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Application of multi-criteria decision making for the selection of a location for crossing a water obstacle by fording in a defense operation

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Abstract:

Introduction/purpose: The paper presents the multi-criteria Fuzzy DIBR-Fuzzy DIBR II-EWAA-BM-DEXi-Fuzzy LMAW model for choosing a location for crossing water obstacles by fording in a defense operation. After the identification of the criteria by experts in this field, the mentioned model was applied and the optimal point was determined. In order to test the consistency of the results and the validity of the model, experts were consulted again, and the sensitivity analysis and the comparative analysis were performed.

Methods: The Fuzzy DIBR and Fuzzy DIBR II methods were used to determine the weighting coefficients of the identified criteria, while the aggregation of the expert opinions and the obtained values was performed using the EWAA and BM operators. To select the optimal location, the Fuzzy LMAW method was applied, while the linguistic descriptors were determined using the DEXi decision support system.

Results: The proposed methodology made it possible to identify all the criteria that determine the choice of a location and the choice of the optimal point for crossing a water obstacle in a defense operation. The testing of the model by experts, the analysis of the sensitivity of the output results to *changes in the weights of the criteria and the comparison of the obtained results with the results of other methods indicated the fact that the model is valid and that it gives consistent results.*

Conclusion: It was concluded that the multi-criteria model provides the necessary help to decision makers in conditions of imprecise and unspecified information and that it is applicable in real situations. Also, the proposed model takes into consideration all the aspects that must be considered when making such a complex decision and helps less experienced officers in the decision-making process, reducing the possibility of errors, which can result in human casualties. Finally, directions for further research in the field of overcoming water obstacles and multi-criteria decision making are suggested.

Key words: wading, location, selection, military, MCDM, DIBR, DIBR II, Fuzzy, LMAW, EWAA, BM, DEXi.

Introduction

Overcoming water obstacles is a challenge that is present in all armies around the world and is considered one of the most difficult, most dangerous and complex combat actions and is a type of counter-engineering action aimed at ensuring the movement (maneuver) of units in combat operations (Pifat, 1980, p.13; Falkowski & Model, 2019). Considering a great number of waterways in our country, overcoming water obstacles in defensive actions against the enemy will be of great importance. Depending on deployment needs, different crossing points can be established: raft crossing point, bridge crossing point, ice crossing point, swimming crossing point, ford crossing point, deep fording crossing point, and underwater fording crossing point (Pifat, 1980, pp.225-233). The specifics of each of the operations determine the different conditions in which the water obstacle is overcome. Successfully overcoming such obstacles requires knowledge of various techniques and tactics, as well as detailed preparation. The preparation process includes collecting information on locations for crossing points, deciding on the most suitable location, and as a final step, establishing the crossing point itself. This is where the role of engineering officers comes into play - they must have a good understanding of the tactical and technical aspects of using various means to overcome water obstacles. Due to the complexity of these tasks, long-term experience of officers working in pontoon units and training is required to ensure the efficiency and safety of operations.

The location where the crossing over the water obstacle is established must meet the necessary conditions (criteria) in the assigned area, in accordance with the given task. The very choice of a location, for each of the crossing points, is basically defined by the normative - legal regulations that regulate this area in the Serbian Armed Forces. The existing documents only outline the criteria and rely on the experience of officers. The criteria that have been established do not consider in detail all the factors that influence the decision on the location, i.e., they are not complete. Also, the mentioned factors are not elaborated in detail, nor are they described to such an extent that they can serve as a standard operating procedure when choosing a location, especially for officers who do not have enough experience in this area. Part of the criteria is of a qualitative nature, so its assessment is influenced by the subjectivity of the decision maker.

In order to eliminate errors when deciding on the choice of locations for overcoming water obstacles in a defense operation, primarily due to the lack of experience of decision makers and the inaccuracy and incompleteness of available information, it is necessary to establish a decision-support model that would allow decision makers to choose the optimal location, based on previously defined criteria, in which subjectivity would be reduced to the smallest possible error. It is necessary to note that mistakes made during the selection of a location for the establishment of a crossing point over a water obstacle can result in human casualties and cause damage to weapons and military equipment.

In order to make faster and better decisions about the choice of the site of crossing by fording, i.e., the point on the water obstacle that is "overcome by treading on the bottom of its bed" (Pifat, 1980, p.226), and better optimization of time and assistance to less experienced officers for making such a decision in a defense operation, in this research a decision support model was established, which includes all the factors necessary for making an optimal decision on the choice of a location. The mentioned model includes the application of multi-criteria decision-making (MCDM) methods for the subject choice. The application of different MCDM methods, for solving different decision-making problems in different areas, is shown in numerous papers (Keshavarz-Ghorabaee et al, 2022; Mishra et al, 2023; Sahoo & Goswami, 2024; De & Nandi, 2024; Aldaghi & Muzik, 2024; Radovanović et al, 2024; Kumar et al, 2024; etc.). The selection of different locations using different methods was also the subject of different research studies (Ulutaş & Karakuş, 2021; Ao Xuan et al, 2022; Aykac et al, 2023; Maghfiroh & Kavirathna, 2023; Nghiem & Chu, 2024; Alwedyan, 2024; Raad & Rajendran, 2024; Yücenur & Maden, 2024; etc.). The field of MCDM was also applied to solving various problems in the military field, including location selection, as evidenced by a large number of papers (Sánchez-Lozano & Rodríguez, 2020; de Araújo Costa et al, 2022;

Swethaa & Felix, 2023; Kurnaz et al, 2023; Tešić & Božanić, 2023; Dağıstanlı & Kurtay, 2024; Bilgin et al, 2024; etc.). The specific choice of locations (points) for crossing a water obstacle using multi-criteria decision-making methods is presented in a small number of papers, which are mainly research studies conducted by the authors of this article, e.g (Tešić & Božanić, 2018; Bozanić et al, 2018; Setiadji et al, 2020; Žnidaršič et al, 2024; etc.), but no research deals with the choice of a fording crossing site in a defensive operation. Given that the choice of indicators is conditioned by data that confirm or refute the hypothesis and reflect the properties of the subject and research objectives, the indicators are based on previous scientific knowledge about the subject of research (Bazić & Danilović, 2015), and, given that there are no detailed criteria that influence the subject selection, that there are no previous research studies in this specific area, and that the area is defined by normative-legal documents, there was a need for this research as well as for this way of defining indicators.

The most frequently used criteria for evaluating alternatives, in the previous research in this area, were: Concealment of preparations, Degree of exposure to enemy fire, Characteristics of shores/banks, Camouflage, Bank characteristics, Characteristics of the terrain for the redirection of units and vehicles, Depth of water obstacles, Protection of own forces, Width of water obstacles, Speed of water current, Quality and number of access routes, Scope of work on the approaches to banks, Bottom composition, Existence of material deposits, Existence of obstacles, etc. From the aforementioned research, it is concluded that the problems of choosing locations for overcoming water obstacles can be successfully solved by applying MCDM methods.

Given that the aspects from which the subject of research is viewed represent incomplete and imprecise data, i.e., that most of them are known through linguistic descriptions, and that in previous research Fuzzy theory was used (which gave good output results with this type of data (Rashid et al, 2023; Bozanić et al, 2018; Setiadji et al, 2020; Wang et al, 2024)), the authors in this paper also decided to use methods that were improved using Fuzzy theory. The model formed and used in this paper includes relevant MCDM methods for defining the weighting coefficients of the criteria Fuzzy DIBR (Defining Interrelationships Between Ranked) and the Fuzzy DIBR II, based on expert opinions, with the DEXi decision support system (used to form linguistic descriptors for qualitative criteria), as well as the Fuzzy LMAW (Logarithm Methodology of Additive Weights) method for determining the optimal location from a set of possible solutions in conditions of imprecise and incomplete input parameters. The EWAA

(Einstein Weighted Arithmetic Average) operator was used for the aggregation of expert opinions, while the BM (Bonferoni Mean) operator was used for the aggregation of weighting coefficients obtained by different methods (Fuzzy DIBR and Fuzzy DIBR II). The validity of the proposed methodology was tested by experts in this field. In order to check the stability and validity of the proposed model, a sensitivity analysis of the output results of the proposed methodological procedure was performed, as well as a comparison of the obtained results with the results obtained using six other fuzzy MCDM methods. The reasons for the formation of such a multi-criteria model are reflected in the following: considering that experts are not always completely sure of their claims, the degree of confidence of the experts was used to form a triangular fuzzy number, which, by reducing the expert's confidence in the statement, blurs the fuzzy number and reduces its crisp value; in order to obtain more precise values of the weights of the criteria, two methods were used to determine the weights, which use different scales to define the relationship between the criteria; and when defining the weights, the competences of the experts were also taken into account using the EWAA operator. The reasons for applying Fuzzy theory have been previously explained. In Figure 1, the algorithm of the proposed methodology is presented.

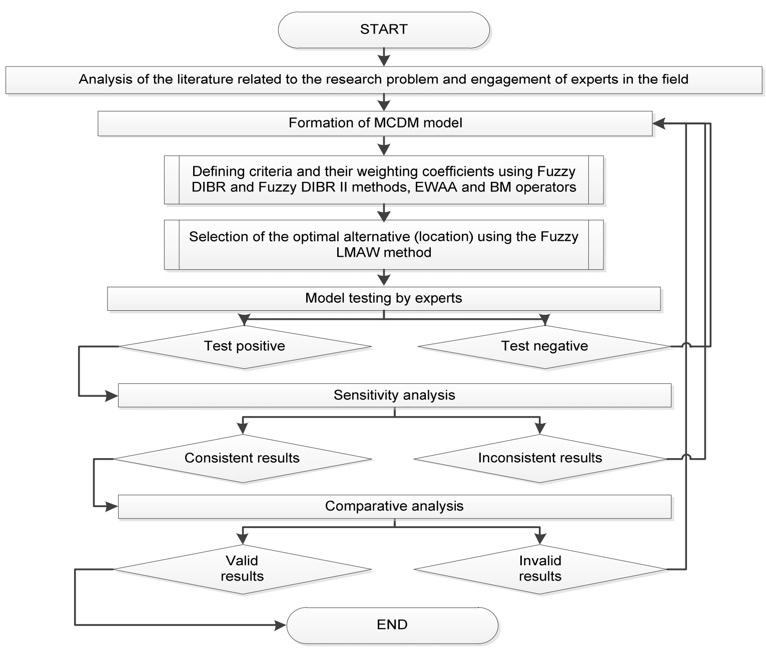

Figure 1 – Algorithm of the proposed MCDM methodology

Description of the methods

So far, various MCDM methods have been developed, both for determining the weighting coefficients of the criteria and for the calculation of the optimal alternative; they have been used in numerous areas to solve various decision-making problems. For the purpose of this research, DIBR, DIBR II, and LMAW methods were used, improved by triangular fuzzy numbers formed using degrees of confidence.

More about Fuzzy theory and numbers can be seen in (Zadeh, 1965; Zadeh, 1973; Pathinathan et al, 2015). Figure 2 shows an example of a triangular fuzzy number based on the degree of confidence of the decision maker in the given statement (Tešić et al, 2024).

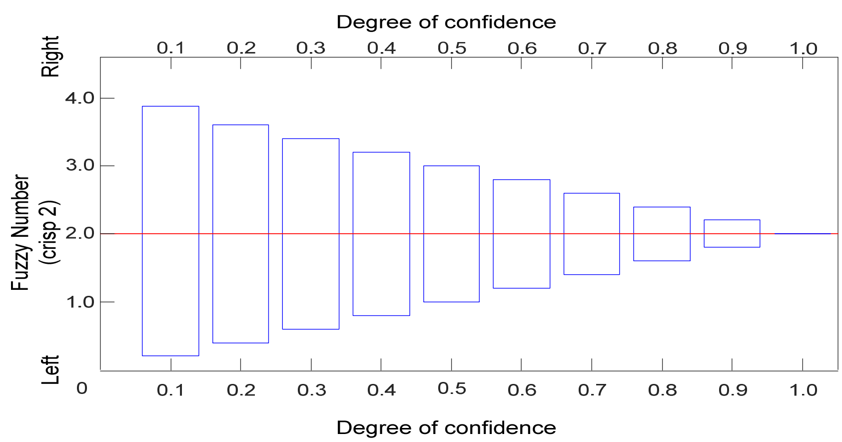

Figure 2 – Example of a triangular fuzzy number based on the degree of confidence of the decision maker

Fuzzy DIBR

The DIBR method (Pamucar et al, 2021a), with its simple mathematical apparatus, is intended for the calculation of weighting coefficients of criteria. In order to apply this method to imprecise and incomplete data, it was improved using triangular fuzzy numbers (Pamucar et al, 2022).

Figure 3 shows the steps of applying the method.

```
# Step 1: Ranking criteria by importance
IF there exists a set of criteria  and criterion is chosen as most importance THEN
    Rank the other criteria  in set C by importance so that criterion is at the first place.
ENDIF

# Step 2: Comparing criteria by importance and defining mutual relationships
FOR each criterion in set C DO
    FOR each other criterion in set C DO
        IF is not equal to THEN
            Enter the value of relationship
            # Ratio values are triangular fuzzy numbers.
        ENDIF
    ENDFOR
ENDFOR

# Step 3: Defining relations for calculating weight coefficients
FOR each criterion in set C DO
    Define relations for calculating weight coefficients of criteria based on defined relationships  and
ENDFOR

# Step 4: Calculating the weight coefficient of the most influential criterion
Calculate the weight coefficient for criterion based on defined relationships
            # The values of the weight coefficients of the criteria are triangular fuzzy numbers

Calculate the weight coefficients for other criteria ( to ) based on defined relationships

Calculate the crisp value of weight coefficients and and

# Step 5: Defining the degree of satisfaction of subjective relationships between criteria
FOR  and  DO
    Calculate
        IF Difference between and is less than 10% THEN
            Print "Relationship between criteria is satisfied."
        ELSE
            Print "Relationship between criteria is not satisfied."
            # It is necessary to define new relationships between the criteria in order to satisfy the stated condition.
        ENDIF
ENDFOR
```

Figure 3 – Pseudocode of the Fuzzy DIBR method

Fuzzy DIBR II

The DIBR II method (Božanić & Pamučar, 2023) represents an improved DIBR method, based on a small number of pairwise comparisons, and has so far found application in various research areas. The method is additionally improved by Fuzzy theory (Tešić et al, 2024), and the steps of the method are presented in Figure 4.

```
# Step 1: Identification of the criteria
Identify_criteria_C(m)  # Where m is the total number of criteria
Print "C(m)"

# Step 2: Determining the importance of each identified criterion
IF there exists a set of criteria C(m)  and criterion is chosen as most importance THEN
   Rank the other criteria  in set C(m)  by importance so that criterion is at the first place.

# Step 3: Defining the relationship between criteria
   FOR each criterion DO
      FOR each criterion DO
         IF is not equal to THEN
            Determine_degree_of_confidence( )
            IF Degree_of_confidence satisfies condition  THEN
               Define_relationship_between_criteria() based on
            ENDIF
         ENDIF
      ENDFOR
   ENDFOR

# Step 4: Defining the relationship between the most significant and other criteria
Define_relationship_between_most_significant_and_other_criteria():

# Step 5: Determination of the value of the weight coefficient of the most significant criterion
Determine_weight_coefficient_of_most_significant_criterion():
# The values of the weight coefficients of the criterion is triangular fuzzy number


# Step 6: Determination of the value of the weight coefficient of the other criteria
# The values of the weight coefficients of the criteria are triangular fuzzy numbers
Determine_weight_coefficient_of_other_criteria( to )

# Step 7: Defuzzification of the value of the weight coefficient of the criteria
Defuzzify_weight_coefficient_of_criteria():

# Step 8: Determining the quality of the relationship between the criteria
Determine_quality_of_relationship_between_criteria():
   Calculate_deviation_values()  # Using Equation
   Calculate_control_value()  # Using Equation
   IF Deviation_values satisfy condition  THEN
      Print "Relationship quality between criteria is satisfactory."
   ELSE
      Print "Relationship quality between criteria is not satisfactory."
       # It is necessary to define new relationships between the criteria in order to satisfy the stated condition.
   ENDIF
```

Figure 4 – Pseudocode of the Fuzzy DIBR II method

Aggregation operators

For aggregating expert opinions, the EWAA operator, presented in (Tešić & Božanić, 2023), was used. The mathematical expression of the operator is presented by expression (1).

$$EWAA\left\{\chi_1,\chi_2,...,\chi_j\right\}=\sum_{j=1}^{e}\chi_j^e\,\frac{\prod_{j=1}^{e}(1+f(\chi_j^e))^{\lambda}-\prod_{j=1}^{e}(1-f(\chi_j^e))^{\lambda}}{\prod_{j=1}^{e}(1+f(\chi_j^e))^{\lambda}+\prod_{j=1}^{e}(1-f(\chi_j^e))^{\lambda}} \tag{1}$$

where e is the total number of experts, $\lambda = 1/e$ when all experts have the same competence coefficient, and $\lambda = \omega^e$ when the competences of the experts are different (ω^e).

The BM operator was used to aggregate the obtained values of the weighting coefficients of the criteria using the Fuzzy DIBR and Fuzzy DIBR II methods and to obtain the final criteria weights (Bonferroni, 1950; Tešić & Božanić, 2023), and its mathematical formulation is presented by expression (2).

$$BM^{r,s}(x_1, x_1, ..., x_n) = \left(\frac{1}{n(n-1)} \sum_{i,j=1}^{n} x_i^r x_j^s \right)^{\frac{1}{r+s}} \tag{2}$$

Fuzzy LMAW

Pamučar et al. (2021b) presented the LMAW method in 2021. It has a dual purpose: 1) determining the weighting coefficients of the criteria, and 2) calculating the optimal alternative. Like the previous methods, this method has been improved using triangular fuzzy numbers and applied in various research areas (Tešić et al, 2023). The mathematical apparatus of the Fuzzy LMAW method for determining the weights of the criteria is presented in the following text.

Step 1: Formation of the initial decision matrix ($\tilde{X} = \left[\tilde{x}_{ij} \right]_{mxn}$)

Step 2. Normalization of the elements of the initial decision matrix ($\tilde{N} = \left[\tilde{n}_{ij} \right]_{mxn}$)

$$\tilde{n}_{ij} = \begin{cases} \left\{ 1 + \dfrac{\tilde{x}_{ij}}{\tilde{x}_j^{(+)}} = \left(1 + \dfrac{x_{ij}^{(l)}}{\tilde{x}_j^{(+)}}, 1 + \dfrac{x_{ij}^{(s)}}{\tilde{x}_j^{(+)}}, 1 + \dfrac{x_{ij}^{(d)}}{\tilde{x}_j^{(+)}} \right) \right. & if \ \ j \in Benefit, \\ \left\{ 1 + \dfrac{\tilde{x}_j^{(-)}}{\tilde{x}_{ij}} = \left(1 + \dfrac{x_j^{(-)}}{x_{ij}^{(d)}}, 1 + \dfrac{x_j^{(-)}}{x_{ij}^{(s)}}, 1 + \dfrac{x_j^{(-)}}{x_{ij}^{(l)}} \right) \right. & if \ \ j \in \mathrm{Cos}t \end{cases} \tag{3}$$

where $\tilde{n}_{ij}$ represents the normalized values of the initial decision matrix, $x_j^{(+)} = \max(x_j^{(d)})$, and $x_j^{(-)} = \min(x_j^{(l)})$, *l* represents the left, *d*- on the right is the distribution of the fuzzy number, and *s* is the value where the membership function of the fuzzy number is equal to 1.

Step 3. Calculation of the weighted matrix ($\tilde{Z} = \left[\tilde{z}_{ij} \right]_{mxn}$).

$$\tilde{z}_{ij} = \frac{2\tilde{\tau}_{ij}^{w_j}}{(2-\tilde{\tau}_{ij})^{w_j} + \tilde{\tau}_{ij}^{w_j}} = \left(\frac{2\tau_j^{(l)^{w_j}}}{(2-\tau_j^{(d)})^{w_j} + \tau_j^{(d)^{w_j}}}, \frac{2\tau_j^{(s)^{w_j}}}{(2-\tau_j^{(s)})^{w_j} + \tau_j^{(s)^{w_j}}}, \frac{2\tau_j^{(d)^{w_j}}}{(2-\tau_j^{(l)})^{w_j} + \tau_j^{(l)^{w_j}}} \right) \quad (4)$$

where $$\tilde{\tau}_{ij} = \frac{\ln(\tilde{n}_{ij})}{\ln(\prod_{i=1}^{m} \tilde{n}_{ij}} = \left(\frac{\ln(n_{ij}^{(l)})}{\ln(\prod_{i=1}^{m} n_{ij}^{(d)}}, \frac{\ln(n_{ij}^{(s)})}{\ln(\prod_{i=1}^{m} n_{ij}^{(s)}}, \frac{\ln(n_{ij}^{(d)})}{\ln(\prod_{i=1}^{m} n_{ij}^{(l)}} \right) \quad (5)$$

Step 4. Calculation of the final index for ranking the alternatives ($\tilde{Q}_i$)

$$\tilde{Q}_i = \sum_{j=1}^{n} \tilde{\tau}_{ij} = \left(\sum_{j=1}^{n} \tau_{ij}^{(l)}, \sum_{j=1}^{n} \tau_{ij}^{(s)}, \sum_{j=1}^{n} \tau_{ij}^{(d)} \right)$$

(6)

The ranking of the alternatives is formed on the basis of defuzzificated index values (Q_i), i.e., a higher value of the index of the alternative implies a higher rank and vice versa.

Application of the MCDM model

For the purpose of this research, 26 experts in this particular field were engaged. The experts were sent a questionnaire to identify the criteria that influence the choice of a location for crossing a water obstacle by fording in a defense operation. After applying the Delphi method and processing the obtained data, the opinions of four experts were rejected due to a large deviation from the opinion of the expert group, so that in the end 22 experts were engaged in the entire research process, i.e. $E \in \{E_1, E_2, ..., E_{22}\}$, and, by applying the methodology presented in Tešić & Božanić (2024), their competencies were defined

$$E_{\omega} \in \left\{ \begin{matrix} 0.0484, 0.0535, 0.0365, 0.0439, 0.038, 0.0375, 0.0424, 0.043, 0.0388, 0.0372, 0.0364, \\ 0.0375, 0.0498, 0.0579, 0.0554, 0.0536, 0.0496, 0.0492, 0.0417, 0.0444, 0.0529, 0.0526 \end{matrix} \right\}$$

Based on expert opinions, a total of 13 criteria affecting the location choice $C \in \{C_1, C_2, ..., C_{13}\}$ were identified (Table 1).

After defining the criteria, each of the experts defined the ranking of the criteria in accordance with their significance and the relationships between the criteria, as well as their degree of confidence.

Table 1 – Criteria that affect the choice of a fording location

Criterion	Criterion type	
	Benefit/Cost	Numerical/ Linguistic
C_1 - Quality of access routes on both banks	Benefit	Linguistic
C_2 - Scope of works on the entry and exit banks	Cost	Linguistic
C_3 - Water obstacle width (m)	Cost	Numerical
C_4 - Water obstacle depth (m)	Cost	Numerical
C_5 - Water current speed (m/sec)	Cost	Numerical
C_6 - Composition of the water obstacle bed	Benefit	Linguistic
C_7 - Camouflage conditions	Benefit	Linguistic
C_8 –Vulnerability of the crossing point to the enemy attacks	Cost	Linguistic
C_9 - Natural and man-made obstructions in and along the water obstacle	Benefit	Linguistic
C_{10} - Conditions for bank preparations	Benefit	Linguistic
C_{11} - Existence of local material sites, resources and workshops (industrial plants)	Benefit	Linguistic
C_{12} - Water level change tendency	Benefit	Linguistic
C_{13} - Possibility of deploying tanks for action and maneuvering on the exit bank	Benefit	Linguistic

By applying the steps of the Fuzzy DIBR method (Figure 3) and the Fuzzy DIBR II method (Figure 4), for each of the experts, aggregation was performed using the EWAA operator, expression (1), and the coefficients of the expert competences, which resulted in the criteria weight values for each method (Table 2).

Table 2 – Aggregated values of the criteria weights for each of the methods

	C_1	**C_2**	**C_3**	**C_4**	**C_5**	**C_6**	**C_7**
Fuzzy DIBR	0.0438	0.0410	0.1219	0.1741	0.1462	0.1417	0.0440
Fuzzy DIBR II	0.0429	0.0396	0.1199	0.1846	0.1511	0.1431	0.0407
	C_8	**C_9**	**C_{10}**	**C_{11}**	**C_{12}**	**C_{13}**	
Fuzzy DIBR	0.0906	0.0345	0.0271	0.0179	0.0552	0.0620	
Fuzzy DIBR II	0.0905	0.0337	0.0263	0.0162	0.0564	0.0550	

In order to arrive at the final values of the weighting coefficients of the criteria using the BM operator, expression (2), the data from Table 2, i.e., the weights of each of the criteria for both methods are aggregated. The final values of the criteria weights are presented in Table 3 and represent the input data for the initial decision matrix.

Table 3 – Final values of the criteria weights

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
w	0.0434	0.0403	0.1209	0.1793	0.1487	0.1424	0.0423
	C_8	**C_9**	**C_{10}**	**C_{11}**	**C_{12}**	**C_{13}**	**C_8**
w	0.0906	0.0341	0.0267	0.0170	0.0558	0.0584	0.0906

In order to choose the optimal location for crossing a water obstacle by fording in a defense operation, it is necessary to evaluate the defined alternatives in accordance with each identified criterion. The evaluation for the linguistic type criteria is performed using Fuzzy linguistic descriptors, presented in Table 4.

Table 4 – Fuzzy linguistic criteria descriptors

Linguistic descriptors for criterion C_{10}		Linguistic descriptors for criterion C_{13}	
Description of the linguistic descriptor	**Scale value**	**Description of the linguistic descriptor**	**Scale value**
Excellent (OD)	(8, 9, 10)	Favorable conditions (PU)	(8, 9, 10)
Very Good (VD)	(5, 6, 7)	Partially favorable conditions (SP)	(5, 6, 7)
Good (DO)	(3, 4, 5)	Partially adverse conditions (DN)	(2, 3, 4)
Sufficient (DV)	(1, 2, 3)	Unfavorable conditions (NU)	(1, 1, 1)
Insufficient (NDV)	(1, 1, 1)		
Linguistic descriptors for criterion C_9		**Linguistic descriptors for criterion C_{12}**	
Description of the linguistic descriptor	**Scale value**	**Description of the linguistic descriptor**	**Scale value**
Positive impact (P)	(8, 9, 10)	Favorable Trend (PT)	(8, 9, 10)
Partial positive impact (PD)	(5, 6, 7)	Partially Favorable Trend (DPT)	(5, 6, 7)
Partially negative impact (ND)	(2, 3, 4)	Partially Unfavorable Trend (DNT)	(2, 3, 4)
Negative impact (N)	(1, 1, 1)	Unfavorable Trend (NT)	(1, 1, 1)

Linguistic descriptors for criterion C_7		Linguistic descriptors for criterion C_1	
Description of the linguistic descriptor	**Scale value**	**Description of the linguistic descriptor**	**Scale value**
Excellent (O)	(8, 9, 10)	Excellent (OD)	(8, 9, 10)
Very good (V)	(5, 6, 7)	Very Good (VD)	(5, 6, 7)
Good (D)	(3, 4, 5)	Good (DO)	(3, 4, 5)
Satisfactory (Z)	(1, 2, 3)	Sufficient (DV)	(1, 2, 3)
Unsatisfactory (NZ)	(1, 1, 1)	Insufficient (ND)	(1, 1, 1)
Linguistic descriptors for criterion C_6		Linguistic descriptors for criterion C_8	
Description of the linguistic descriptor	**Scale value**	**Description of the linguistic descriptor**	**Scale value**
The bottom of the water obstacle has sufficient bearing capacity and is flat (DDR)	(8, 9, 10)	Very Large (VV)	(8, 9, 10)
The bottom of the water obstacle has sufficient bearing capacity, but it is not flat (DDN)	(5, 6, 7)	Large (VE)	(5, 6, 7)
The bottom of the water obstacle does not have sufficient load-bearing capacity (the load-bearing capacity can be increased), but it is flat (DNR)	(3, 4, 5)	Middle (SR)	(3, 4, 5)
The bottom of the water obstacle does not have sufficient load-bearing capacity (the load-bearing capacity can be increased) and is not flat (DMN)	(1, 2, 3)	Small (MA)	(1, 2, 3)
The bottom of the water obstacle does not have sufficient load capacity (the load capacity cannot be increased) and is not flat (DNN)	(1, 1, 1)	Does not exist (NP)	(1, 1, 1)
Linguistic descriptors for criterion C_{11}		Linguistic descriptors for criterion C_2	
Description of the linguistic descriptor	**Scale value**	**Description of the linguistic descriptor**	**Scale value**
Exist (P)	(6, 8, 10)	Big (VEL)	(6, 8, 10)
Partially Exist (DP)	(2, 4, 6)	Medium (SRE)	(2, 4, 6)
Non Existant (NPo)	(1, 1, 1)	Small (MAL)	(1, 1, 2)

To determine the linguistic descriptor, for the purposes of this research, the DEXi decision support system (Bohanec, 2023), based on the DEX methodology (Bohanec et al, 2013), was used. The DEXi uses a system of logical rules to make decisions. Each linguistic descriptor is broken down into several criteria and sub-criteria and depending on the logical rules, its value is determined.

Based on all the above, an initial decision-making matrix was formed. It consists of five alternatives $A \in \{A_1, A_2, ..., A_5\}$ and 13 criteria (Table 1), previously identified by experts (Table 5).

Table 5 – Initial decision matrix

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
A1	DO	SRE	60	1.1	0.8	DDR	D
A2	DV	SRE	55	1.1	0.9	DNR	O
A3	DV	MAL	58	1.2	0.8	DDN	NZ
A4	ND	SRE	51	1	2	DDR	Z
A5	ND	MAL	60	0.9	2.1	DDN	D
	C8	**C9**	**C10**	**C11**	**C12**	**C13**	
A1	VV	ND	DO	DP	DPT	PU	
A2	VE	ND	NDV	DP	PT	PU	
A3	VE	N	VD	NPo	DNT	DP	
A4	VV	N	DV	DP	DPT	DN	
A5	SR	ND	NDV	P	PT	PD	

The initial decision matrix (Table 5), using fuzzy linguistic descriptors (Table 4), is translated into the Fuzzy initial decision matrix (Table 6).

Table 6 – Fuzzy initial decision matrix

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
A1	(3, 4, 5)	(2, 4, 6)	(60, 60, 60)	(1.1, 1.1, 1.1)	(0.8, 0.8, 0.8)	(8, 9, 10)	(3, 4, 5)
A2	(1, 2, 3)	(2, 4, 6)	(55, 55, 55)	(1.1, 1.1, 1.1)	(0.9, 0.9, 0.9)	(3, 4, 5)	(8, 9, 10)
A3	(1, 2, 3)	(1, 1, 2)	(58, 58, 58)	(1.2, 1.2, 1.2)	(0.8, 0.8, 0.8)	(5, 6, 7)	(1, 1, 1)
A4	(1, 1, 1)	(2, 4, 6)	(51, 51, 51)	(1, 1, 1)	(2, 2, 2)	(8, 9, 10)	(1, 1, 1)
A5	(1, 1, 1)	(1, 1, 2)	(60, 60, 60)	(0.9, 0.9, 0.9)	(2.1, 2.1, 2.1)	(5, 6, 7)	(3, 4, 5)
	C8	**C9**	**C10**	**C11**	**C12**	**C13**	
A1	(8, 9, 10)	(2, 3, 4)	(3, 4, 5)	(2, 4, 6)	(5, 6, 7)	(8, 9, 10)	

A_2	(5, 6, 7)	(2, 3, 4)	(1, 1, 1)	(2, 4, 6)	(8, 9, 10)	(8, 9, 10)
A_3	(5, 6, 7)	(1, 1, 1)	(5, 6, 7)	(1, 1, 1)	(2, 3, 4)	(5, 6, 7)
A_4	(8, 9, 10)	(1, 1, 1)	(1, 2, 3)	(2, 4, 6)	(5, 6, 7)	(2, 3, 4)
A_5	(3, 4, 5)	(2, 3, 4)	(1, 1, 1)	(6, 8, 10)	(8, 9, 10)	(5, 6, 7)

The formation of the initial decision matrix represents the first step in the application of the Fuzzy LMAW method. After the other steps of the method, expressions from (3) to (6), have been applied, the final ranking indices are defined for each of the alternatives, and, by dephasing the specified values, the final rankings of the alternatives are obtained (Table 7).

Table 7 – Values of the final index (Q) and the ranking of the alternatives

Alternative	$\tilde{Q}_i$	Q_i	Rank
A_1	(11.71, 11.95, 12.21)	11.950	**1**
A_2	(11.64, 11.9, 12.18)	11.907	**2**
A_3	(11.63, 11.87, 12.11)	11.866	**4**
A_4	(11.56, 11.79, 12.04)	11.797	**5**
A_5	(11.67, 11.9, 12.13)	11.898	**3**

In order to validate the obtained results, the experts were asked to rank the alternatives (Table 8) based on the initial decision matrix (Table 5).

Table 8 – Ranking alternatives based on the expert opinions

	A_1	A_2	A_3	A_4	A_5		A_1	A_2	A_3	A_4	A_5
E1	2	1	4	5	3	**E12**	1	4	2	3	5
E2	1	2	5	4	3	**E13**	2	1	4	5	3
E3	1	3	2	5	4	**E14**	2	1	3	5	4
E4	2	1	5	4	3	**E15**	1	2	4	5	3
E5	3	2	1	4	5	**E16**	1	2	4	5	3
E6	1	5	3	2	4	**E17**	1	2	5	4	3
E7	1	2	4	5	3	**E18**	1	2	4	5	3
E8	1	2	4	5	3	**E19**	1	2	4	5	3
E9	2	1	4	5	3	**E20**	1	2	4	5	3
E10	1	2	5	4	3	**E21**	1	2	4	5	3
E11	1	3	2	5	4	**E22**	1	3	2	5	4

Given that there is a consensus of expert opinions (Tešić & Božanić, 2024), the ranks were aggregated using the EWAA operator and the final ranking of the alternatives was obtained by the experts (Table 9).

Table 9 – Final ranking of the alternatives based on the expert opinions

Alternative	EWAA	Rank
A_1	1.286692	1
A_2	2.058976	2
A_3	3.778465	4
A_4	4.528116	5
A_5	3.350265	3

Based on the ranks obtained by expert evaluation, it can be concluded that the proposed methodology is valid, i.e., that it gives correct results.

Sensitivity analysis

In order to check the stability of the model to changes in the weighting coefficients of the criteria, 40 different change scenarios were formed (Figure 5).

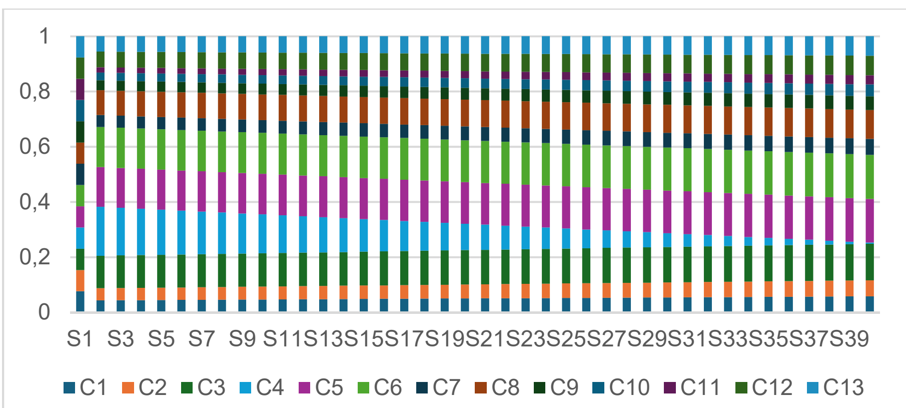

Figure 5 – Scenarios of changes in criteria weights

Applying the mentioned scenarios in the Fuzzy LMAW method leads to the following results (Figure 6):

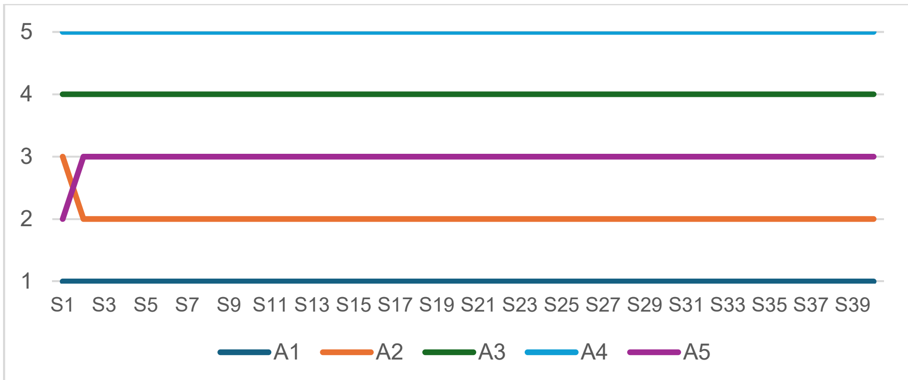

Figure 6 – Rankings of the alternatives obtained by applying scenarios

As it can be seen from the previous figure, the methodology used in this research produces very consistent results. The first-ranked alternative A_1 was chosen as optimal in all cases, while the last-ranked alternative was in the last place in all cases. Also, it can be stated that the ranking of alternatives A_5 and A_2 changes slightly in the scenario S1, i.e., in the case when all criteria have equal weights.

Comparative analysis

In order to validate the model, the obtained results were compared with the results obtained by the Fuzzy WASPAS (Weighted Aggregated Sum Product Assessment) (Turskis et al, 2015), Fuzzy VIKOR (VIšekriterijumsko KOmpromisno Rangiranje) (Chang, 2014), Fuzzy SAW (Simple Additive Weighting) (Roszkowska & Kacprzak, 2016), Fuzzy MABAC (Multi-Attributive Border Approximation Area Comparison) (Bozanić et al, 2018), Fuzzy COPRAS (Complex Proportional Assessment) (Zarbakhshnia et al, 2018) and Fuzzy CoCoSo (Combined Compromise Solution) (Fernández-Portillo et al, 2023) methods. As it can be concluded from the obtained results shown in Figure 7, the alternative A_1 is ranked first in all methods. Also, in Figure 8, it can be seen that the Pearson correlation coefficient of the ranks (Rodgers & Nicewander, 1988) obtained by the mentioned methods, in relation to the Fuzzy LMAW method, tends to an ideal positive correlation.

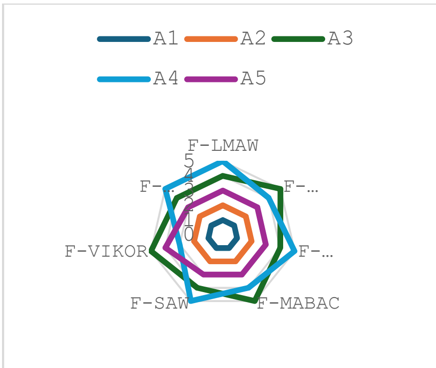

Figure 7 – Rankings of the alternatives obtained by different methods

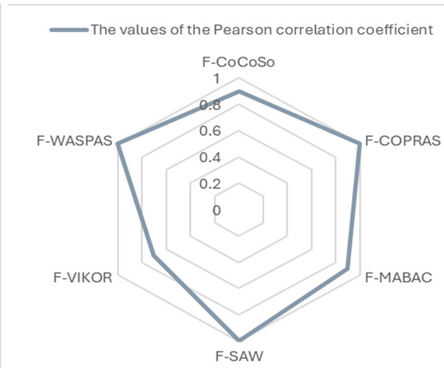

Figure 8 – The values of the Pearson correlation coefficient of the obtained ranks

Conclusion

In this research, a model was developed for the selection of a location for fording a water obstacle in a defense operation using MCDM methods, i.e., the Fuzzy DIBR-Fuzzy DIBR II-EWAA-BM-Fuzzy LMAW model. The proposed model represents significant progress in the field of overcoming water obstacles and decision making, enabling more accurate and efficient decisions in choosing a site to cross a water obstacle in conditions of uncertainty and inaccuracy, in a defense operation. The application of the Fuzzy DIBR and Fuzzy DIBR II methods, which are based on expert opinions and use the DEXi decision system, allows the inclusion of imprecision in the decision process, which is of extreme importance in the context of defense operations where information is usually incomplete or unclear. At the same time, the application of the Fuzzy LMAW method contributes to the determination of the optimal location in conditions of uncertainty in the input parameters. The use of the EWAA and BM operators for the aggregation of expert opinions and weighting coefficients implies the importance of taking into account different aspects in decision making. This approach provides a complex evaluation of various criteria and aspects that influence the choice of location.

The validity of the proposed methodology was confirmed by expert testing, which guarantees the relevance and applicability of the model in real situations. Additionally, the performed sensitivity analysis and a comparison with other MCDM methods confirm the stability and validity of the proposed model.

The developed model represents a significant contribution to the field of military decision making and provides necessary assistance to less experienced officers. Its application can significantly improve the selection of the location for fording water obstacles, which is crucial for the successful execution of defense operations. The main innovation in this research is the introduction of MCDM methods and DEXi software in this area, specifically in solving this problem, as well as comprehensively defining the criteria that condition the subject choice. Practical application is reflected in clearly defined criteria and the MCDM model that can easily be converted into an application, the use of which will be adjusted to the user.

This research opens up new opportunities for further research and applications of other theories that deal well with inaccuracies and uncertainties, as well as the development of application software for wider use. Also, the proposed methodology can be used for any research problem, with the definition of new criteria and new decision models in DEXi software.The main limitations of this research are related to the subject of the research itself; namely, the criteria that have been defined refer exclusively to deciding on a location in a defense operation while for other types of operations it would be necessary to redefine the criteria.

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Aplicación de la toma de decisiones multicriterio para la selección de un lugar para cruzar un obstáculo de agua mediante vadeo en una operación de defensa

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CAMPO: matemáticas aplicadas, ciencias militares
TIPO DE ARTÍCULO: artículo científico original

Resumen:

Introducción/objetivo: El artículo presenta el modelo multicriterio Fuzzy DIBR-Fuzzy DIBR II-EWAA-BM-DEXi-Fuzzy LMAW para elegir una ubicación para cruzar obstáculos de agua al vadear en una operación de defensa. Luego de la identificación de los criterios por parte de expertos en este campo, se aplicó el modelo mencionado y se determinó el punto óptimo. Para comprobar la consistencia de los resultados y la validez del modelo, se consultó nuevamente a expertos y se realizaron análisis de sensibilidad y análisis comparativo.

Métodos: Se utilizaron los métodos Fuzzy DIBR y Fuzzy DIBR II para determinar los coeficientes de ponderación de los criterios identificados, mientras que la agrupacion de las opiniones de los expertos y los valores obtenidos se realizó utilizando los operadores EWAA y BM. Para seleccionar la ubicación óptima se aplicó el método Fuzzy LMAW, mientras que los descriptores lingüísticos se determinaron mediante el sistema de soporte a la decisión DEXi.

Resultados: La metodología propuesta permitió identificar todos los criterios que determinan la elección de una ubicación y la elección del punto óptimo para cruzar un obstáculo de agua en una operación de defensa. La prueba del modelo por parte de expertos, el análisis de la sensibilidad de los resultados de salida a los cambios en los pesos de los criterios y la comparación de los resultados obtenidos con los resultados de otros métodos indicaron el hecho de que el modelo es válido y que proporciona resultados consistentes.

Conclusión: Se concluyó que el modelo multicriterio brinda la ayuda necesaria a los tomadores de decisiones en condiciones de información imprecisa y no especificada y que es aplicable en situaciones reales. Además, el modelo propuesto toma en consideración todos los aspectos que deben considerarse al tomar una decisión tan compleja y ayuda a los *oficiales menos experimentados en el proceso de toma de decisiones, reduciendo la posibilidad de errores que pueden resultar en víctimas humanas. Finalmente, se sugieren direcciones para futuras investigaciones en el campo de la superación de los obstáculos del agua y la toma de decisiones multicriterio.*

Palabras claves: vadeo, ubicación, selección, militar, MCDM, DIBR, DIBR II, Fuzzy, LMAW, EWAA, BM, DEXi

Применение многокритериального принятия решений для выбора места преодоления водного препятствия вброд в ходе оборонительной операции

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ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: В данной статье представлена многокритериальная модель Fuzzy DIBR-Fuzzy DIBR II-EWAA-BM-DEXi-Fuzzy LMAW для выбора места преодоления водных преград вброд в ходе оборонительной операции. После определения критериев экспертами в данной области была применена упомянутая модель и определено оптимальное место. Для проверки согласованности результатов и достоверности модели были проведены повторные консультации с экспертами, а также анализ чувствительности и сравнительный анализ.

Методы: Для определения весовых коэффициентов выявленных критериев использовались методы Fuzzy DIBR и Fuzzy DIBR II, а агрегирование мнений экспертов и полученных значений осуществлялось с помощью операторов EWAA и BM. Для выбора оптимального местоположения применялся метод Fuzzy LMAW, а лингвистические дескрипторы определялись с помощью системы поддержки принятия решений DEXi.

Результаты: Предложенная методология позволила выявить все критерии, обуславливающие выбор местоположения и сам выбор оптимального места для преодоления водной преграды *вброд в ходе оборонительной операции. Тестирование модели экспертами, анализ чувствительности выходных результатов к изменению весов критериев и сравнение полученных результатов с результатами других методов показали, что модель надежна и результативна.*

Выводы: На основании результатов исследования сделан вывод, что многокритериальная модель оказывает необходимую помощь лицам, принимающим решения в условиях неточной и неопределенной информации, и что она применима в реальных ситуациях. Также предложенная модель учитывает все аспекты, которые необходимо иметь в виду при принятии столь сложного решения. Помимо того, она помогает менее опытным командирам в процессе принятия решения, снижая вероятность ошибок, которые могут привести к человеческим жертвам. В заключение предложены направления дальнейших исследований в области преодоления водных препятствий и многокритериального принятия решений.

Ключевые слова: брод, локация, выбор, армия, многокритериальное принятие решений, DIBR, DIBR II, Fuzzy, LMAW, EWAA, BM, DEXi.

Примена вишекритеријумског одлучивања за избор локације за савлађавање водене препреке газом у одбрамбеној операцији

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КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: У раду је приказан вишекритеријумски модел Fuzzy DIBR-Fuzzy DIBR II-EWAA-BM-DEXi-Fuzzy LMAW помоћу којег се врши избор локације за савлађивање водених препрека газом у одбрамбеној операцији. Након идентификације критеријума од стране експерата, примењен је наведени модел и одређена је оптимална локација. Ради тестирања конзистентности *резултата и валидности модела, поново су ангажовани експерти, извршена је анализа осетљивости и компаративна анализа.*

Методе: Методе Fuzzy DIBR и Fuzzy DIBR II коришћене су за одређивање тежинских коефицијената идентификованих критеријума, док је агрегација експертских мишљења и добијених вредности вршена помоћу EWAA и BM оператора. За избор оптималне локације примењена је метода Fuzzy LMAW, док су лингвистички дескриптори одређивани помоћу DEXi система за подршку одлучивању.

Резултати: Предложена методологија омогућила је идентификацију свих критеријума који условљавају избор локације и сам избор оптималне локације за прелазак газом преко водене препреке у одбрамбеној операцији. Тестирањем модела, анализом осетљивости излазних резултата на промене тежина критеријума и поређењем добијених резултата са резултатима других метода, указано је на чињеницу да је модел валидан и да даје конзистентне резултате.

Закључак: Закључено је да вишекритеријумски модел пружа неопходну помоћ доносиоцима одлука у условима непрецизних и неодређених информација и да је примењив у реалним ситуацијама. Такође, предложени модел разматра све аспекте које је неопходно сагледати приликом доношења једне комплетне одлуке и помаже мање искусним старешинама у процесу одлучивања, смањујући могућност настанка грешака, које за последицу могу имати и људске жртве. На крају, предложени су правци даљих истраживања из области савлађивања водених препрека и вишекритеријумског одлучивања.

Кључне речи: газ, локација, избор, војска, вишекритеријумско одлучивање, DIBR, DIBR II, Fuzzy, LMAW, EWAA, BM, DEXi.

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