–No; 5–Yes	Connectivity with logistics and service facilities	Cost	Closer proximity may reduce flexibility or introduce conflicts
14	existingB	Proximity to existing moorings or anchorages	1–No; 5–Yes	Planning and capacity distribution	Cost	Crowding near existing moorings reduces usability
15	environment	Inclusion in Natura 2000 ecological network	1–No; 5–Yes	Environmental sustainability criterion	Cost	Protected areas limit anchoring options
16	harmfulness	Potential environmental damage from anchoring	1–No; 5–Yes	Ecological risk	Cost	Higher environmental impact is undesirable
17	site	Presence of archaeological site	1–No; 5–Yes	Cultural and legal restriction	Cost	Archaeological constraints reduce accessibility
18	spatial_dist	Spatial centrality—mean distance to all other anchorages	meters	Calculated using Haversine formula; ensures even spatial coverage for top 10 selection	Benefit	More central location improves accessibility and even distribution

The criteria are divided into Benefit and Cost based on their impact on the functionality, safety, and sustainability of the anchorage. Benefit criteria (surfaceF, surfaceB, percentage, distance, depth, and spatial_dist) are variables for which higher values contribute to better spatial coverage, operational efficiency, and location functionality. Cost criteria (protection, numberF, traffic, anchorage, cables, danger, tide, proximityP, existingB, environment, harmfulness, and site) are variables for which higher values indicate greater risk, constraints, or negative impacts on safety, ecological sustainability, and regulatory compliance.

Table 2 presents the frequency of different values for the criteria “protection,” “traffic,” “anchorage,” “cables,” “danger,” “depth,” “tide,” “proximityP,” and “existingB.” This shows the occurrence of specific anchorage characteristics, facilitating the analysis of their distribution and the interpretation of the spatial and functional diversity of the locations.

Table 2. Frequency distribution of ordinal anchorage criteria/variable.

Variable/Criteria	Value	Frequency	Meaning of Value
protection	1	25	Protected
	5	47	Partially protected
	9	14	Unprotected
traffic	1	82	Maritime traffic exists
	5	4	No traffic
anchorage	1	86	Official anchorage exists
cables	1	85	Underwater cables/pipelines < 500 m exist
	5	1	No cables/pipelines
danger	3	81	Medium risk
	4	1	High risk
	5	4	Very high risk
depth	5	86	Satisfactory
tide	1	82	Small tide/currents
	5	4	Large tide/currents
proximityP	1	86	No proximity to public ports
existingB	1	85	No existing berths
	5	1	Existing berths
environment	1	68	No environmental protection zone
	5	18	Environmentally protected area
harmfulness	1	18	No potential environmental damage
	5	68	Potential environmental damage from anchoring
site	1	85	No archaeological site
	5	1	Presence of archaeological site

Table 3 presents a quantitative overview and distribution of the input criteria values for the 86 anchorage fields, using key parameters: mean, median, standard deviation, minimum, and maximum.

The criteria “surfaceF,” “surfaceB,” “distance,” and “spatial_dist” are continuous decimal values, as they quantify the basic spatial and capacity characteristics of the locations. Other variables are integers and are encoded with selective values, most often 1, 3, 5, or 9 (“protection,” “traffic,” “anchorage,” “cables,” “danger,” “depth,” “tide,” “proximityP,” “existingB,” “environment,” “harmfulness,” and “site”). This encoding reflects ordinal levels or categorical degrees of the criteria, enabling clear differentiation in terms of safety, accessibility, and functional characteristics of the anchorages.

The variables “anchorage,” “depth,” and “proximityP” have a uniform value (1 or 5) across all analysed locations, as all alternatives in the dataset meet the minimum safety and

spatial requirements for anchoring. Their inclusion in the MCDM framework is justified because they represent baseline safety constraints, ensuring the completeness of the criteria set and consistent weighting. Although they do not contribute to rank differentiation, they serve as a safety filter, confirming that all locations meet essential navigational, depth, and distance conditions, thereby enhancing the transparency and validity of the final consensus ranking.

Table 3. Descriptive statistical analysis of the input criteria for the 86 evaluated anchorage locations.

No	Criteria	Mean	Median	SD	Min	Max
1	surfaceF	11,460.3	7561.4	12,514.6	900.0	76,654.4
2	surfaceB	169,714.0	99,286.2	168,308.2	11,800.6	723,767.1
3	percentage	10.3	7.6	8.3	0.3	39.6
4	protection	4.5	5	2.7	1	9
5	distance	18.2	12.3	16.2	0	81.2
6	numberF	1.9	2	1.0	1	4
7	traffic	1.2	1	0.8	1	5
8	anchorage	1	1	0	1	1
9	cables	1.0	1	0.4	1	5
10	danger	3.1	3	0.4	3	5
11	depth	5	5	0	5	5
12	tide	1.2	1	0.8	1	5
13	proximityP	1	1	0	1	1
14	existingB	1.0	1	0.4	1	5
15	environment	4.2	5	1.6	1	5
16	harmfulness	4.2	5	1.6	1	5
17	site	1.0	1	0.4	1	5
18	spatial_dist	27.9	25.8	7.8	19.8	51.5

2.2. Methodological Approach and Data Processing

The complete methodological workflow is illustrated in Figure 1 and described in detail, including data preprocessing, criterion classification, normalisation, weighting strategy, and implementation of the six MCDM algorithms. This comprehensive description is intended to ensure transparency, facilitate reproducibility, and support the practical application of the proposed anchorage evaluation framework in future studies and real-world decision-making scenarios.

The research process begins by loading raw data from an external MS Excel file, which includes spatial coordinates, location and field identifiers, and the corresponding anchorage characteristics. Using the loaded coordinates, the spatial distance (spatial_dist) between all pairs of anchorages is calculated, providing an indicator of spatial centrality and ensuring an even spatial distribution of the locations.

All numerical data were previously checked and cleaned to ensure consistency and accuracy in the analysis, eliminating the possibility of erroneous or mismatched records. Due to the different units of measurement and the nature of the variables, linear *Min–Max* normalisation (Equation (4)) is applied, transforming the data to a dimensionless scale from 0 to 1 according to the following formula:

$$x' = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (4)$$

Since x is the original variable value, x_{min} is the minimum value in the dataset, and x_{max} is the maximum value, normalisation enables comparability of variables with different units and ranges, and their mathematical integration into the MCDM, ensuring an objective evaluation of all criteria without dominance by those with larger numerical ranges.

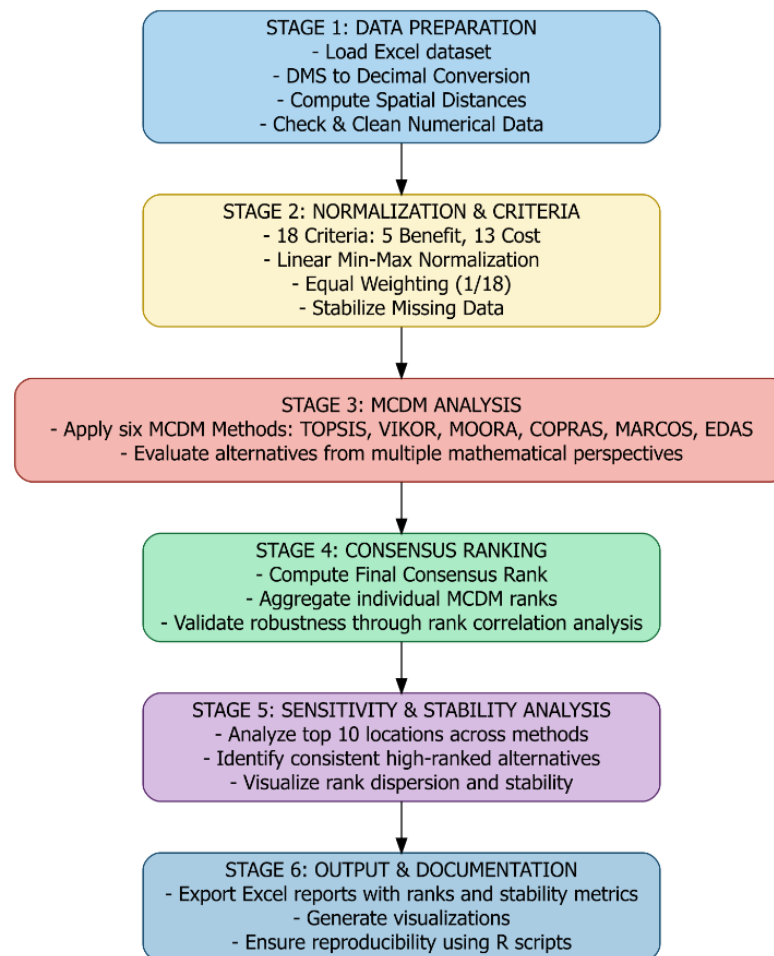


Figure 1. Workflow diagram of the integrated GIS–MCDM methodology for evaluating maritime anchorage sites.

The central part of the methodology involves applying six distinct MCDM methods to the 18 criteria to achieve robustness and reliability in the final rankings. Detailed mathematical formulations of each method are beyond the scope of this study. Instead, their significance and contribution within the hybrid approach, which reduces the influence of method-specific algorithms on the final order, are described.

1. TOPSIS ranks alternatives by measuring how close each alternative is to the positive ideal solution (best values across all criteria) and how far it is from the negative ideal solution, allowing a balance among criteria in multi-objective problems [37–40].
2. VIKOR focuses on a compromise solution in the presence of conflicting criteria, balancing aggregated deviations from ideal values, which is particularly useful when criteria do not align in the same direction [40].
3. MOORA employs ratio analysis to assess the overall performance of alternatives and is recognised in the literature as providing stable results through direct integration of all criteria into a single measurement function [31].
4. COPRAS evaluates alternatives based on the relative importance and proportional utility of criteria, combining maximisation of beneficial and minimisation of detrimental aspects, enabling quantitative and proportional interpretation of the rankings [40,41].
5. MARCOS introduces the concept of the relation of alternatives to ideal and anti-ideal points during normalisation, providing an additional perspective that can reveal specific advantages or risks not equally highlighted by other methods [32].

6. EDAS evaluates alternatives according to their positive and negative distances from the average value of all criteria, emphasising stable and above-average performance within the set of alternatives, which is useful for identifying “above-average” solutions in spatial and functional analyses [30].

As each of the six applied MCDM methods evaluates the locations from different mathematical perspectives using distinct normalisation and aggregation logics, all individual rankings are synthesised through a consensus model. The Consensus Rank represents an aggregated ranking of locations obtained as the arithmetic mean of ranks from all six methods, neutralising method-specific mathematical biases. Unlike conventional spatial statistical approaches, which assess spatial autocorrelation only after obtaining the final results, the proposed framework explicitly incorporates spatial relationships as an optimisation criterion through the *Spatial_dist* variable. Consequently, spatial distribution is not treated merely as a descriptive characteristic of the selected anchorages but directly influences the multi-criteria evaluation process. By considering the average spatial distance among all candidate locations, the model discourages excessive spatial concentration of priority anchorages and promotes a balanced geographical allocation, while simultaneously satisfying navigational, environmental, technical, and operational criteria. Thus, spatial effects are integrated into the optimisation process itself rather than being analysed solely as a post hoc statistical property of the final ranking. This approach ensures that the highest-ranked anchorage locations truly possess top characteristics across multiple criteria and mathematical perspectives, providing the most robust and balanced scientific basis for prioritising anchorages in the SDC. The reliability and stability of the model are further confirmed by correlation analysis among the MCDM methods.

The final phase of the methodological framework focuses on verifying the stability, reliability, and sensitivity of location rankings and integrating them into a final consensus order. After calculating the final consensus rank, agreement among individual MCDM methods is analysed, along with the sensitivity of the rankings of the top ten locations, thereby confirming the robustness and low sensitivity of the model regardless of the algorithm applied. The final consensus ranking represents a balanced integration of the results from all six MCDM methods and provides a reliable scientific basis for priority anchorage planning. All analyses and visualisations were generated in the R programming environment, ensuring full transparency, documentation, and reproducibility of the methodology.

2.3. Normalisation Procedures and Benefit/Cost Criteria Transformation

As the six applied MCDM methods are based on different mathematical principles, the normalisation procedure is a fundamental step to ensure comparability among criteria expressed in different units and numerical ranges. Before applying the MCDM algorithms, all criteria were transformed into dimensionless values, enabling objective comparison and preventing variables with larger numerical scales from dominating the final evaluation.

In this study, an initial linear *min–max* normalisation was applied to the decision matrix. The ideal and anti-ideal solutions were then defined according to the criterion type. For benefit criteria, higher values indicate better performance; thus, the ideal solution corresponds to the maximum normalised value, while the anti-ideal solution corresponds to the minimum normalised value. Conversely, for cost criteria, lower values are preferable; therefore, the ideal solution is represented by the minimum normalised value and the anti-ideal solution by the maximum normalised value.

The mathematical expressions below correspond directly to the computational implementation used in this study and are provided to ensure complete methodological transparency and reproducibility.

The initial *Min–Max* normalisation is calculated according to Equation (5). The ideal and anti-ideal solutions for benefit criteria are defined by Equations (6) and (7), while the corresponding definitions for cost criteria are given by Equations (8) and (9).

$$r_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (5)$$

$$A_j^+ = \max(r_{ij}) \quad (6)$$

$$A_j^- = \min(r_{ij}) \quad (7)$$

$$A_j^+ = \min(r_{ij}) \quad (8)$$

$$A_j^- = \max(r_{ij}) \quad (9)$$

The TOPSIS method determines the relative closeness of each alternative to the ideal solution by calculating the Euclidean distances from the positive and negative ideal solutions. The relative closeness coefficient is calculated according to Equation (10), and the positive and negative separation measures are obtained using Equations (11) and (12), respectively.

$$CC_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (10)$$

$$D_i^+ = \sqrt{\sum_{j=1}^n (r_{ij} - A_j^+)^2} \quad (11)$$

$$D_i^- = \sqrt{\sum_{j=1}^n (r_{ij} - A_j^-)^2} \quad (12)$$

The VIKOR method evaluates each alternative through its normalised distance from the ideal solution. The normalised deviation is first calculated using Equation (13), after which the group utility measure and the individual regret measure are obtained by Equations (14) and (15). Finally, the compromise ranking index is calculated according to Equation (16).

$$f_{ij} = \frac{A_j^+ - r_{ij}}{A_j^+ - A_j^-} \quad (13)$$

$$S_i = \sum_{j=1}^n w_j f_{ij} \quad (14)$$

$$R_i = \max_j (w_j f_{ij}) \quad (15)$$

$$Q_i = 1 - \left[0.5 \frac{S_i - S_{\min}}{S_{\max} - S_{\min}} + 0.5 \frac{R_i - R_{\min}}{R_{\max} - R_{\min}} \right] \quad (16)$$

The MOORA method evaluates alternatives by simultaneously maximising benefit criteria and minimising cost criteria. The final assessment score is obtained as the difference between the aggregated normalised benefit and cost criteria according to Equation (17).

$$MOORA_i = \sum_{j \in B} r_{ij} - \sum_{j \in C} r_{ij} \quad (17)$$

The COPRAS method separately evaluates the weighted sums of beneficial and non-beneficial criteria. The weighted benefit component is calculated using Equation (18), while the weighted cost component is determined by Equation (19). The final proportional assessment index is then obtained according to Equation (20).

$$P_i = \sum_{j \in B} w_j r_{ij} \quad (18)$$

$$R_i = \sum_{j \in C} w_j r_{ij} \quad (19)$$

$$Q_i = P_i + \frac{\min_i(R_i) \sum_i R_i}{R_i \sum_i \left(\frac{\min_i(R_i)}{R_i} \right)} \quad (20)$$

The MARCOS method evaluates alternatives by comparing their weighted normalised values with the weighted ideal solution. The final utility function used in this study is calculated according to Equation (21).

$$M_i = \frac{\sum_{j=1}^n w_j r_{ij}}{\sum_{j=1}^n w_j A_j^+} \quad (21)$$

Unlike the previous methods, EDAS evaluates alternatives relative to the average solution rather than the ideal solution. Positive Distance from Average (PDA) and Negative Distance from Average (NDA) are calculated separately for benefit and cost criteria using Equations (22)–(25). The final EDAS assessment score is then determined according to Equation (26).

$$PDA_{ij} = \max \left(0, \frac{x_{ij} - AV_j}{AV_j} \right) \quad (22)$$

$$NDA_{ij} = \max \left(0, \frac{AV_j - x_{ij}}{AV_j} \right) \quad (23)$$

$$PDA_{ij} = \max \left(0, \frac{AV_j - x_{ij}}{AV_j} \right) \quad (24)$$

$$NDA_{ij} = \max \left(0, \frac{x_{ij} - AV_j}{AV_j} \right) \quad (25)$$

$$EDAS_i = \frac{1}{2} \left(\frac{\sum_j PDA_{ij}}{\max_i \left(\sum_j PDA_{ij} \right)} + 1 - \frac{\sum_j NDA_{ij}}{\max_i \left(\sum_j NDA_{ij} \right)} \right) \quad (26)$$

As each MCDM method applies a different normalisation strategy and mathematical aggregation procedure, their individual rankings are subsequently integrated into a consensus ranking model. Combining six mathematically independent evaluation mechanisms substantially reduces method-specific bias and increases the robustness, stability, and reliability of the final anchorage prioritisation.

The proposed methodology was developed to ensure methodological transparency, objectivity, and full reproducibility throughout the evaluation process. Each stage of the framework—from data acquisition and preprocessing to criterion definition, normalisation, weighting, and the application of six complementary MCDM algorithms—is explicitly described to enable independent verification and replication.

A key objective of this study was to minimise the influence of subjective judgement, which is widely recognised as a principal limitation of MCDM-based evaluations. To address this, all criteria were first standardised to eliminate differences in measurement scales, ensuring direct comparability among heterogeneous indicators. A neutral (equal-weight) weighting strategy was then adopted so that each criterion contributed equally to the overall assessment. Consequently, the final rankings are determined solely by the normalised data and the mathematical decision rules of the selected MCDM methods, rather than by expert-defined preference coefficients or subjective assumptions regarding criterion importance.

It should be noted that the classification of criteria into “Benefit” and “Cost” categories serves a fundamentally different purpose from weighting. This classification specifies only the optimisation direction of each criterion—that is, whether higher or lower values are preferable within the decision model—and is an inherent requirement of MCDM algorithms. It does not assign greater or lesser importance to any criterion, nor does the unequal number of “Benefit” and “Cost” criteria introduce additional weighting effects. All criteria retain identical numerical weights throughout the analysis, preserving methodological neutrality while allowing each algorithm to interpret correctly the optimisation objective associated with every criterion.

3. Results

For visual analysis and data interpretation, interactive maps of all anchorage locations were generated. These maps accurately represent the spatial characteristics of each location, with each site marked by a reference number and the values of individual variables indicated by different circle colours and sizes. This visualisation provides an intuitive understanding of the spatial distribution of anchorages and the variability of criteria, facilitating the identification of locations with specific operational, safety, and functional characteristics.

Figure 2 shows an interactive map of all offshore anchorage locations, labelled with identification numbers. The size and colour of the circles represent scaled values of the surfaceF variable. The map allows users to toggle layers, zoom in or out, and display selected variables, facilitating analysis of the spatial distribution and functional characteristics of the locations.

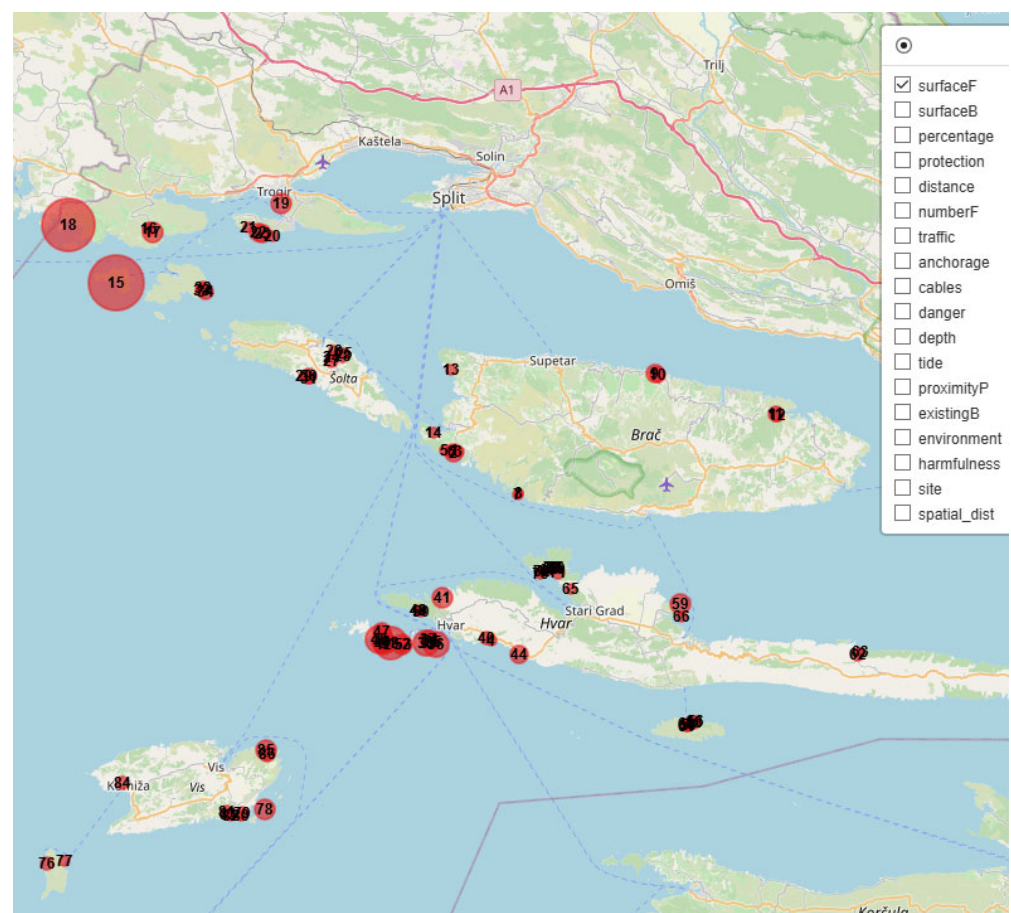


Figure 2. Interactive map of anchorage locations at sea showing “surfaceF”.

Figure 3 presents a more detailed map of part of Hvar Island with anchorage locations, highlighting the scaled variables “percentage” and “traffic”. Location numbers are shown, and the interactive map enables users to select which variables to display, facilitating the analysis of local spatial distribution, maritime traffic, and proportional space utilisation.



Figure 3. Partial thematic map of anchorage locations around Hvar Island illustrating traffic intensity and protection distribution.

After graphically interpreting the input data using interactive maps (Figures 2 and 3), the analysis proceeds with a quantitative evaluation of the results through the application of MCDM methods. Figure 4 displays all anchorage locations as black circles, while the top ten locations according to each of the six applied MCDM methods are highlighted in different colours, with the final Consensus rank additionally marked by gold stars (Figure 5). Each method is presented separately (“TOPSIS—red”, “VIKOR—green”, “MOORA—purple”, “COPRAS—orange”, “MARCOS—turquoise”, “EDAS—blue”), with circle size proportional to the ranking of each location. The interactive layers allow users to enable or disable the display of each method individually, as well as to zoom in and out as needed, which is particularly useful for detailed inspection and precise visual comparison of locations. This approach provides clear insight into the level of agreement among MCDM methods and confirms the role of the final Consensus rank as an aggregated criterion for priority anchorage planning.



Figure 4. Interactive visualisation of the top ten anchorages selected by six MCDM methods.

Figure 6 presents the Spearman rank correlation between all six applied MCDM methods and the final Consensus rank, offering insight into the degree of agreement among the algorithms in evaluating the quality of 86 nautical anchorage locations. Spearman's rank correlation measures the strength of the monotonic relationship between two sets of ranks, with values ranging from -1 (perfect negative correlation) to $+1$ (perfect positive correlation), while a value of 0 indicates no correlation. Values above 0.9 indicate a very strong positive association.

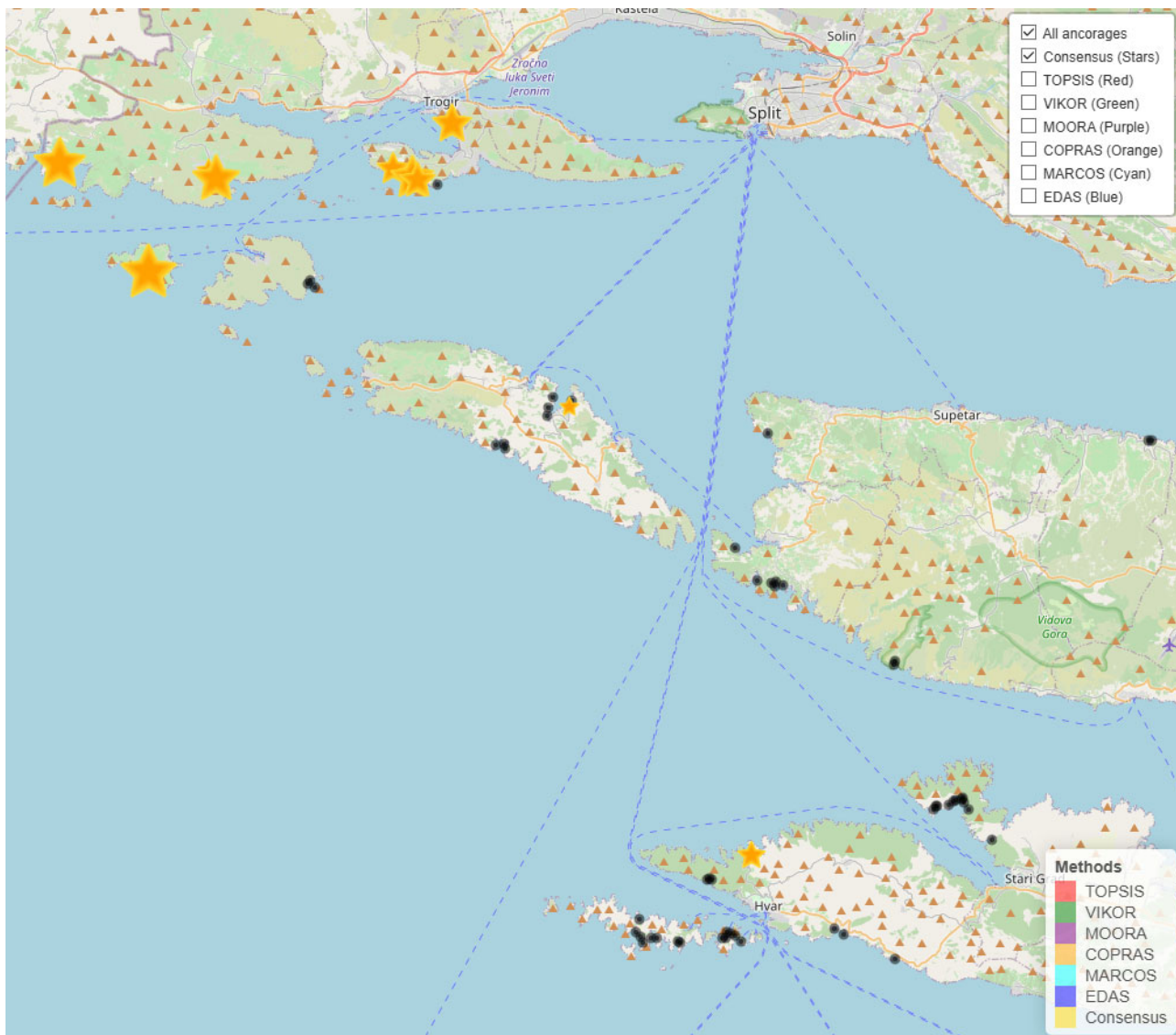


Figure 5. Interactive visualisation of the top ten anchorages selected by the final consensus method.

The visualisation clearly shows that the TOPSIS, VIKOR, MOORA, and COPRAS methods are almost perfectly aligned, with correlation coefficients exceeding 0.99, confirming the stability of the rankings and their independence from the specifics of any single method. The final consensus rank exhibits a very high positive correlation with most methods (0.93–0.96), confirming its representativeness and the validity of aggregating the ranks. The MARCOS method shows a negative correlation with other algorithms, indicating its specific evaluative logic that provides an inverse perspective, while EDAS exhibits moderate positive correlation, further highlighting the diversity of approaches.

This graphical analysis demonstrates that the consensus rank effectively integrates the results of all methods, neutralising extreme deviations of individual models and providing a robust, reliable, and objective basis for prioritising anchorages. The visual representation also enables intuitive recognition of the degree of agreement among methods, enhancing the credibility of the hybrid approach without the need for detailed numerical tables.

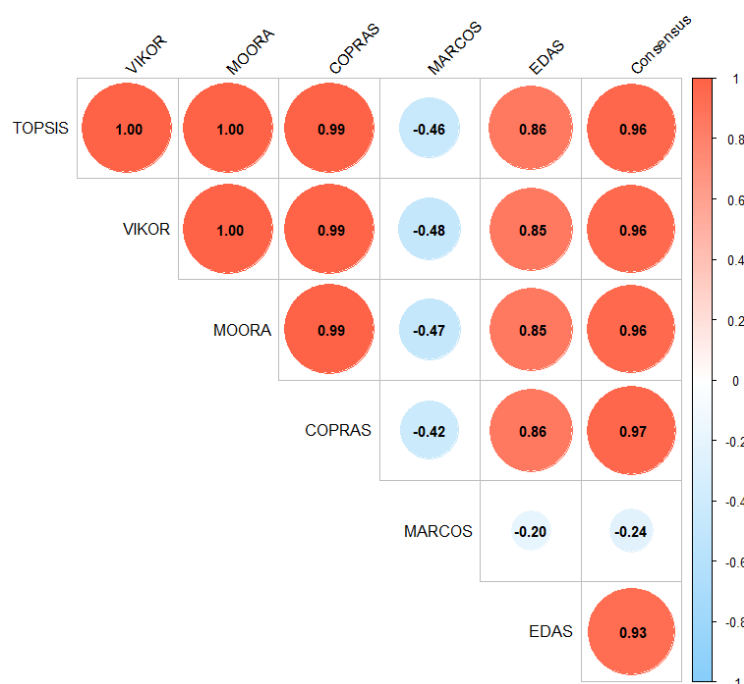


Figure 6. Graphical representation of the Spearman rank correlation matrix between MCDM methods and the consensus ranking.

Figure 7 illustrates the degree of rank overlap among the applied MCDM methods at the level of individual anchorage locations. Each value in the matrix quantifies the number or proportion of locations occupying the same or very close rank positions between two methods, allowing direct assessment of their mutual consistency. High overlap values confirm the stability of the ranking and indicate that different algorithms identify a similar set of priority locations, while lower values point to methods with a more pronounced specific ranking logic. This analysis complements the correlation validation by considering not only the overall relationship between ranks but also the actual alignment in the selection of key locations, further strengthening the reliability of the consensus solution.



Figure 7. Rank overlap matrix across methods.

Table 4 shows how different MCDM methods produce varying rankings for the same locations, while consensus ranking helps to identify the most generally suitable anchorage sites.

Table 4. Comparative ranking of anchorage sites using multiple MCDM methods.

Name	Field	Consensus	TOPSIS	VIKOR	MOORA	COPRAS	MARCOS	EDAS
DRVENIK MALI Uvala Vela Rina	A	1	2	6	2	5	11	2
MARINA Uvala Miline—Istocna obala Ostrica mala	A	2	1	1	1	1	31	1
MARINA Luka Vinisce	B	3	3	2	3	3	72	3
OKRUG GORNJI Uvala Sveta Fumija	B	4	16	17	17	18	17	7
OKRUG GORNJI Uvala Duboka	A	5	6	12	6	12	59	5
OKRUG GORNJI Zaljev Saldun, Punta Rozac	A	6	4	3	5	7	76	6
OKRUG GORNJI Uvala Sveta Fumija	A	7	17	18	18	20	18	11
HVAR Uvala Pribinja	A	8	5	10	4	2	83	4
MARINA Luka Vinisce	A	9	7	7	7	6	77	12
SOLTA Uvala Necujam—Uvala Supetar	A	10	10	5	10	10	78	8

The graphical representation of rank distributions (Figures 8 and 9), using boxplots with a jitter effect, provides detailed insight into the variability of location rankings across different MCDM methods. Locations such as DRVENIK MALI—Uvala Vela Rina and MARINA—Uvala Miline show relatively high consensus among the methods, with their ranks mostly concentrated at the top of the scale, although minor variations exist (for example, MARINA—Uvala Miline exhibits an extreme rank of 31 in the MARCOS method). In contrast, locations such as OKRUG GORNJI—Uvala Sveta Fumija_B and OKRUG GORNJI—Uvala Sveta Fumija_A display more pronounced deviations in ranks across methods, evident from wider interquartile ranges and higher ranks in certain algorithms (TOPSIS, VIKOR) compared to lower ranks in MARCOS and EDAS. Medium-ranked locations, such as HVAR—Uvala Pribinja and SOLTA—Uvala Necujam, also show variability, highlighting the importance of an aggregated approach for reliable ranking of all locations.

The rationale for using two complementary visualisations (Figures 8 and 9) lies in clearly separating the effect of methodological variability from the influence of individual methods. The first figure provides insight into rank stability when MARCOS, the most divergent algorithm, is included in the analysis, while the second figure shows the full range of variability when this method is excluded. This two-stage approach enables more precise interpretation of ranking sensitivity and confirms that the consensus ranking remains stable even in the presence of methodologically demanding algorithms.

Thus, the analysis clearly differentiates locations that represent stable and robust priorities from those whose acceptability depends on the choice of method, providing a scientifically grounded and reliable basis for decision-making in the spatial planning of anchorages.

The layered circular diagram (Figure 10) provides detailed insight into the contribution of each individual MCDM method to the final consensus ranking. Notably, the MARCOS method consistently deviates from the other algorithms, as shown by the downward shift of certain alternatives compared to most methods. This behaviour indicates greater sensitivity to extreme values and stricter penalisation of unfavourable criteria, making MARCOS a conservative component within the hybrid model. The visualisation clearly distinguishes alternatives where this deviation is marginal from those where MARCOS significantly affects the ranking.

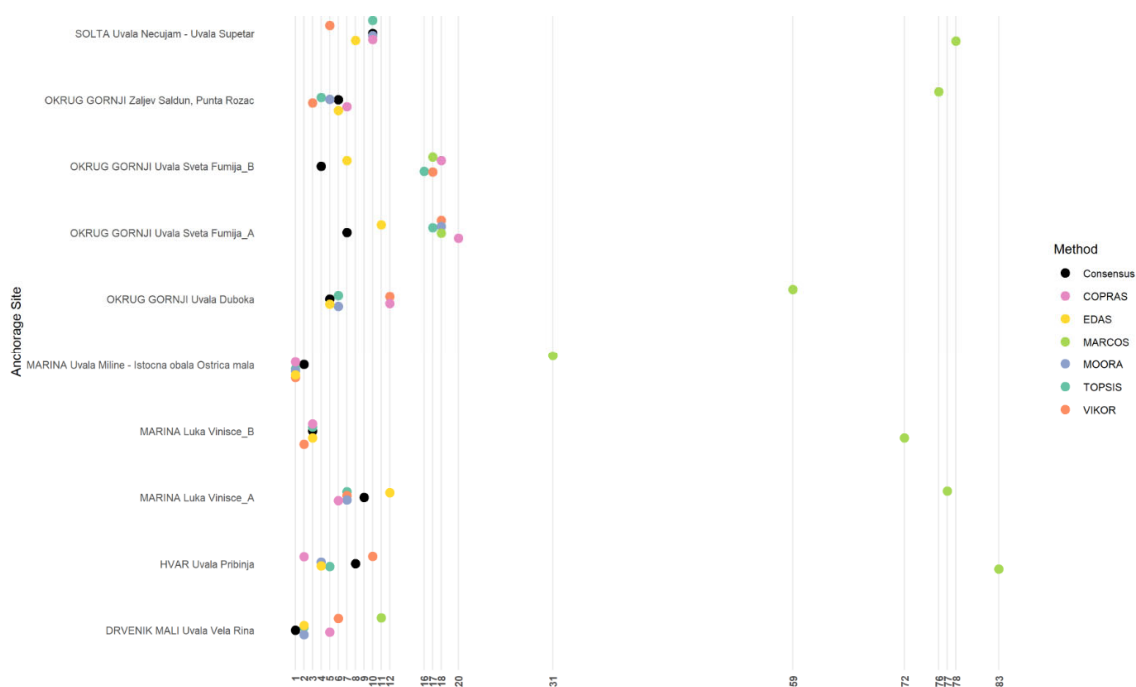


Figure 8. Detailed sensitivity analysis and rank stability of the top 10 anchorage locations across all MCDM methods: comparative evaluation of methodological variance across hybrid MCDM algorithms.

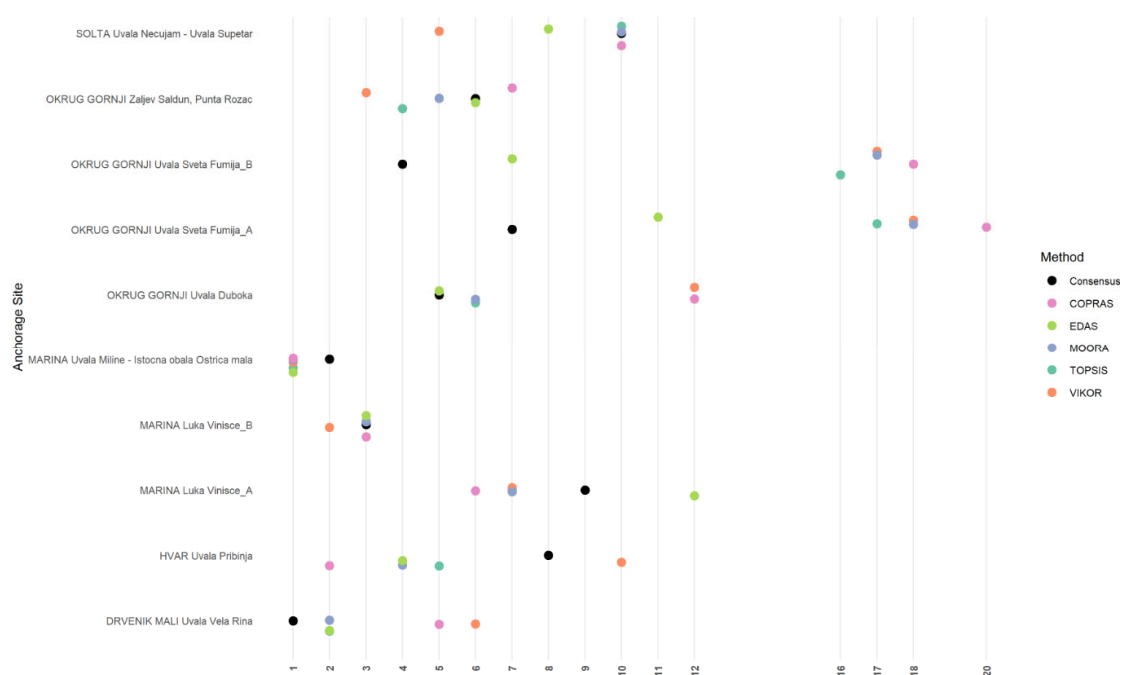


Figure 9. Detailed sensitivity analysis and rank stability assessment of the top 10 anchorage locations by all MCDM methods, excluding MARCOS: a comparative evaluation of methodological variance across hybrid MCDM algorithms.

The hierarchical representation of the consensus rankings (Figure 11) offers a comprehensive and concise overview of the final results, clearly demonstrating that, despite the deviation of the MARCOS method, the overall consensus remains stable. Alternatives that maintain high positions confirm their robustness, as their ranking is unaffected by methodological divergences. Conversely, alternatives for which the MARCOS deviation results in lower ranks can be identified as methodologically sensitive, which is important for interpreting results in the context of risk management.

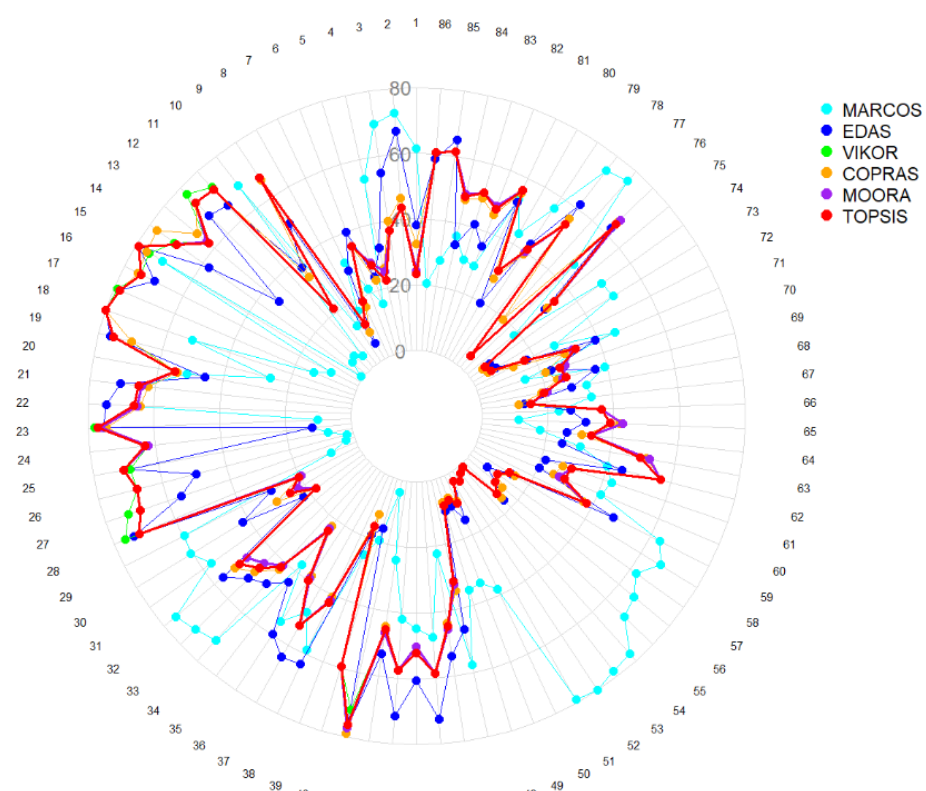


Figure 10. Layered circular representation of individual method contributions.

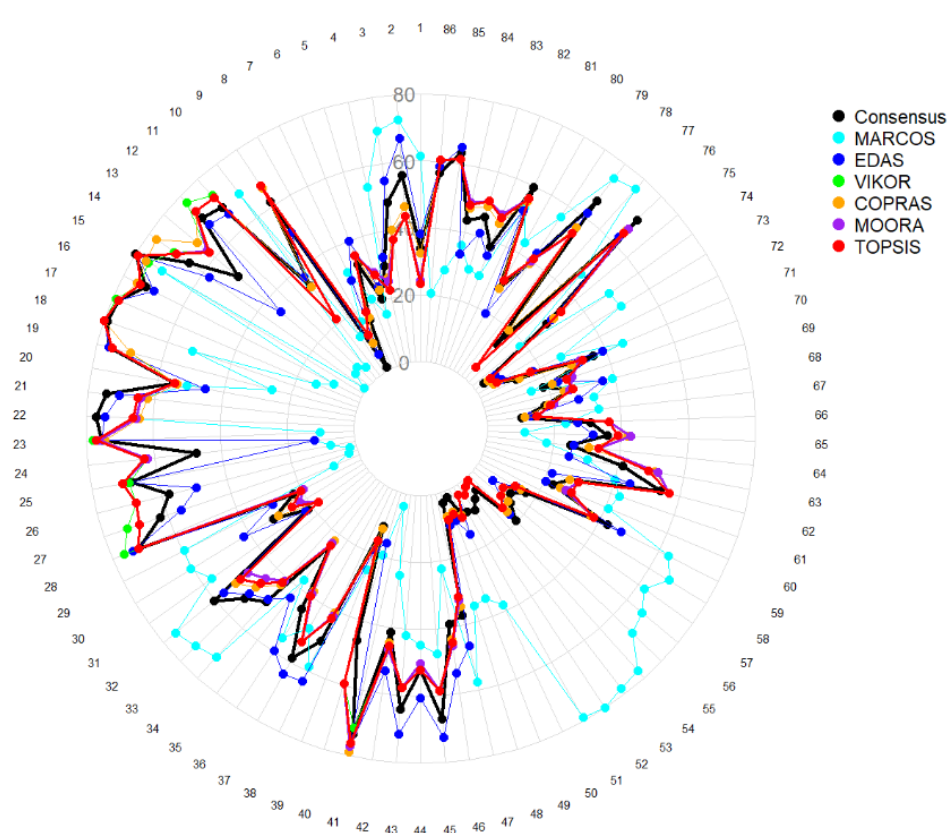


Figure 11. Consensus rankings with visual hierarchy—global view.

Figure 10 enables precise localisation and interpretation of the methodological deviation of the MARCOS method, while Figure 11 illustrates the significance of this deviation in the final consensus ranking. Together, they confirm that the hybrid MCDM approach does not obscure differences between algorithms but transparently integrates them, further strengthening the reliability and scientific validity of the final rankings.

4. Discussion

Compared with earlier approaches, particularly those used in the study by [3,15], the results of this research demonstrate a substantial methodological and analytical advance in the evaluation and ranking of nautical anchorages. Previous studies mainly relied on a single MCDM method or a limited set of algorithms, without systematically examining their mutual consistency or sensitivity. In contrast, the hybrid MCDM framework adopted here enables comprehensive, multi-layered validation of results.

The findings confirm that the applied hybrid MCDM approach is methodologically robust and analytically sound for ranking nautical anchorages. Interactive spatial visualisations were used not merely as descriptive tools but as an initial analytical phase to identify spatial patterns, local constraints, and criterion heterogeneity. This establishes a clear and consistent link between the spatial structure of the data and the quantitative outcomes of the MCDM ranking, representing a significant improvement over previous studies in which the spatial component was not explicitly integrated into the decision-making process.

The very high mutual correlations among the TOPSIS, VIKOR, MOORA, and COPRAS methods indicate the overall stability and reliability of the rankings. Such alignment suggests that the criteria are well balanced and that the dominant effects arise from genuine differences in the performance of the evaluated locations, rather than from methodological peculiarities of individual methods. Unlike earlier approaches, correlation analysis in this study is not treated as a supplementary check but as a core element of overall framework validation. The strong correlation between the final consensus ranking and most individual methods further supports its role as a reliable aggregated indicator for decision-making. This effectively addresses a key limitation observed in prior studies, including [3,15], where result interpretation largely depended on the outcomes of a single dominant method.

The deviation observed in the MARCOS method, reflected in negative correlations and less favourable rankings for certain locations, has clear interpretative and analytical value. MARCOS shows heightened sensitivity to extreme and unfavourable criterion values, functioning as a conservative component within the hybrid model. Rather than representing a methodological weakness, this behaviour enables the identification of method-sensitive locations and contributes to a more realistic risk assessment, an aspect not explicitly addressed in previous research.

The observed differences among the six MCDM methods can be attributed to their distinct mathematical optimisation principles, which influence how criterion information is aggregated, rather than indicating inconsistencies in the evaluation framework. This is supported by both the correlation matrix and the rank-overlap analysis. The exceptionally high correlations among TOPSIS, VIKOR, MOORA, and COPRAS ($\rho > 0.99$ for several method pairs) demonstrate that these methods produce highly consistent rankings despite employing different computational procedures. This consistency is further evidenced by the large number of identical ranking positions: VIKOR and MOORA share 75 identical ranks out of 86 alternatives, MOORA and TOPSIS share 54, and VIKOR and TOPSIS share 45 identical positions.

In contrast, MARCOS exhibits negative correlations with all other methods and almost no identical ranking positions, indicating that its mathematical formulation responds differently to the distribution of criterion values. Unlike the additive aggregation strategies used by MOORA and COPRAS or the distance-based optimisation employed by TOPSIS and VIKOR, MARCOS simultaneously evaluates alternatives with respect to both the ideal and anti-ideal solutions, making it more sensitive to differences in criterion distributions. EDAS displays intermediate behaviour because it evaluates alternatives relative to the average solution rather than the ideal solution, resulting in lower, yet still substantial, agreement with the other methods. These findings indicate that the observed ranking differences arise from the complementary mathematical foundations of the applied MCDM algorithms rather than from inconsistencies in the decision matrix.

Rank variability is mainly observed among mid-ranked alternatives, which show the greatest sensitivity to different evaluation logics. This finding further justifies the use of consensus ranking as a mechanism for reducing methodological bias and enhancing the robustness of final recommendations. Sensitivity testing through the exclusion and subsequent re-inclusion of the MARCOS method demonstrates that the final consensus ranking remains stable, confirming the robustness of the hybrid MCDM framework.

This clearly differentiates locations that represent reliable priorities from those whose acceptability depends on the choice of method. Such a multi-level validation strategy constitutes a key novel contribution of this study relative to the existing literature and provides a stronger scientific basis for strategic planning and management of nautical infrastructure.

5. Conclusions

The main innovation of the proposed model is the transition from fragmented, intuitive planning methods to an integrated, algorithmically grounded framework based on objective decision-making. By combining six MCDM algorithms with 18 quantified parameters derived from GIS and hydrometeorological analyses, the model achieves robust consensus and effectively eliminates subjectivity. Sensitivity analysis and Spearman's rank correlation confirm the stability of the results. Implementation in the R environment enables a reproducible, transparent, and scalable workflow, surpassing existing methods. The key advantages are objectivity, robustness, transparency, and the integration of safety and environmental criteria, while the main limitation is reliance on static and historical data. Future research should focus on developing adaptive models that incorporate real-time Automatic Identification System (AIS) and meteorological data, as well as AI and Machine Learning (ML) techniques, to support more accurate and environmentally sustainable anchorage planning. Within this framework, anchorages are treated as critical infrastructure embedded in a safe and sustainable blue economy of the Adriatic Sea.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AIS	Automatic Identification System
AHP	Analytical Hierarchy Process
COPRAS	Complex Proportional Assessment
CRITIC	Criteria Importance Through Intercriteria Correlation
DSS	Decision Support System
EDAS	Evaluation based on Distance from Average Solution
ELECTRE III	Elimination Et Choice Translating Reality
GIS	Geographic Information System
ISM	International Safety Management
MARCOS	Measurement of Alternatives and Ranking according to COMpromise Solution
MCA	Multi-Criteria Analysis
MCDA	Multiple-Criteria Decision Analysis
MCDM	Multi-Criteria Decision-Making
MCDP	Multiple-Criteria Decision Problem
ML	Machine Learning
MOORA	Multi-Objective Optimization on the basis of Ratio Analysis
PIANC	The World Association for Waterborne Transport Infrastructure
PROMETHEE I, II, III	Preference Ranking Organization METHod for Enrichment Evaluation I, II, III
SDC	Split-Dalmatia County
TOPSIS	The Technique for Order of Preference by Similarity to Ideal Solution
UNESCO	United Nations Educational, Scientific and Cultural Organization
VIKOR	Multi-Criteria Optimization and Compromise Solution—ViseKriterijska Optimizacija I Kompromisno Rjesenje

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