Unmanned Aircraft Selection for Electronic Warfare: A Combined Multicriteria Decision Analysis Approach

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Abstract

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Our primary goal is to identify the optimal UA among various options, meticulously considering distinct EW criteria. We implement three MCDA techniques: the Analytic Hierarchy Process (AHP), AHP-Gaussian, and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Notably, these methods consistently converge in favor of Alternative 4, substantiating the robustness and minimizing subjective bias.

These findings hold profound implications for strategic decision-making within EW operations and offer a sturdy framework for UA selection. This study not only advances the understanding of UA selection within EW but also underscores MCDA's enduring value as a potent tool for guiding strategic choices.

We anticipate that this work will inspire future research in UA selection, including the exploration of more intricate aircraft and the optimization of EW capabilities through sensor allocation and radiation-absorbing materials. Effective UA integration into EW is pivotal for modern military success, and our research provides a comprehensive roadmap to achieve this objective.

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Index Terms— **Defense Strategy, Decision Analysis, Electronic Warfare, Military Unmanned Aircraft, Unmanned Aerial Vehicles.**

I. INTRODUCTION

In contemporary military operational scenarios, technological advancements have bestowed Unmanned Aerial Vehicles (UAVs) with a crucial role, particularly in the realm of Electronic Warfare [1]. In this context, the Brazilian Navy is directing efforts towards harnessing the potential of these technologies as strategic tools to support Electronic Warfare, underscoring the importance of a meticulous and effective selection of these devices [2]. The proper selection of UAVs that best align with the specific requirements of this application demands a detailed and well-informed approach, considering a variety of technical and operational criteria.

However, amid the escalating innovations and complexities involved in UAV selection for Electronic Warfare, the decision-making process becomes a intricate task. In this scenario, the challenge of how to choose the most suitable UAVs emerges as a prominent issue [3]. A judicious selection entails the meticulous evaluation of a myriad of criteria ranging from technical specifications to operational capabilities, aiming to optimize the performance and effectiveness of naval operations.

The justification for this research is clear: the complexity of UAV selection for Electronic Warfare calls for robust methodologies that can underpin the decision-making process. In this context, Multicriteria Decision Analysis (MCDA) methods emerge as a promising approach to address the intricate nature of this selection [4]. The combined application of different MCDA methods promises to provide a comprehensive perspective on UAV selection, allowing technical and operational criteria to be balanced.

Based on this context, this research aims to achieve specific objectives that will contribute to a deeper understanding of the application of MCDA methods in UAV selection for Electronic Warfare. The joint application of these methods will be exemplified by classifying the UAVs presented in the Robotic Experimentation and Prototyping augmented by Maritime Unmanned Systems (REP(Mus)) 2021 Exercise, offering a detailed assessment of their feasibility and utility in Brazilian Navy operations.

To fulfill these objectives, this study will adopt a methodological approach that combines qualitative and quantitative elements, exploring MCDA methods as key instruments to guide UAV selection. The following section will detail this methodology, highlighting how the research seeks to accomplish its goals within the challenging realm of investigation.

II. LITERATURE REVIEW

In this section, we provide essential background information, including a detailed exploration of three Multicriteria Decision Analysis (MCDA) methods: Analytic Hierarchy Process (AHP), Gaussian AHP, and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Additionally, we delve into the realm of Electronic Warfare (EW) and its Measures of Electronic Warfare Support (MEWS).

A. Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a prominent

MCDA method used for prioritizing alternatives based on weighted criteria [5]. AHP has found application in various domains, such as naval vessel selection [6], unmanned aerial vehicle (UAV) procurement [7], industrial site selection [8], military airport location determination [9], and landslide risk assessment in Japan [10]. These applications underscore AHP's efficacy in addressing complex and uncertain decision problems.

To compute AHP, pairwise comparison matrices are constructed, normalized, and used to derive criterion weights. These weights guide the evaluation of alternatives against criteria. The final scores of alternatives are computed by multiplying normalized pairwise comparison matrices by criterion weights.

B. Method of Consistency and Concordance

The AIJ method (Analysis of Judgment Inconsistency), proposed by Saaty [11], is an approach used to assess the coherence of judgments in decision-making processes. It relies on two main calculations: the random index (RI) and λ_{max}, which are employed to determine the consistency of judgments.

The calculation of the Consistency Index (CI) involves subtracting the average of the eigenvalues from the maximum value of the comparison matrix. This formula, (1), uses the number of criteria or alternatives (represented by "n") for computation.

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

Next, the Relative Consistency Index (CR) is calculated, which involves dividing CI by the corresponding random index for the matrix size, as per (2):

$$CR = CI / RI. \quad (2)$$

The λ_{max} represents the principal eigenvalue of the comparison matrix and is used to determine the Consistency Vector (CV), quantifying the difference between the criteria's priority vector and its maximum value.

Judgment consistency is verified through the Consistency Ratio (CR), which is obtained by dividing CR by the established consistency limit. Generally, an RC below 10% is expected to consider judgments as consistent.

By applying the AIJ method, it is possible to assess the coherence of expert judgments, providing high-quality and reliable results in the decision-making process.

Fig. 1 contains a table with random indices developed by Saaty [5] for different matrix sizes, facilitating the calculation of judgment consistency.

C. Gaussian AHP

Gaussian AHP is an extension of AHP designed to handle uncertainty in decision-makers' judgments by incorporating probability distributions [12]. Like AHP, it employs pairwise comparisons but uses a Gaussian function to model uncertainty. Gaussian AHP has demonstrated applicability in diverse domains, including large aircraft selection for the Brazilian Air Force [13], sensor evaluation for escalators [14], classification of hospital sanitizers [15], pneumatic stunner selection [16], and thermal feasibility analysis of Expanded Polystyrene panels [17].

D. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS is an intuitive MCDA method that ranks alternatives based on their proximity to positive and negative ideals [18]. While robust and versatile, it does not explicitly address judgment consistency. TOPSIS has seen wide application in military aviation for training aircraft selection [19], cargo aircraft selection [20], weapon selection [21], and naval base selection for piracy and related operations [22].

E. Electronic Warfare (EW) and Measures of EW Support (MEWS)

Electronic Warfare (EW) plays a pivotal role in military operations, encompassing the entire electromagnetic spectrum. The concept of Electronic Warfare includes activities ranging from gamma-ray to radio wave frequencies, both visible and invisible. Electronic Warfare capabilities encompass a set of means and resources that enable effective EW actions in support of military operations [23].

Within the Electronic Warfare Capability (EW Capability), we find Measures of Electronic Warfare Support (MEWS), which comprise actions aimed at the analysis, immediate threat recognition, and exploitation of electromagnetic emissions. These activities include search, interception, identification, and electronic localization of electromagnetic energy sources in a specific electromagnetic environment [23].

Aircraft represent crucial assets in EW operations due to their versatility regarding range, altitude, and speed. However, manned aircraft have limitations, such as vulnerability to enemy fire and limited time on station [24].

Unmanned Aerial Vehicles (UAVs) emerge as a promising alternative to overcome these limitations, offering the capability for continuous operations over extended periods. They excel in Intelligence, Surveillance, and Reconnaissance (ISR) missions, including Measures of Electronic Warfare Support (MEWS), such as the identification of enemy emitters [24].

In the context of MEWS, UAVs play a vital role in gathering intelligence on enemy transmissions. These measures are primarily passive and aim to survey the electromagnetic spectrum. Employing electronic and electro-optical sensors, UAVs seek, intercept, locate, monitor, and identify sources of electromagnetic signals across the infrared to ultraviolet spectrum emitted by the adversary. Such data is crucial for Signals Intelligence (SIGINT) production [24].

III. METHODOLOGY

The Methodology section elucidates the research design employed in this study, detailing the classification of the research concerning its purpose and methods, method limitations, the universe and sampling, as well as data collection and processing procedures.

A. Research Classification

The classification of research is pivotal for steering the investigative process and understanding the problem under study. In this work, the research aims to demonstrate the efficacy of employing a combined approach of various Multi-Criteria Decision Analysis (MCDA) methods in the selection of Unmanned Aerial Vehicles (UAVs) for Electronic Warfare. This purpose aligns with both the research's objectives and its methods. Concerning objectives, this research seeks to deepen the understanding of the feasibility of UAVs for this specific application within the Brazilian Navy. In terms of methods, it employs a mixed-method approach, combining qualitative and quantitative elements for analysis.

This section aims to provide a clear understanding of the adopted methodological framework, enabling the reader to contextualize the study and comprehend how different approaches were integrated to achieve the stated objectives.

B. Objectives

In terms of objectives, this research endeavors to illustrate that the combined use of different types of Multi-Criteria Decision Analysis (MCDA) is an effective method for the selection of UAVs in Electronic Warfare. The application of this method is exemplified by the classification of UAVs presented in the Robotic Experimentation and Prototyping augmented by Maritime Unmanned Systems (REP(Mus)) 2021 Exercise. This research falls within the category of exploratory, seeking a more profound understanding of the viability of UAVs as support for Electronic Warfare in the Brazilian Navy.

C. Methods

In terms of methods, following the classification proposed by [25], this research can be characterized as mixed-method qualitative-quantitative. It combines a case study approach with mathematical modeling [26]. This mixed approach allows for a more comprehensive analysis of the problem, leveraging both qualitative and quantitative elements to evaluate the viability of UAVs in Electronic Warfare.

The qualitative approach is manifested in data collection through direct observations conducted by a Brazilian Navy observer during the REP(Mus) 2021 Exercise. This collection provided a detailed understanding of UAV operations in the context of Electronic Warfare, capturing nuances and contexts contributing to a more comprehensive assessment of viability.

Conversely, the quantitative approach is evident in the mathematical modeling applied to UAV analysis. This step involved the objective measurement of criteria, assignment of weights and scores to alternatives, and the application of three Multi-Criteria Decision Analysis (MCDA) methods - namely, the conventional Analytic Hierarchy Process (AHP), Gaussian AHP, and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). These methods apply mathematical and statistical principles to evaluate and rank UAV alternatives.

The combination of these approaches enabled a holistic and comprehensive analysis of UAV feasibility for Electronic Warfare, exploring both operational nuances and objective performance aspects. Thus, the research leverages the synergy between qualitative and quantitative methods to provide a broad and informed perspective on UAV application within the Brazilian Navy.

The choice of this mixed-method approach not only enriches the understanding of the problem but also reinforces the validity of results, as multiple perspectives and methodologies are considered in the analysis. The research benefits from the complementarity between these approaches to offer a more robust and informed assessment of UAV viability for Electronic Warfare.

D. Method Limitations

When conducting research, it is essential to acknowledge and address inherent method limitations. In this context, this research is not exempt from limitations that could impact the interpretation and generalization of results.

One primary limitation lies in the intrinsic complexity of the evaluation criteria considered for UAV selection. Although meticulously defined, these criteria may still not encompass all nuances of the naval Electronic Warfare scenario, potentially influencing results.

Another limitation pertains to the reliance on available information about UAVs and their technical and operational characteristics. The quality and comprehensiveness of this information can vary, introducing potential bias into the analysis.

Additionally, the choice of specific Multi-Criteria Decision Analysis (MCDA) methods may introduce their limitations. While methods were selected based on their properties and capabilities, each method has its underlying assumptions that can impact results.

Finally, the sampling of participating experts may have limitations in terms of representativeness. Although all are Senior or Intermediate Officers of the Brazilian Navy, additional perspectives could further enrich the analysis.

These limitations do not invalidate the results but underscore the importance of interpreting results within the context of these constraints. By recognizing and addressing these limitations, the research strengthens itself by providing a more precise and realistic assessment of the applicability of MCDA methods in UAV selection for Electronic Warfare.

E. Universe and Sampling

The precise definition of the research universe and the appropriate selection of the sample are crucial to ensuring the representativeness and applicability of results, especially in a study aiming to explore the combined application of different Multi-Criteria Decision Analysis (MCDA) methods.

In this study, the research universe encompasses Unmanned Aerial Vehicles (UAVs) initially selected for evaluation during the REP(Mus) 2021 Exercise, focusing on their potential application in Electronic Warfare in the Brazilian Navy. Initially, six UAVs were chosen for the study. However, due to a lack of response from manufacturers, the necessary information for evaluating two UAVs was not obtained. Thus, the UAV alternatives used in the study were only those provided by manufacturers who responded to contact.

The sampling was strategically conducted, considering Brazilian Navy experts with in-depth knowledge of naval operations and Electronic Warfare. They were intentionally selected to ensure relevance and the expertise necessary for evaluating UAV alternatives. This sample of experts is crucial for the application and analysis of the different combined MCDA methods since their opinions underpin underlying judgments.

Regarding the selection of UAV alternatives, criteria were defined based on technical and operational characteristics of the vehicles, aiming to capture the diversity of available options. This ensures that the UAV alternative sample adequately represents the spectrum of relevant possibilities for the Brazilian Navy's choice.

The clear definition of the universe and the careful selection of the sample are fundamental for applying the different combined MCDA methods and obtaining robust and reliable results. The universe and sampling strategy aim to ensure that the conclusions of this study are applicable to the specific context of UAV selection in Electronic Warfare, thereby allowing recommendations to support effective and informed decisions.

F. Data Collection and Processing

The data collection and processing phase plays a fundamental role in conducting research aimed at evaluating the viability of Unmanned Aircraft Systems (UAS) as support for Electronic Warfare in the Brazilian Navy through the combined application of different Multi-Criteria Decision Analysis (MCDA) methods.

Data collection was carried out comprehensively and meticulously, focusing on the technical and operational characteristics of UAS. Initially, six UAS were selected for the study, based on the availability of information from manufacturers. However, only the manufacturers of four UAS responded to the inquiry and provided the necessary information. This information included details on technical specifications, operational capabilities, and relevant characteristics for Electronic Warfare application.

The collected data underwent a rigorous treatment process to ensure data integrity and consistency. Analyses of consistency, identification of potential discrepancies, and cross-validation of information provided by manufacturers were conducted. This step is crucial to ensure that the data used in the MCDA methods accurately reflect the characteristics of the evaluated UAS.

In the context of the applied methodology, the data were used in assigning weights and scores to the evaluation criteria, as defined in the decision-making process. The application of MCDA methods, including the conventional Analytic Hierarchy Process (AHP), Gaussian AHP, and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), requires a consistent and standardized treatment of data to ensure comparable and robust results.

Rigor in data collection and processing is fundamental for the reliability and validity of the results obtained. The combined application of different MCDA methods relies directly on the quality of the information used to assess UAS alternatives. Therefore, the data collection and processing process adopted in this study ensures that the conclusions reached are solid, based on accurate information, and applicable to the context of UAS selection for Electronic Warfare in the Brazilian Navy.

IV. REP(MUS) EXERCISE AND OBSERVED UNMANNED AIRCRAFT (UA)

The Robotic Experimentation and Prototyping augmented by Maritime Unmanned Systems, known as REP(Mus), is an initiative aimed at experimenting with Maritime Unmanned Systems [27]. This international collaboration plays a pivotal role in the development and enhancement of these technologies.

In this section, we will delve into our understanding of the REP(Mus) 2021 exercise and its international context. Subsequently, we will examine the Unmanned Aircraft (UA) observed during the exercise, providing crucial information about their characteristics and performance, which are fundamental to the scope of this study focused on the meticulous selection of UAs for Electronic Warfare (EW) operations.

A. REP(Mus) 2021 Exercise

The REP(Mus) 2021 is an event that has its roots in 2010 when a cooperation protocol was established between the Portuguese Navy and the Faculty of Engineering of the University of Porto (FEUP). Since then, this exercise has consistently grown, attracting the interest of various national and international entities. The 2021 edition was co-organized by a coalition of notable organizations, including the Portuguese Navy, the Faculty of Engineering of FEUP, the Centre for Maritime Research and Experimentation (NATO STO CMRE), and the NATO Maritime Unmanned Systems Initiative (NATO MUSI) [28].

The REP(Mus) represents a significant milestone in promoting international collaboration, bringing together more than 40 entities, including 17 Navies, including those of the United States and the United Kingdom, 15 Research & Development Entities, 1 University, and 8 NATO agencies. Furthermore, the presence of the Brazilian Navy as an observer in this exercise opens up prospects for the participation of various national entities, such as the Brazilian Army, the Brazilian Air Force, companies, and universities in future editions of REP(Mus) [27].

The importance of this exercise goes beyond the national scenario since its primary focus lies in the research and experimentation of maritime autonomous systems. REP(Mus) plays a fundamental role in the evolution of these technologies, promoting multinational collaboration, innovation, and interoperability between systems, essential elements for enhancing naval capabilities. Through this exercise, allied nations share resources, knowledge, and ingenuity to create more flexible, versatile, and capable maritime unmanned systems that can work in conjunction with manned assets, making naval fleets more adaptable and effective [28].

Next, we will detail the Unmanned Aircraft (UA) observed during the REP(Mus) 2021 exercise, providing essential information about their characteristics and performance. These data are crucial for the scope of this study, which focuses on the meticulous selection of UAs for Electronic Warfare (EW) operations.

B. Data of Observed Unmanned Aircraft (UA) in REP(Mus) 2021

In this section, we present the selection criteria and the methodology used to obtain data on the UAs that participated in the REP(Mus) 2021 exercise.

To assess and compare the capabilities of Unmanned Aircraft (UA) in the context of Electronic Warfare (EW) operations, we defined eleven essential criteria. Each of these criteria describes a crucial feature that impacts the performance of UAs in scenarios involving the detection and identification of electromagnetic signals.

The criteria are as follows: Maximum Range (KM), Endurance (Hours), Maximum Altitude (Feet), Maximum Speed (Knots), Payload (KG), Radar Capability (Yes or No), Electro-Optical Sensor Resolution (MP), Electro-Optical Sensor Range (KM), Infrared Sensor Resolution (MP), Infrared Sensor Range (KM), and AIS Sensor Capability (Yes or No).

These criteria are listed in Table 1 for easy identification and future reference.

TABLE I
SELECTED CRITERIA

CRITERIA	**DEFINITION**
C1	Maximum Range (KM): The maximum distance the UA can travel on a single mission.
C2	Autonomy (hours): The maximum time the UA can remain airborne without refueling.
C3	Maximum Ceiling (feet): The maximum altitude the UA can reach during its operations.
C4	Maximum Speed (knots): The maximum speed the UA can achieve in flight.
C5	Payload (kg): The maximum weight of equipment and devices the UA can carry.
C6	Radar Equipped (yes or no): Indicates whether the UAV has an onboard radar system.
C7	Electro-Optical Sensor Resolution (MP): Capability to capture high-definition images.
C8	Electro-Optical Sensor Range (KM): Maximum distance at which the electro-optical sensor can identify objects.
C9	Infrared Sensor Resolution (MP): Capability to capture high-definition thermal images.
C10	Infrared Sensor Range (KM): Maximum distance at which the infrared sensor can identify objects.
C11	AIS Sensor Equipped (yes or no): Indicates whether the UAV has an Automatic Identification System (AIS) for vessels.

Based on these criteria, we proceeded to collect data from the UAVs that participated in the REP(Mus) 2021 exercise. The observer from the Brazilian Navy obtained this data through presentations by participating suppliers and brochures, and some data was complemented and obtained through telephone contact to complete the study. As mentioned in Section III of this work, six UAVs were selected for the study, but only the suppliers of four of them responded to the request for additional data.

The data obtained has been organized in Table II, which presents detailed information for each of the Unmanned Aerial Vehicles observed in the exercise. When an aircraft did not possess a specific piece of equipment, a zero value was assigned to the corresponding criterion.

A detailed analysis of this data will be crucial for the selection of the most suitable aircraft for EW operations in specific scenarios, an aspect that will be discussed in the next section of this work.

TABLE II
DATA OBTAINED FROM UAVS IN REP(MUS) 2021

Criteria / Alternatives	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
A1	33,33	11,5	10500	45	4	0	13	23	0	0	0
A2	60	6,5	1000	76	2,36	1	15	27	0,33	25	0
A3	100	16	10000	75	4	0	15	30	0,31	25	1
A4	1056	12	13000	95	50	1	20	40	0,35	30	1

V. USE OF UNMANNED AIRCRAFT IN ELECTRONIC WARFARE

Electronic Warfare (EW) is a critical area of military operations involving the management of the electromagnetic spectrum to gain tactical advantage [2]. In this context, Unmanned Aircraft (UAVs) emerge as crucial assets for collecting strategic information and supporting EW operations [24]. This section focuses on the application of UAVs in the EW scenario, with an emphasis on the aircraft observed during the REP(Mus) 2021 exercise.

A. Unmanned Aircraft Classification

A standardized classification of UAVs, as proposed by NATO and mentioned by [29], is essential for understanding the capabilities and applications of these aircraft. Categorization based on maximum takeoff weight, ranging from micro (less than 2kg) to large/tactical (greater than 600kg), plays a crucial role in selecting the appropriate UAV for a specific EW mission. The aircraft in this study fall within the mini and medium categories, with their maximum takeoff weight ranging from 4 to 180kg. This allocation is essential, considering that, for the proposed activity, aircraft must be capable of launching and recovering from naval platforms.

B. Role of Unmanned Aircraft in Electronic Warfare

The study presented by [30] highlights the practical application of lessons learned from the use of Remotely Piloted Aircraft Systems (RPAS) in Military Support to Civil Authorities (MAGE) operations. Although focused on Law and Order Guarantee operations, the study emphasizes the need to adapt aircraft capabilities to the specific requirements of EW operations, reinforcing the importance of conducting field tests to assess the performance and feasibility of employing these platforms in EW scenarios.

UAVs represent a valuable extension of information collection capabilities in EW operations [31]. However, the aircraft used in the REP(Mus) 2021 exercise do not have the direct capability to detect electromagnetic signals. Instead, they act as essential complements to the detection capabilities of other platforms, such as ships and manned aircraft.

The role proposed by this study for UAVs in the context of EW is the visual identification of electromagnetic signal emitters. The application of high-resolution electro-optical and infrared sensors allows these aircraft to accurately identify emitters, which is vital for understanding the electromagnetic environment. This approach also reduces direct exposure of human crews to potential threats, increasing operational safety.

C. Comparative Study of UAVs in Electronic Warfare

Conducting a comprehensive comparative study of UAVs is crucial to determine which aircraft are best suited to meet the specific requirements of EW operations [3]. This involves evaluating various individual aircraft capabilities, including autonomy, payload, sensor quality, among others.

By applying AMD to these criteria, it is possible to more accurately determine which UAV is best suited for a specific EW operation. This ensures a careful selection of the most efficient and adaptable aircraft, optimizing the use of available resources while ensuring the effectiveness and safety of EW missions. Therefore, AMD plays a central role in the UAV selection process, ensuring that the decision is solid and well-founded.

VI. DESCRIPTION AND ANALYSIS OF RESULTS

In this section, we compare the individual results obtained from three Multi-Criteria Decision Analysis (MCDA) methods to determine the most suitable Unmanned Aerial Vehicle (UAV) for Electronic Warfare among those evaluated. This approach provides a consolidated evaluation that strongly supports the final choice.

Each method was independently calculated, and the results were later compared.

A. Aggregation of Assessments For AHP Method

To ensure consistency in applying the AHP method, we consolidated assessments from six experts. These experts were selected based on specific criteria, including rank (Intermediate Officer or higher), academic background (at least a Master's degree), affiliation with Technical Military Organizations of the Brazilian Navy, and technical or operational experience in Electronic Warfare.

Following [32] recommendation we adopted the Geometric Mean as the aggregation method due to its effectiveness. Individual Consistency Ratios (CRs) for each assessment were calculated using Saaty's Analytic Inconsistency of Judgments (AIJ) method [11]. Assessments with CRs under 10% received a weight of 3, those between 10% and 15% received a weight of 2, and those above 15% received a weight of 1. This approach prioritized more consistent assessments, ensuring a coherent final evaluation.

The CR values were inserted into (1) to calculate the CR. This CR was divided by the Random Index (RI) obtained from Fig. 1, resulting in the Consistency Ratio (CR). Fig. 1 provides the RI for n equal to 11 as 1.51. Inserting these values into (2) yielded the CR for each expert. Thus, each expert's assessment was weighted for the final evaluation.

Table III displays the CR values obtained by each Expert and their respective weights. Using these weights, we consolidated the assessments from the six experts into a single assessment.

TABLE III

WEIGHT OF ASSESSMENTS FOR EACH EXPERT

Expert	CR	Weight
Expert 1	73,53%	1
Expert 2	66,34%	1
Expert 3	8,15%	3
Expert 4	4,54%	3
Expert 5	11,44%	2
Expert 6	8,11%	3

Each cell of the final assessment corresponds to the weighted geometric mean of the respective cells in the expert assessments. An example calculation is provided in (3) for cell a_{21} of the consolidated assessments matrix.

$$a_{21} = \sqrt[13]{1^1 + (1/8)^1 + (1/5)^3 + (1/6)^3 + (1/3)^2 + 5^3}. \quad (3)$$

The result of this calculation is 0.4759 for cell a_{21}. Fig. 2 presents the matrix with the consolidated assessments from the six experts, which will be used in the AHP method calculation.

By following the steps described above to obtain the Consistency Ratio of the consolidated assessments, a value of 1.73% was obtained. This value is considered satisfactory, according to [11], which indicates that the CR should be less than 10%. This suggests a high degree of consistency in the consolidated assessments, reinforcing the reliability of the results obtained through the AIJ method.

B. Analytic Hierarchy Process (AHP) Calculation

To process the collected data and execute the AHP method, we employed a pre-developed spreadsheet by [33] within Microsoft Excel. This spreadsheet allows for the input of UAV data and expert assessments, providing a hierarchical evaluation for each of them after computation. Fig. 3 illustrates the data entered into the software for method execution.

Fig. 4 displays the AHP method calculations using [33] spreadsheet and presents the results.

As evident from Fig. 4, the results of the AHP method indicate that Alternative 4 is the most suitable, with a score of 47%. Alternative 2 ranks second, with a score of 22.5%. This outcome highlights a robust preference for Alternative 4 using this method.

C. AHP-Gaussian Data Processing

As described in Section II of this work, the AHP-Gaussian method, developed by [12], is an extension of the conventional AHP method that incorporates judgment uncertainty. This is achieved through the calculation of Standard Deviation and the Gaussian Factor, aiming to determine the best alternative. The approach of this method aims to eliminate the need for criteria assessments by experts, making it entirely statistical and impersonal.

To process data using the AHP-Gaussian method, we employed the spreadsheet developed by [33]. Data is entered in the same manner as in the conventional AHP method, except for the pairwise criteria assessments, which are not required for this approach. Fig. 5 presents the data entered and processed by the spreadsheet.

As observed in Fig. 5, Alternative 4 obtained a higher score, with 57.01%, significantly outperforming Alternative 3, which reached the second position with 20.13%. This demonstrates a significant preference for Alternative 4 over the other options.

D. TOPSIS Method Data Processing

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), developed by [18], ranks alternatives based on their distances to a positive ideal and a negative ideal, as explained in Section II of this work. Scores are assigned based on the proximity of the alternative to the positive ideal and the distance from the negative ideal, evaluating this relationship for each decision criterion. The most favorable alternative will be the one that achieves the highest score.

To execute the TOPSIS method, we used the spreadsheet developed by [34] for Microsoft Excel, which allows for the insertion of data for the UAVs and calculates the scores for each alternative. Fig. 6 presents the data entered into the spreadsheet and the result of data processing.

As observed in Fig. 6, Alternative 4 obtained the highest score with a Performance Index (PI) of 0.65, followed by Alternative 3 with a PI of 0.56. This result solidifies Alternative 4 as the best choice according to the TOPSIS method.

E. Comparison of Results

Analyzing the results obtained through the three methods, it is evident that Alternative 4 consistently maintained the highest score across all applied methods. Conversely, Alternative 1 remained the least scored. This demonstrates complete convergence in results for both of these alternatives.

Concerning Alternatives 2 and 3, there was agreement between the TOPSIS and AHP-Gaussian methods, but divergence from these in relation to the conventional AHP method. This discrepancy highlights how the subjectivity of decision-makers in the AHP method influenced the results for these two alternatives.

Taking into consideration the consistency of results regarding Alternative 4 across the three Multi-Criteria Decision Analysis (MCDA) methods, this alternative consistently positioned itself as the best choice of UAV for Electronic Warfare applications. Despite the discrepancy resulting from the subjectivity present in the AHP method, which influenced the results of Alternatives 2 and 3, Alternative 4 maintained a significantly higher score, with a considerable margin over the second position in all employed methods. Table IV summarizes the results of the three methods and presents the final ranking of alternatives.

TABLE IV
FINAL RANKING OF ALTERNATIVES

	AHP	AHP-Gaussian	TOPSIS	Final Ranking
A1	4	4	4	4
A2	2	3	3	3
A3	3	2	2	2
A4	1	1	1	1

Upon examining the rankings presented in Table IV, it is evident that Alternative 4 stands out as the best UAV choice for Electronic Warfare applications, followed by Alternative 3, which maintained the second position in two out of the three MCDA methods used. Thus, based on data analysis, Alternative 4 emerges as the most favorable choice of UAV to meet Electronic Warfare needs.

VII. CONCLUSION

The central objective of this work was to demonstrate the utility of combining different Multi-Criteria Decision Analysis (MCDA) methods as a rigorous approach in the selection of Unmanned Aerial Vehicles (UAVs) for Electronic Warfare (EW) applications. The results obtained throughout this research have proven to be highly satisfactory, as all three applied MCDA methods converged on the same alternative as the most suitable.

Through thorough analysis and detailed comparison of each alternative, Alternative 4 emerged as the superior choice for UAVs in Electronic Warfare scenarios. This alternative consistently demonstrated outstanding performance, firmly establishing itself as the top choice. Following closely behind, Alternative 3 maintained its position as the second most promising alternative, ranking second in two out of the three MCDA methods used, while in the AHP method, it appeared as the third-best choice.

Therefore, based on the in-depth analysis conducted in this study, Alternative 4 stands out as the most favorable UAV selection to meet the specific and complex needs of Electronic Warfare. This result is of great significance, as the selection of UAVs plays a crucial role in EW operations, and the combined approach of multiple MCDA methods has proven to be an effective tool in strategic decision-making.

This research significantly contributes to the understanding of the UAV selection process in a context as critical as Electronic Warfare. Furthermore, it underscores the continued importance of the judicious application of MCDA as a robust and reliable methodology in making complex and strategic decisions in various fields of study.

However, it is important to highlight the inherent limitations of this study. The complexity of evaluation criteria, the reliance on available information about UAVs, the limitations of the chosen MCDA methods, and the sampling of experts are factors that can influence the results and should be considered.

As suggestions for future work employing this method, we propose three promising directions. Firstly, expanding the selection of UAVs for more complex Electronic Warfare scenarios, with UAVs having greater Electronic Warfare capabilities, may provide additional insights and expand the applicability of this combined method. Secondly, the selection of sensors to allocate in the payload of UAVs represents a valuable next step in optimizing EW capabilities. Finally, the selection of radiation-absorbing materials for the construction of these aircraft could be an interesting and promising approach for technological advancement in this domain.

Ultimately, this work contributes to improving decision-making in UAV selection for Electronic Warfare, offering a solid framework and rigorous methods to guide strategic choices. The combined use of different MCDA types has proven to be satisfactory, providing consistent and reliable results. As EW operations and the use of UAVs continue to evolve, the approach presented here may be critical in ensuring that naval forces are equipped with the most suitable tools to face future threats and challenges.

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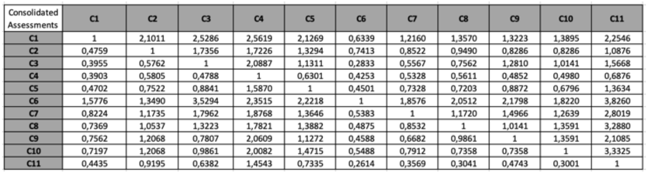
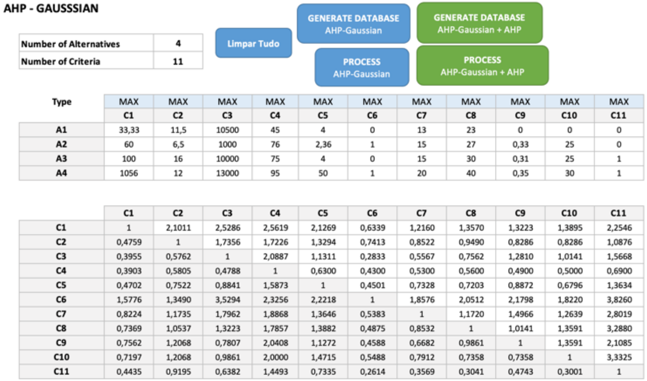
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0,0	0,0	0,58	0,90	1,12	1,24	1,32	1,41	1,48	1,49	1,51	1,48	1,56	1,57	1,59

Fig. 1. Random Indices by Saaty. [35]



Consolidated Assessments	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	1	2,1011	2,5286	2,5619	2,1269	0,6339	1,2160	1,3570	1,3223	1,3895	2,2546
C2	0,4759	1	1,7356	1,7226	1,3294	0,7413	0,8522	0,9490	0,8286	0,8286	1,0876
C3	0,3955	0,5762	1	2,0887	1,1311	0,2833	0,5567	0,7562	1,2810	1,0141	1,5668
C4	0,3903	0,5805	0,4788	1	0,6301	0,4253	0,5328	0,5611	0,4852	0,4980	0,6876
C5	0,4702	0,7522	0,8841	1,5870	1	0,4501	0,7328	0,7203	0,8872	0,6796	1,3634
C6	1,5776	1,3490	3,5294	2,3515	2,2218	1	1,8576	2,0512	2,1798	1,8220	3,8260
C7	0,8224	1,1735	1,7962	1,8768	1,3646	0,5383	1	1,1720	1,4966	1,2639	2,8019
C8	0,7369	1,0537	1,3223	1,7821	1,3882	0,4875	0,8532	1	1,0141	1,3591	3,2880
C9	0,7562	1,2068	0,7807	2,0609	1,1272	0,4588	0,6682	0,9861	1	1,3591	2,1085
C10	0,7197	1,2068	0,9861	2,0082	1,4715	0,5488	0,7912	0,7358	0,7358	1	3,3325
C11	0,4435	0,9195	0,6382	1,4543	0,7335	0,2614	0,3569	0,3041	0,4743	0,3001	1

Fig. 2. Matrix with the consolidated assessments from the six experts

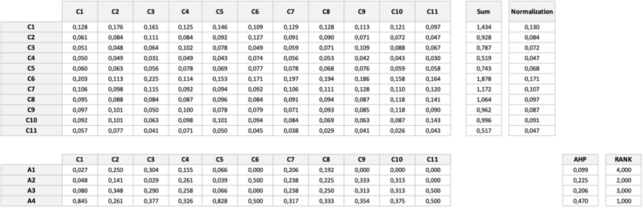


Number of Alternatives	4
Number of Criteria	11

Type	MAX	MAX	MAX	MAX	MAX	MAX	MAX	MAX	MAX	MAX	MAX
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
A1	33,33	11,5	10500	45	4	0	13	23	0	0	0
A2	60	6,5	1000	76	2,36	1	15	27	0,33	25	0
A3	100	16	10000	75	4	0	15	30	0,31	25	1
A4	1056	12	13000	95	50	1	20	40	0,35	30	1

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	1	2,1011	2,5286	2,5619	2,1269	0,6339	1,2160	1,3570	1,3223	1,3895	2,2546
C2	0,4759	1	1,7356	1,7226	1,3294	0,7413	0,8522	0,9490	0,8286	0,8286	1,0876
C3	0,3955	0,5762	1	2,0887	1,1311	0,2833	0,5567	0,7562	1,2810	1,0141	1,5668
C4	0,3903	0,5805	0,4788	1	0,6300	0,4300	0,5300	0,5600	0,4900	0,5000	0,6900
C5	0,4702	0,7522	0,8841	1,5873	1	0,4501	0,7328	0,7203	0,8872	0,6796	1,3634
C6	1,5776	1,3490	3,5294	2,3256	2,2218	1	1,8576	2,0512	2,1798	1,8220	3,8260
C7	0,8224	1,1735	1,7962	1,8868	1,3646	0,5383	1	1,1720	1,4966	1,2639	2,8019
C8	0,7369	1,0537	1,3223	1,7857	1,3882	0,4875	0,8532	1	1,0141	1,3591	3,2880
C9	0,7562	1,2068	0,7807	2,0408	1,1272	0,4588	0,6682	0,9861	1	1,3591	2,1085
C10	0,7197	1,2068	0,9861	2,0000	1,4715	0,5488	0,7912	0,7358	0,7358	1	3,3325
C11	0,4435	0,9195	0,6382	1,4493	0,7335	0,2614	0,3569	0,3041	0,4743	0,3001	1

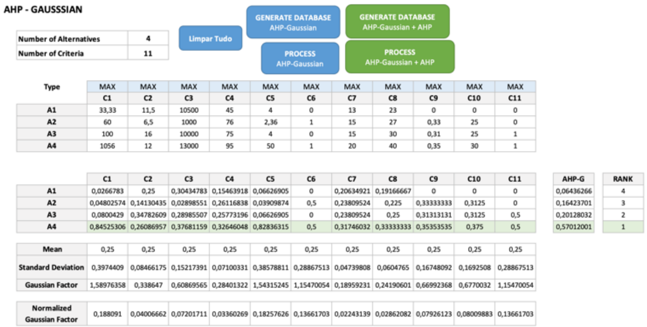
Fig. 3. Data Entered in the Spreadsheet for the AHP Method [33]



	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Sum	Normalization
C1	0,128	0,176	0,161	0,125	0,146	0,109	0,129	0,128	0,113	0,121	0,097	1,434	0,130
C2	0,061	0,084	0,111	0,084	0,092	0,127	0,091	0,090	0,071	0,072	0,047	0,928	0,084
C3	0,051	0,048	0,064	0,102	0,078	0,049	0,059	0,071	0,109	0,088	0,067	0,787	0,072
C4	0,050	0,049	0,031	0,049	0,043	0,074	0,056	0,053	0,042	0,043	0,030	0,519	0,047
C5	0,060	0,063	0,056	0,078	0,069	0,077	0,078	0,068	0,076	0,059	0,058	0,743	0,068
C6	0,203	0,113	0,225	0,114	0,153	0,171	0,197	0,194	0,186	0,158	0,164	1,878	0,171
C7	0,106	0,098	0,115	0,092	0,094	0,092	0,106	0,111	0,128	0,110	0,120	1,172	0,107
C8	0,095	0,088	0,084	0,087	0,096	0,084	0,091	0,094	0,087	0,118	0,141	1,064	0,097
C9	0,097	0,101	0,050	0,100	0,078	0,079	0,071	0,093	0,085	0,118	0,090	0,962	0,087
C10	0,092	0,101	0,063	0,098	0,101	0,094	0,084	0,069	0,063	0,087	0,143	0,996	0,091
C11	0,057	0,077	0,041	0,071	0,050	0,045	0,038	0,029	0,041	0,026	0,043	0,517	0,047

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	AHP	RANK
A1	0,027	0,250	0,304	0,155	0,066	0,000	0,206	0,192	0,000	0,000	0,000	0,099	4,000
A2	0,048	0,141	0,029	0,261	0,039	0,500	0,238	0,225	0,333	0,313	0,000	0,225	2,000
A3	0,080	0,348	0,290	0,258	0,066	0,000	0,238	0,250	0,313	0,313	0,500	0,206	3,000
A4	0,845	0,261	0,377	0,326	0,828	0,500	0,317	0,333	0,354	0,375	0,500	0,470	1,000

Fig. 4. Data Processed by the AHP Method. [33]



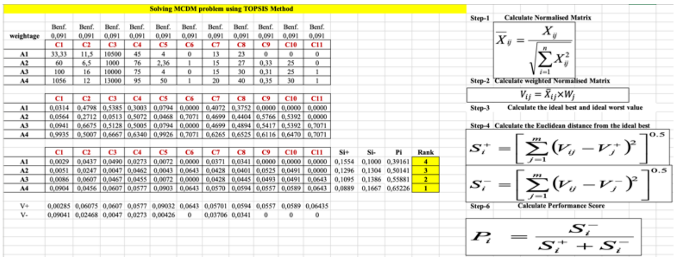
Number of Alternatives	4
Number of Criteria	11

Type	MAX	MAX	MAX	MAX	MAX	MAX	MAX	MAX	MAX	MAX	MAX
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
A1	33,33	11,5	10500	45	4	0	13	23	0	0	0
A2	60	6,5	1000	76	2,36	1	15	27	0,33	25	0
A3	100	16	10000	75	4	0	15	30	0,31	25	1
A4	1056	12	13000	95	50	1	20	40	0,35	30	1

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	AHP-G	RANK
A1	0,0266783	0,25	0,30434783	0,15463918	0,06626905	0	0,20634921	0,19166667	0	0	0	0,06436266	4
A2	0,04802574	0,14130435	0,02898551	0,26116838	0,03909874	0,5	0,23809524	0,225	0,33333333	0,3125	0	0,16423701	3
A3	0,0800429	0,34782609	0,28985507	0,25773196	0,06626905	0	0,23809524	0,25	0,31313131	0,3125	0,5	0,20128032	2
A4	0,84525306	0,26086957	0,37681159	0,32646048	0,82836315	0,5	0,31746032	0,33333333	0,35353535	0,375	0,5	0,57012001	1

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
Mean	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25
Standard Deviation	0,3974409	0,08466175	0,15217391	0,07100331	0,38578811	0,28867513	0,04739808	0,0604765	0,16748092	0,1692508	0,28867513
Gaussian Factor	1,58976358	0,338647	0,60869565	0,28401322	1,54315245	1,15470054	0,18959231	0,24190601	0,66992368	0,6770032	1,15470054
Normalized Gaussian Factor	0,188091	0,04006662	0,07201711	0,03360269	0,18257626	0,13661703	0,02243139	0,02862082	0,07926123	0,08009883	0,13661703

Fig. 5. Data Processing by the AHP-Gaussian Method. [33]



Solving MCDM problem using TOPSIS Method

	Benf.	Benf.	Benf.	Benf.	Benf.	Benf.	Benf.	Benf.	Benf.	Benf.	Benf.
weightage	0,091	0,091	0,091	0,091	0,091	0,091	0,091	0,091	0,091	0,091	0,091
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
A1	33,33	11,5	10500	45	4	0	13	23	0	0	0
A2	60	6,5	1000	76	2,36	1	15	27	0,33	25	0
A3	100	16	10000	75	4	0	15	30	0,31	25	1
A4	1056	12	13000	95	50	1	20	40	0,35	30	1

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
A1	0,0314	0,4798	0,5385	0,3003	0,0794	0,0000	0,4072	0,3752	0,0000	0,0000	0,0000
A2	0,0564	0,2712	0,0513	0,5072	0,0468	0,7071	0,4699	0,4404	0,5766	0,5392	0,0000
A3	0,0941	0,6675	0,5128	0,5005	0,0794	0,0000	0,4699	0,4894	0,5417	0,5392	0,7071
A4	0,9935	0,5007	0,6667	0,6340	0,9926	0,7071	0,6265	0,6525	0,6116	0,6470	0,7071

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Si+	Si-	Pi	Rank
A1	0,0029	0,0437	0,0490	0,0273	0,0072	0,0000	0,0371	0,0341	0,0000	0,0000	0,0000	0,1554	0,1000	0,39161	4
A2	0,0051	0,0247	0,0047	0,0462	0,0043	0,0643	0,0428	0,0401	0,0525	0,0491	0,0000	0,1296	0,1304	0,50141	3
A3	0,0086	0,0607	0,0467	0,0455	0,0072	0,0000	0,0428	0,0445	0,0493	0,0491	0,0643	0,1095	0,1386	0,55881	2
A4	0,0904	0,0456	0,0607	0,0577	0,0903	0,0643	0,0570	0,0594	0,0557	0,0589	0,0643	0,0889	0,1667	0,65226	1
V+	0,00285	0,06075	0,0607	0,0577	0,09032	0,0643	0,05701	0,0594	0,0557	0,0589	0,06435				
V-	0,09041	0,02468	0,0047	0,0273	0,00426	0	0,03706	0,0341	0	0	0				

Step-1 Calculate Normalised Matrix

$$\overline{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}}$$

Step-2 Calculate weighted Normalised Matrix

$$V_{ij} = \bar{X}_{ij} \times W_j$$

Step-3 Calculate the ideal best and ideal worst value

Step-4 Calculate the Euclidean distance from the ideal best

$$S_i^+ = \left[\sum_{j=1}^{m} (V_{ij} - V_j^+)^2 \right]^{0.5}$$

$$S_i^- = \left[\sum_{j=1}^{m} (V_{ij} - V_j^-)^2 \right]^{0.5}$$

Step-6 Calculate Performance Score

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

Fig. 6. Data Processing by the TOPSIS Method. [34]