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Optimization of the short-range surface-to-air artillery-missile system design process using the hybridized triangular IT2FS-DEMATEL-MABAC approach

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Abstract:

Introduction/purpose: The possibility of optimizing a short-range surface-to-air artillery- missile (short-range SAAM) system design process by applying the hybridized multi-criteria decision-making (integration of DEMATEL and MABAC methods) approach in the triangular interval type 2 fuzzy environments is shown in the paper. By analyzing the content of the literature, the tactical-technical requirements and sub-requirements were selected. Furthermore, the weights of these requirements and sub-requirements are determined. After that, a multi-criteria decision-making (MCDM) model was created for the evaluation of different initial projects of designing a short-range SAAM, which was also tested in this paper.

Methods: The proposed approach that combine the DEMATEL and MABAC methods have been modified by triangular interval type 2 fuzzy sets (IT2FSs). The triangular IT2F-DEMATEL method was applied to determine the weights of the requirements and sub-requirements, while the triangular IT2FS -MABAC method was applied to evaluate the alternatives – initial project designs of a short-range SAAM.

Results: Integrating the multiple triangular IT2FS-MCDM approach into a unique model that can be applied in the process of defining the optimal initial design project of a short-range SAAM.

Conclusion: The paper contributes to military science in making decisions related to the design of a short-range SAAM.

Keywords: DEMATEL, MABAC, Triangular Interval Type 2 Fuzzy Sets, Short-Range Surface-to-Air Artillery-Missile System.

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Introduction

This paper will rely on the state's ability to design and mostly produce new air defense weapons in its limited qualitative and quantitative capabilities (in terms of population, size of territory, development of the military-industrial complex, GDP, geopolitical influence, etc.). An example of the development of a short-range air defense missile system is given in the paper. This case is possible only in conditions of exponential development of the military-industrial complex and the transfer of technology and knowledge (Petrović & Petrović, 2024). As an initial step in the design of a new, technologically advanced, short-range air defense missile system, the formation of a certain number of tactical and technical requirements and sub-requirements is imposed, which the weapon must meet in order to oppose modern threats from the air space. An example of the evaluation of these requirements is given in order to determine their importance in the formation of requirements and sub-requirements of each requirement for the design of a modern short-range SAAM (Petrović & Petrović, 2024). The research aims to optimize the design process of a short-range SAAM using a hybrid MCDM approach. The specific objective is aimed at improving the accuracy of the decision-making process, handling uncertainty, and optimizing the selection of tactical-technical requirements. Namely, the process of forming requirements for military technical-technological solutions is currently based on normative-legal documents that do not take into account precise scientific validation. The current process is based on a detailed content analysis, a large database of processed data, but scientific methodology is not used when drawing conclusions. Bearing in mind that military organizations are used in partially controlled conditions (in a combat environment they depend on the enemy and other components of the operational environment), it is clear that the selection of requirements for the selection of weapon systems takes place in conditions of uncertainty (military decision making is realized in partially determined and indeterminate conditions). Bearing this in mind, the aforementioned military decision making can be improved by applying fuzzy theory, in this case IT2FSs. Also, decision making in military processes aims to create optimal conditions for the implementation of the decision, based on the proposals of experts from several fields (as is the case when defining the initial requirements for designing a weapon system). This results in the need to improve the decision-making process in order to optimize the decision, which results in the application of MCDM methods.

By analyzing the literature, it was concluded that there are scientific articles that researched this problem or similar research problems. There are also studies relating to the development of the technology of individual elements of weapons systems including anti-aircraft missile systems (Cheng & Mon, 1994; Ding et al, 2018; Jiang et al, 2011). Particularly interesting is the work that deals with the formation of initial requirements for designing a fighter aircraft based on overall evaluation criteria by Mavris & DeLaurentis (1995). The optimization of equipping with a missile system for combat operations using multi-criteria decision-making methods was also investigated in some scientific papers (Tešić & Božanić, 2023; Karadayi et al, 2019; Dağıstanlı, 2025; Dağdeviren et al, 2009). Based on the aforementioned papers, initial tactical and technical requirements were formed in this research, with the help of a group of experts who evaluated them for the needs of optimizing the design of a new short-range air defense missile system. The formed requirements are as follows: spatial capabilities (R1), fire capabilities (R2), time capabilities (R3), forces protection capability (R4), and accessibility and technological reliability (R5) (Petrović & Petrović, 2024). These requirements are further classified into sub-requirements. The spatial capabilities (R1) can be classified into: ability to detect targets (R11), size of the destruction zone of aerodynamic and ballistic targets (R12), RCS of the detected target (R13). The fire capabilities (R2) can be classified into: probability of target destruction (R21), mathematical expectation of the number of destroyed targets (R22), channel by target (R23), channel by missile (R24), and system armament (R25). The time capabilities (R3) can be classified into: fire maneuver (R31), movement maneuver (32), firing cycle (R33), ability to provide ordnance and anti-aircraft rockets (R34), and reaction time (R35). The forces protection capability (R4) can be classified into: frequency agility of autonomous radars (R41), pulse repetition frequency (R42), autonomy in operation of combat platforms (R43), ability of passive sensors (R44), combined guidance (R45), and the ability to protect against continuous interference (JATDS) (R46). The accessibility and technological reliability (R5) can be classified into: investment costs (R51), operating costs (R52), possibility of an "offset" component production (R53), possibility of installation of components of domestic production (R54), and possibility of linking with the existing surface to air assets (R55). The sub-requirements investment costs (R51) and the operating costs (R52) are the cost sub-requirements. Other sub-requirements are benefit sub-requirements. The research is conducted by using multi-criteria decision-making methods (MCDM). The types of MCDM methods used in the research are multiple-attribute decision-making (MADM) methods. MADM involves the selection of the "best" alternative from the pre-specified alternatives described in terms of multiple attributes (Zavadskas et al, 2014; Sabaei et al, 2015). These methods enable the prioritization of a discrete - finite number of requirements and sub-requirements and attributes in hierarchically structured qualitative - quantitative ambiguous (imperfect) problems (Petrović & Milenković, 2024). Bearing in mind that in the work it is necessary to prioritize the final number of requirements and sub-requirements, as well as the ranking of the final number of the alternatives – initial project documentation, the application of hybridized MADM methods is completely approved. For the purpose of determining the mutual influence between the requirements and the sub-requirements, the Decision - Making Trial and Evaluation Laboratory (DEMATEL) method was applied in the paper. The evaluation of the project documentation was performed using the Multi-Attributive Border Approximation area Comparison (MABAC) method. The justification for applying the hybridized DEMATEL-MABAC approach is based on the following facts. Using the DEMATEL method, it is possible to investigate the mutual influence of the requirements and the sub-requirements for choosing the optimal offer for designing a SAAM. Bearing in mind that all the capabilities of a weapon system depend on the mutual influence of its tactical-technical characteristics, as well as on the influence of other factors of the operational environment during combat operations, the application of the DEMATEL method fully ensures the prioritization of the requirements and sub-requirements of the weapon system, such as a SAAM. The MABAC method ensures optimal ranking of the project documentation from a pre-defined number of bidders. Also, this method provides an assessment of the distance of the quantitatively expressed characteristics (requirements and sub-requirements) of the offered project documentation from the boundary approximate areas, which, in addition to the numerical results, enables the visualization of the obtained results. Also, the MABAC method provides a solution to problems where there is a conflict between criteria - requirements, which is also the case when designing a SAAM (for example, increasing the number of target aircraft affects the reduction of the protection of forces from the enemy action). All this results in the DEMATEL-MABAC approach being completely complementary to the research problem.

The research algorithm is shown in Figure 1.

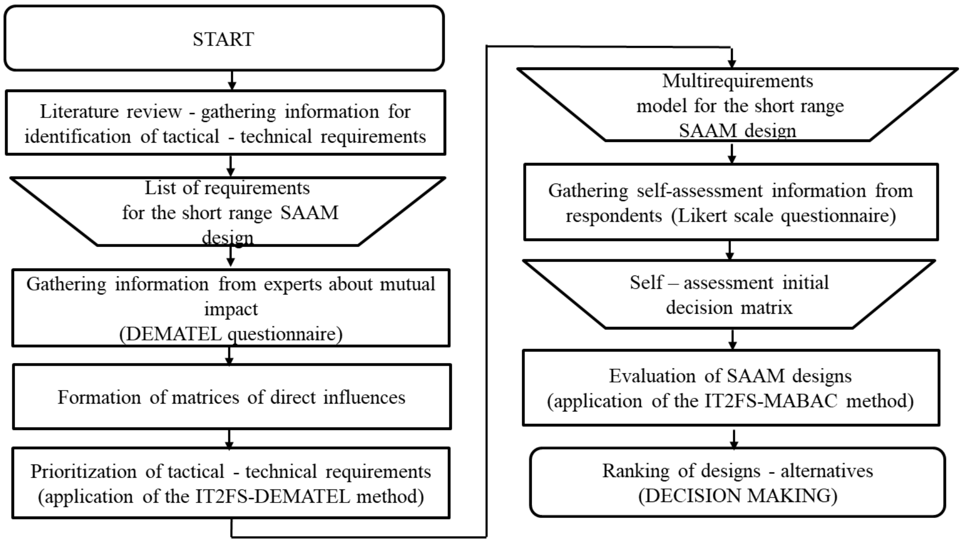

Figure 1 – Algorithm of the research

Background of the methodology

Bearing in mind that type 1 fuzzy sets are not appropriate to model words, T2FSs are developed. This type of fuzzy sets is an extension of type 1 fuzzy sets, and they ensure the use of a linguistic variable in the conditions of linguistic uncertainty (Kahraman et al, 2014). Type-1 fuzzy sets have been applied successfully in many areas including modeling, control, and data mining (Huang et al, 2014). Other types of fuzzy numbers have been developed in fuzzy theory. For example, unlike type 1 fuzzy sets, intuitionistic fuzzy sets take into account more uncertainties in the form of the membership function (membership degree, non-membership degree, and hesitation degree, Deng et al, 2016). However, neither type-1 fuzzy sets nor intuitionistic fuzzy sets represent the optimal choice when making decisions in conditions of uncertainty characterized by the ambiguity of the collected linguistic data. A Type-2 Fuzzy Set (T2FS) is characterized by membership functions, i.e., the membership values for each element of this set. The membership value of a T2FS is a fuzzy set in [0,1], not a crisp number (Huang et al, 2014). The T2FS can express more fuzzy semantics of humans' thoughts, and recently it has attracted the researchers' attention. It has been widely developed and successfully used in many practical real-world applications and many areas, including signal processing, human silhouette extraction, diet application, and pattern recognition design (Huang et al, 2014). Bearing in mind the aforementioned, the use of T2FSs when solving the problem of evaluating the project documentation for designing the short-range SAAM is fully justified. The data, collected for the research purpose, and referring to the determination of the importance of requirements and sub-requirements for the creation of the model, as well as for the evaluation of the initial project documentation, are ambiguous and of a qualitative type. Also, these data reflect the subjective assessment of a small number of respondents. The foregoing implies that decision making takes place in conditions of uncertainty and multi-knowledge, which is the reason why the triangular interval type 2 fuzzy sets (IT2FSs) were applied in the paper. IT2FSs are widely used in solving optimization issues in various fields. For example, Hsien-De Huang et al. (2014) proposed a novel soft-computing mechanism based on the ontology model for malware behavioral analysis by using IT2FSs. Liu et al. (2024) used IT2FSs for the control design of uncertain dynamical systems to relax this limitation of conventional T1FS-based control design. Tekeli et al. (2024) conducted a numerical performance analysis of tank coatings in chemical tankers to contribute to the decision-making process of shipowners and safety professionals by IT2FSs. This type of fuzzy sets ensures the unambiguity of the answers obtained from a small number of corespondents in conditions of uncertainty and increases the reliability of the obtained results. Namely, in contrast to a type-1 fuzzy set, which has the membership grade as a crisp number, an IT2FS has membership functions which are also fuzzy numbers. Whilst type-1 fuzzy sets have membership functions which are two-dimensional, type-2 fuzzy sets are three-dimensional (Baratimehr et al, 2023; Kiracı & Akan, 2020; Uçal Sari et al, 2013). The third dimension provides additional degrees of freedom for possibility in models of uncertainty (Uçal Sari et al, 2013).

The form of the triangular ITFS is (Kahraman et al, 2014):

$$\tilde{\tilde{A}}_i = \left(\tilde{A}_i^U, \tilde{A}_i^L\right) = \left(a_{i1}^U, a_{i2}^U, a_{i3}^U; H\left(\tilde{A}_i^U\right)\right), \left(a_{i1}^L, a_{i2}^L, a_{i3}^L; H\left(\tilde{A}_i^L\right)\right) \tag{1}$$

where:

$H\left(\tilde{A}_i^U\right)$ is the membership value of the element a_{i2}^U in the upper triangular function of the membership, and $H\left(\tilde{A}_i^L\right)$ is the membership value of the element a_{i2}^L in the lower triangular function of the membership, $H\left(\tilde{A}_i^U\right) \in [0,1], H\left(\tilde{A}_i\right) \in [0,1], 1 \le i \le n$ (Kiracı & Akan, 2020; Baykasoğlu & Gölcük, 2017; Petrović & Petrović, 2024).

For two triangular IT2FSs:

$$\tilde{\tilde{A}}_1 = \left(\tilde{A}_1^U, \tilde{A}_1^L\right) = \left(a_{11}^U, a_{12}^U, a_{13}^U; H\left(\tilde{A}_1^U\right)\right), \left(a_{11}^L, a_{12}^L, a_{13}^L; H\left(\tilde{A}_1^L\right)\right)$$

$$\tilde{\tilde{A}}_2 = \left(\tilde{A}_2^U, \tilde{A}_2^L\right) = \left(a_{21}^U, a_{22}^U, a_{23}^U; H\left(\tilde{A}_2^U\right)\right), \left(a_{21}^L, a_{22}^L, a_{23}^L; H\left(\tilde{A}_2^L\right)\right)$$

Their elementary operations are respectively given as follows (Kiracı & Akan, 2020; Kahraman et al, 2014):

$$\tilde{\tilde{A}}_1 \oplus \tilde{\tilde{A}}_2 = \left[a_{11}^U + a_{21}^U, a_{12}^U + a_{22}^U, a_{13}^U + a_{23}^U; \min\left(H\left(\tilde{A}_1^U\right)\right), \min\left(H\left(\tilde{A}_2^U\right)\right)\right], \left[a_{11}^L + a_{21}^L, a_{12}^L + a_{22}^L, a_{13}^L + a_{23}^L; \min\left(H\left(\tilde{A}_1^L\right)\right), \min\left(H\left(\tilde{A}_2^L\right)\right)\right] \quad (2)$$

$$\tilde{\tilde{A}}_1 - \tilde{\tilde{A}}_2 = \left[a_{11}^U - a_{23}^U, a_{12}^U - a_{22}^U, a_{13}^U - a_{21}^U; \min\left(H\left(\tilde{A}_1^U\right), H\left(\tilde{A}_2^U\right)\right)\right], \left[a_{11}^L - a_{23}^L, a_{12}^L - a_{22}^L, a_{13}^L - a_{21}^L; \min\left(H\left(\tilde{A}_1^L\right), H\left(\tilde{A}_2^L\right)\right)\right] \quad (3)$$

$$\tilde{\tilde{A}}_1 \otimes \tilde{\tilde{A}}_2 = \left[a_{11}^U \times a_{21}^U, a_{12}^U \times a_{22}^U, a_{13}^U \times a_{23}^U; \min\left(H\left(\tilde{A}_1^U\right)\right), \min\left(H\left(\tilde{A}_2^U\right)\right)\right], \left[a_{11}^L \times a_{21}^L, a_{12}^L \times a_{22}^L, a_{13}^L \times a_{23}^L; \min\left(H\left(\tilde{A}_1^L\right)\right), \min\left(H\left(\tilde{A}_2^L\right)\right)\right] \quad (4)$$

$$\frac{\tilde{\tilde{A}}_1}{\tilde{\tilde{A}}_2} = \left[\frac{a_{11}^U}{a_{23}^U}, \frac{a_{12}^U}{a_{22}^U}, \frac{a_{13}^U}{a_{21}^U}; \min\left(H\left(\tilde{A}_1^U\right), H\left(\tilde{A}_2^U\right)\right)\right], \left[\frac{a_{11}^L}{a_{23}^L}, \frac{a_{12}^L}{a_{22}^L}, \frac{a_{13}^L}{a_{21}^L}; \min\left(H\left(\tilde{A}_1^L\right), H\left(\tilde{A}_2^L\right)\right)\right] \quad (5)$$

$$k \otimes \tilde{\tilde{A}}_i = k \otimes \left(\tilde{A}_i^U, \tilde{A}_i^L\right) = \left(k \times a_{i1}^U, k \times a_{i2}^U, k \times a_{i3}^U; H\left(\tilde{A}_i^U\right)\right), \left(k \times a_{i1}^L, k \times a_{i2}^L, k \times a_{i3}^L; H\left(\tilde{A}_i^L\right)\right) \quad (6)$$

$$\frac{\tilde{\tilde{A}}_i}{k} = \left[\frac{a_{i1}^U}{k}, \frac{a_{i2}^U}{k}, \frac{a_{i3}^U}{k}; H\left(\tilde{A}_i^U\right)\right], \left[\frac{a_{i1}^L}{k}, \frac{a_{i2}^L}{k}, \frac{a_{i3}^L}{k}; H\left(\tilde{A}_i^L\right)\right] \quad (7)$$

k is a scalar.

$$\frac{1}{\tilde{\tilde{A}}_i} = \left[\frac{1}{a_{i3}^U}, \frac{1}{a_{i2}^U}, \frac{1}{a_{i1}^U}; H\left(\tilde{A}_i^U\right)\right], \left[\frac{1}{a_{i3}^L}, \frac{1}{a_{i2}^L}, \frac{1}{a_{i1}^L}; H\left(\tilde{A}_i^L\right)\right] \quad (8)$$

$$\sqrt[m]{\tilde{\tilde{A}}_i} = \left[\left(\sqrt[m]{a_{i1}^U}, \sqrt[m]{a_{i2}^U}, \sqrt[m]{a_{i3}^U}; H\left(\tilde{A}_i^U\right)\right), \left(\sqrt[m]{a_{i1}^L}, \sqrt[m]{a_{i2}^L}, \sqrt[m]{a_{i3}^L}; H\left(\tilde{A}_i^L\right)\right)\right] \quad (9)$$

The ranking value of the triangular IT2FS $\widetilde{A}_i$ can be calculated as follows (Kiracı & Akan, 2020; Baykasoğlu & Gölcük, 2017; Petrović & Petrović, 2024):

$$Rank\left(\tilde{\tilde{A}}_i\right)=M_1\left(\tilde{A}_i^U\right)+M_1\left(\tilde{A}_i^L\right)+M_2\left(\tilde{A}_i^U\right)+M_2\left(\tilde{A}_i^L\right)-\frac{1}{3}$$
$$\left(S_1\left(\tilde{A}_i^U\right)+S_1\left(\tilde{A}_i^L\right)+S_2\left(\tilde{A}_i^U\right)+S_2\left(\tilde{A}_i^L\right)+S_3\left(\tilde{A}_i^U\right)+S_3\left(\tilde{A}_i^L\right)\right)+H\left(\tilde{A}_i^U\right)+H\left(\tilde{A}_i^L\right) \quad (10)$$

$$M_p\left(\tilde{A}_i^j\right)=\left(a_{ip}^j+a_{i(p+1)}^j\right)\Big/2 \quad ,1\leq p\leq 2 \quad (11)$$

$S_p\left(\widetilde{A}_i^j\right)$ - the standard deviation of the elements a_{ip}^j and $a_{i(p+1)}^j$:

$$S_p\left(\tilde{A}_i^j\right)=\sqrt{\frac{1}{2}\sum_{k=p}^{p+1}\left(a_{ik}^j-\frac{1}{2}\sum_{k=p}^{p+1}a_{ik}^j\right)^2} \quad ,1\leq p\leq 2 \quad (12)$$

$S_3\left(\tilde{A}_i^j\right)$ - the standard deviation of the elements a_{ip}^j, $1\leq p\leq 3$:

$$S_3\left(\tilde{A}_i^j\right)=\sqrt{\frac{1}{3}\sum_{k=1}^{3}\left(a_{ik}^j-\frac{1}{3}\sum_{k=1}^{3}a_{ik}^j\right)^2} \quad (13)$$

The formula for the defuzzification of the triangular IT2FS $\widetilde{\widetilde{A}}_i$ is (Kahraman et al, 2014):

$$DTriT\widetilde{\widetilde{A}}_i=\frac{1}{2}\left\{\begin{matrix}\left[\left(a_{i3}^U-a_{i1}^U\right)+\left(a_{i2}^U-a_{i1}^U\right)\right]/3+a_{i1}^U+\\ H(\widetilde{A}_i^L)\times\left[\left[\left(a_{i3}^L-a_{i1}^L\right)+\left(a_{i2}^L-a_{i1}^L\right)\right]/3+a_{i1}^L\right]\end{matrix}\right\} \quad (14)$$

Interval type-2 fuzzy sets-DEMATEL method

The weights of the requirements and the sub-requirements of each requirement were calculated by using the triangular IT2FS-DEMATEL method. This method is based on the determination of direct and indirect influences between each criterion on each criterion (Lee et al, 2013; Kahraman et al, 2014). It was developed with the aim of studying groups with complex and connected relationships. This method was chosen for the prioritization of criteria because it analyzes structures with complex causal relationships between their elements in partially determined or non-deterministic organizational systems and processes (Petrović &

Milenković, 2024; Shieh & Wu, 2016). It should be noted that there are limitations when using the hybridized MCDM approach when using the DEMATEL method, as has been written about by a number of authors (Demir, 2025; Kolour et al, 2025). The procedure of the triangular IT2FS-DEMATEL method is as follows (Baykasoğlu & Gölcük, 2017; Petrović & Petrović, 2024):

1) The average IT2FS matrix of the influence between the tactical - technical requirements was obtained as follows:

$$\tilde{\tilde{D}} = \left[\tilde{\tilde{D}}_{ij} \right]_{n\times n} = \left[\frac{\tilde{\tilde{D}}_{ij}^{(1)} \oplus \tilde{\tilde{D}}_{ij}^{(2)} \oplus \ldots \oplus \tilde{\tilde{D}}_{ij}^{(k)}}{k} \right]_{n\times n} \quad (15)$$

$\tilde{\tilde{D}}^{(k)} = \left[\tilde{\tilde{D}}_{ij}^{(k)} \right]_{n\times n}$ - individual IT2FS matrix of the influence between the requirements of the k-th expert (after the transformation of linguistic variables in the IT2FS),

k - number of experts,

n - number of requirements.

$\tilde{\tilde{D}}_{ij} = \left(\tilde{D}_{ij}^{U}, \tilde{D}_{ij}^{L}\right) = \left(d_{ij1}^{U}, d_{ij2}^{U}, d_{ij3}^{U}; H\left(\tilde{D}_{ij}^{U}\right)\right), \left(d_{ij1}^{L}, d_{ij2}^{L}, d_{ij3}^{L}; H\left(\tilde{D}_{ij}^{L}\right)\right)$ is the triangular IT2FS element of the non-negative average IT2FS matrix of the influence between tactical - technical requirements.

If $s = 1 / \max\left(\max_{1\le i\le n} \sum_{j=1}^{n} d_{ij3}^{U}, \max_{1\le j\le n} \sum_{i=1}^{n} d_{ij3}^{U} \right)$, the normalized direct-relation matrix is:

$$\tilde{\tilde{X}} = \left[\tilde{\tilde{x}}_{ij} \right]_{n\times n},$$

$\tilde{\tilde{x}}_{ij} = \left(\tilde{x}_{ij}^{U}, \tilde{x}_{ij}^{L}\right) = \left(x_{ij1}^{U}, x_{ij2}^{U}, x_{ij3}^{U}; H\left(\tilde{x}_{ij}^{U}\right)\right), \left(x_{ij1}^{L}, x_{ij2}^{L}, x_{ij3}^{L}; H\left(\tilde{x}_{ij}^{L}\right)\right)$ is the triangular IT2FS element of the normalized direct-relation matrix.

$$\tilde{\tilde{x}}_{ij} = s \otimes \tilde{\tilde{D}}_{ij}$$

$$H\left(\tilde{x}_{ij}^{U}\right) = H\left(\tilde{D}_{ij}^{U}\right), H\left(\tilde{x}_{ij}^{L}\right) = H\left(\tilde{D}_{ij}^{L}\right), i = 1, \ldots n, j = 1, 2, \ldots, n \quad (16)$$

2) The total relation matrix is:

$\tilde{\tilde{T}} = \left[\tilde{\tilde{t}}_{ij} \right]_{n\times n}, \tilde{\tilde{t}}_{ij} = \left(\tilde{t}_{ij}^{U}, \tilde{t}_{ij}^{L}\right) = \left(t_{ij1}^{U}, t_{ij2}^{U}, t_{ij3}^{U}; H\left(\tilde{t}_{ij}^{U}\right)\right), \left(t_{ij1}^{L}, t_{ij2}^{L}, t_{ij3}^{L}; H\left(\tilde{t}_{ij}^{L}\right)\right)$ - The IT2FS element of the total relation matrix, where:

$$t_{ij1}^{U} = x_{ij1}^{U} \times (i_{ij1}^{U} - x_{ij1}^{U})^{-1}, ..., t_{ij3}^{U} = x_{ij3}^{U} \times (i_{ij3}^{U} - x_{ij3}^{U})^{-1},$$

$$t_{ij1}^{L} = x_{ij1}^{L} \times (i_{ij1}^{L} - x_{ij1}^{L})^{-1}, ..., t_{ij3}^{L} = x_{ij3}^{L} \times (i_{ij3}^{L} - x_{ij3}^{L})^{-1},$$

$$H\left(\tilde{t}_{ij}^{U}\right) = H\left(\tilde{x}_{ij}^{U}\right), H\left(\tilde{t}_{ij}^{L}\right) = H\left(\tilde{x}_{ij}^{L}\right), i = 1,...n, j = 1,2,...,n \quad (17)$$

$\tilde{\tilde{I}} = \left[\tilde{\tilde{i}}_{ij}\right]_{n\times n}, \tilde{\tilde{i}}_{ij} = \left(i_{ij1}^{U}, i_{ij2}^{U}, i_{ij3}^{U}; H\left(\tilde{x}_{ij}^{U}\right)\right), \left(i_{ij1}^{L}, i_{ij2}^{L}, i_{ij3}^{L}; H\left(\tilde{x}_{ij}^{L}\right)\right)$ - is the triangular IT2FS identity square matrix with the elements on the main diagonal:

$$\tilde{\tilde{i}}_{ij} = \left(1,1,1; H\left(\tilde{x}_{ij}^{U}\right)\right), \left(1,1,1; H\left(\tilde{x}_{ij}^{L}\right)\right), 1 \le i \le n, 1 \le j \le n, i = j,$$

Other elements are:

$$\tilde{\tilde{i}}_{ij} = \left(0,0,0; H\left(\tilde{x}_{ij}^{U}\right)\right), \left(0,0,0; H\left(\tilde{x}_{ij}^{L}\right)\right), 1 \le i \le n, 1 \le j \le n, i \ne j$$

3) Using formula 10, the defuzzification of the elements of the triangular IT2FS total relation matrix elements $DTriT\tilde{\tilde{T}} = T = \left[t_{ij}\right]_{n\times n}$ was obtained. From the defuzzificated total relation matrix, the sum of the rows $D_i, i = 1,2,...,n$ (efect each requirements on other requirements) and the sum of the columns $R_j, j = 1,2,...,n$ (cause relationship – influence other requirements on each requirement) were calculated as follows (Baykasoğlu & Gölcük, 2017; Petrović & Petrović, 2024):

$$D_i = \sum_{j=1}^{n} t_{ij}^{def} \quad (19)$$

$$R_j = \sum_{i=1}^{n} t_{ij}^{def} \quad (20)$$

4) The requirements' weights of importance are :

$$impw_i = \sqrt{(D_i + R_i)^2 + (D_i - R_i)^2} \quad (21)$$

5) The normalized requirements' weights of importance are:

6) $impW_i = \frac{impw_i}{\sum_{i=1}^{n} impw_i}$, $i = 1,...,n$ - number of requirements(22)

The same procedure was used to evaluate all sub-requirements of each requirement. After normalization, the sum of weights for all sub-requirements of each i - requirement is:

$W_i = \sum_{r=1}^{m} w_r^i$, $r = 1,\ldots,m$ - the number of the sub-requirements of the i - requirement, respectively, sum of all sub-requirements, is:

$$\sum_{r=1}^{m} \sum_{i=1}^{n} w_r^i = 1 \tag{23}$$

Where w_r^i represents the weights of the r sub-requirements of the i - requirement.

Interval type-2 fuzzy sets-MABAC method

One of the MADM methods that provides a solution to a wide range of problems is the MABAC method developed by Pamučar & Ćirović (2015). The application of the MABAC method ensures evaluation and selection of the most appropriate alternative among a set of pre-specified alternatives. By applying the MABAC method with simplier computation steps, the most suitable solution is determined based on the comparison of the distance of each observed alternative from the boundary approximate areas - BAA (Pamučar & Ćirović, 2015). Furthermore, this method ensures solving the MADM problem with the properties of attributes that can be in conflict. Also, it allows selection and ranking of alternatives using linguistic variables for forming the initial decision matrix (Torkayesh et al, 2023). There are also limitations related to the application of MABAC as described by Mehdiabadi et al. (2025) and Yalçın et al. (2025). For model testing, the integrated IT2FS-MABAC approach was applied. This approach provides valid results in the conditions of high level of uncertainty, which is the situation with the initial projects of designing combat systems.

The procedure of the IT2FS-MABAC method is as follows (Pamučar & Ćirović, 2015; Torkayesh et al, 2023):

1) In the first step, from the data about the sub-requirements and the alternatives (project designs of the short-range artillery-missile air defense system) the initial decision matrix is formed by applying formulas 2 and 7.

$$\tilde{\tilde{F}} = \left[\tilde{\tilde{f}}_{ij} \right]_{n\times n} \cong \left[\tilde{\tilde{f}}_{ij}^{(1)} \oplus \tilde{\tilde{f}}_{ij}^{(2)} \oplus \ldots \oplus \tilde{\tilde{f}}_{ij}^{(k)} \right]_{n\times m}$$

$$\tilde{\tilde{F}} = \left[\tilde{\tilde{f}}_{ij} \right]_{n\times m}, 1 \le i \le n, 1 \le j \le m$$

$$\tilde{\tilde{f}}_{ij} = \left(\tilde{f}_{ij}^{U}, \tilde{f}_{ij}^{L} \right) = \left(f_{ij1}^{U}, f_{ij2}^{U}, f_{ij3}^{U}; H\left(\tilde{f}_{ij}^{U} \right) \right), \left(f_{ij1}^{L}, f_{ij2}^{L}, f_{ij3}^{L}; H\left(\tilde{f}_{ij}^{L} \right) \right)$$

- The IT2FS element of the initial decision matrix,
n - number of sub-requirements,
m - number of alternatives – number of offers for designing a short-range artillery-missile air defense system,
k - number of experts who evaluate the submitted documentation for each element of the initial decision matrix (the summary initial decision matrix is calculated from the individual initial decision matrices that were formed on the basis of expert evaluation - for each expert individually).

2) The normalized IT2FS decision matrix is calculated as follows:

$$\tilde{\tilde{R}} = \left[\tilde{\tilde{r}}_{ij} \right]_{n\times m}, \tilde{\tilde{r}}_{ij} = \left(\tilde{r}_{ij}^{U}, \tilde{r}_{ij}^{L} \right) = \left(r_{ij1}^{U}, r_{ij2}^{U}, r_{ij3}^{U}; H\left(\tilde{r}_{ij}^{U} \right) \right), \left(r_{ij1}^{L}, r_{ij2}^{L}, r_{ij3}^{L}; H\left(\tilde{r}_{ij}^{L} \right) \right)$$

- The IT2FS element of the normalized decision matrix, where:

a) For the sub-requirements of the benefit type:

$$\tilde{\tilde{r}}_{ij} = \begin{bmatrix} \left(\dfrac{f_{ij1}^{U} - f_{j}^{U-}}{f_{j}^{U+} - f_{j}^{U-}}, \dfrac{f_{ij2}^{U} - f_{j}^{U-}}{f_{j}^{U+} - f_{j}^{U-}}, \dfrac{f_{ij3}^{U} - f_{j}^{U-}}{f_{j}^{U+} - f_{j}^{U-}}; H\left(\tilde{r}_{ij}^{U} \right) \right), \\ \left(\dfrac{f_{ij1}^{L} - f_{j}^{U-}}{f_{j}^{U+} - f_{j}^{U-}}, \dfrac{f_{ij2}^{L} - f_{j}^{U-}}{f_{j}^{U+} - f_{j}^{U-}}, \dfrac{f_{ij3}^{L} - f_{j}^{U-}}{f_{j}^{U+} - f_{j}^{U-}}; H\left(\tilde{r}_{ij}^{L} \right) \right) \end{bmatrix}, \quad (24)$$

b) For the sub-requirements of the cost type:

$$\tilde{\tilde{r}}_{ij} = \begin{bmatrix} \left(\dfrac{f_{j}^{U+} - f_{ij3}^{U}}{f_{j}^{U+} - f_{j}^{U-}}, \dfrac{f_{j}^{U+} - f_{ij2}^{U}}{f_{j}^{U+} - f_{j}^{U-}}, \dfrac{f_{j}^{U+} - f_{ij1}^{U}}{f_{j}^{U+} - f_{j}^{U-}}; H\left(\tilde{r}_{ij}^{U} \right) \right), \\ \left(\dfrac{f_{j}^{U+} - f_{ij3}^{L}}{f_{j}^{U+} - f_{j}^{U-}}, \dfrac{f_{j}^{U+} - f_{ij2}^{L}}{f_{j}^{U+} - f_{j}^{U-}}, \dfrac{f_{j}^{U+} - f_{ij1}^{L}}{f_{j}^{U+} - f_{j}^{U-}}; H\left(\tilde{r}_{ij}^{L} \right) \right) \end{bmatrix}, \quad (25)$$

where:

$$f_j^{U+} = \max\left(j \le 1 \le m(f_{ij3}^U)\right),$$
$$f_j^{U-} = \min\left(j \le 1 \le m(f_{ij1}^U)\right),$$
$$H\left(\tilde{r}_{ij}^U\right) = H\left(\tilde{f}_{ij}^U\right),$$
$$H\left(\tilde{r}_{ij}^L\right) = H\left(\tilde{f}_{ij}^L\right),$$

3) In the next step, the weighted decision matrix is constructed: $\tilde{\tilde{V}} = \left[\tilde{\tilde{v}}_{ij}\right]_{n\times m}, \tilde{\tilde{v}}_{ij} = \left(\tilde{v}_{ij}^U, \tilde{v}_{ij}^L\right) = \left(v_{ij1}^U, v_{ij2}^U, v_{ij3}^U; H\left(\tilde{v}_{ij}^U\right)\right), \left(v_{ij1}^L, v_{ij2}^L, v_{ij3}^L; H\left(\tilde{v}_{ij}^L\right)\right)$ -The triangular IT2FS element of the weighted decision matrix, where: $\tilde{\tilde{v}}_{ij} = W_i \otimes \left(\tilde{\tilde{r}}_{ij} \oplus \tilde{\tilde{1}}\right)$, or (according to formulas 2 and 6):

$$\tilde{\tilde{v}}_{ij} = \left(W_i \times (r_{ij1}^U + 1), W_i \times (r_{ij2}^U + 1), W_i \times (r_{ij3}^U + 1); H\left(\tilde{v}_{ij}^U\right)\right),$$
$$\left(W_i \times (r_{ij1}^L + 1), W_i \times (r_{ij2}^L + 1), W_i \times (r_{ij3}^L + 1); H\left(\tilde{v}_{ij}^L\right)\right)$$
$$H\left(\tilde{v}_{ij}^U\right) = H\left(\tilde{r}_{ij}^U\right),$$
$$H\left(\tilde{v}_{ij}^L\right) = H\left(\tilde{r}_{ij}^L\right), \quad (26)$$

4) Using formulas 4 and 9, the border approximation area (BAA) is calculated as follows (for each sub-requirement):

$$\tilde{\tilde{G}} = \left[\tilde{\tilde{g}}_i\right]_{n\times 1}, \tilde{\tilde{g}}_i = \sqrt[m]{\tilde{\tilde{v}}_{i1} \otimes \tilde{\tilde{v}}_{i2} \otimes ... \otimes \tilde{\tilde{v}}_{im}}, 1 \le i \le n \quad (27)$$

5) The distance matrix from the BAA is calculated as follows:

$$\tilde{\tilde{Q}} = \left[\tilde{\tilde{q}}_{ij}\right]_{n\times m} = \left[\tilde{\tilde{v}}_{ij} - \tilde{\tilde{g}}_i\right]_{n\times m} \quad (28)$$

6) By summing the elements of the matrix $\tilde{\tilde{Q}}$ for each alternative (for all values of n) the final values of the requirement functions of the alternative (the closeness coefficient $\tilde{\tilde{S}}_j$ to the BAA for each alternative) are obtained:

$$\tilde{\tilde{S}}_j = \tilde{\tilde{q}}_{1j} \oplus \tilde{\tilde{q}}_{2j} \oplus ... \oplus \tilde{\tilde{q}}_{nj}, j = 1,...,m \quad (29)$$

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7) Ranking values S_j are calculated by formulas 10-13:

$$S_j = Rank\left(\tilde{\tilde{S}}_j\right), j = 1,...,m$$

8) Finally, the alternatives are ranked. The optimal alternative is the one that has the largest value of S .

Results

The requirements' weights (R1-R5) were calculated by using the triangular IT2FS-DEMATEL method. There is no influence of the requirement in itself. The values of influence expressed by linguistic variables and IT2FS are shown in Table 1.

Table 1 – DEMATEL Causal influence linguistic variables

Linguistic variable of influence	Triangular IT2FS
No (N)	((0,0,0;1),(0,0,0;0.8))
Low (L)	((0,0.2,0.4;1),(0,0.1,0.3;0.8))
Medium (M)	((0.2,0.4,0.6;1),(0.1,0.3,0.5;0.8))
High (H)	((0.4,0.6,0.8;1),(0.3,0.5,0.7;0.8))
Very high (VH)	((0.6,0.8,1;1),(0.5,0.7,0.9;0.8))

Firstly, by using DEMATEL causal influence linguistic variables of pairwise comparisons between requirements, the mutual influence between the requirements was determined by four experts individually (Table 2), and transformed into the triangular IT2FS (based on Table 1).

The average IT2FS matrix of the influence between the requirements $\tilde{\tilde{D}}$ was obtained by using formula 11 (Table 3).

Table 2 – Answers of experts in linguistic variables - matrix of mutual influence (Petrović & Petrović, 2024)

R	R1	R2	R3	R4	R5
R1	N	3L+M	2L+2M	H+3VH	H+3VH
R2	3L+M	N	2M+2H	4VH	H+3VH
R3	3L+M	3L+M	N	H+3VH	2H+2VH
R4	L+M+2H	2M+2H	2H+2VH	N	4VH
R5	L+3M	3M+H	2M+2VH	4VH	N

Table 3 – Average IT2FS matrix of influence (Petrović & Petrović, 2024)

R	R1	R2	R3	R4	R5
R1	0,0,0; 0,0,0	0.05,0.25,0.45; 0.03,0.15,0.35	0.1,0.3,0.5; 0.05,0.2,0.4	0.55,0.75,0.95; 0.45,0.65,0.85	0.55,0.75,0.95; 0.45,0.65,0.85
R2	0.05,0.25,0.45; 0.03,0.15,0.35	0,0,0; 0,0,0	0.3,0.5,0.7; 0.2,0.4,0.6	0.6,0.8,1; 0.5,0.7,0.9	0.55,0.75,0.95; 0.45,0.65,0.85
R3	0.05,0.25,0.45; 0.03,0.15,0.35	0.05,0.25,0.45; 0.03,0.15,0.35	0,0,0; 0,0,0	0.55,0.75,0.95; 0.45,0.65,0.85	0.5,0.7,0.9; 0.4,0.6,0.8
R4	0.25,0.45,0.65; 0.18,0.35,0.55	0.2,0.4,0.6; 0.3,0.5,0.7	0.5,0.7,0.9; 0.4,0.6,0.8	0,0,0; 0,0,0	0.6,0.8,1; 0.5,0.7,0.9
R5	0.13,0.35,0.55; 0.08,0.25,0.45	0.25,0.45,0.65; 0.15,0.35,0.55	0.4,0.6,0.8; 0.3,0.5,0.7	0.6,0.8,1; 0.5,0.7,0.9	0,0,0; 0,0,0
$H\left(\tilde{D}_{ij}^{U}\right)=1, H\left(\tilde{D}_{ij}^{L}\right)=0.8, i=1,\ldots,5; j=1,\ldots,5$					

The normalized direct-relation matrix $\tilde{\tilde{X}}$ and the total relation matrix $\tilde{\tilde{T}}$ were obtained using formulas 12-13. The defuzzificated total relation matrix was obtained using formula 10, and the sum of rows and the sum of columns of the total relation matrix were calculated using formulas 14 and 15. The weights of importance of the requirements were calculated using formulas 16-17, respectively (Table 4) (Petrović & Petrović, 2024).

Table 4 – Defuzzificated total relation matrix and requirements'weights (Petrović & Petrović, 2024)

R	R1	R2	R3	R4	R5	D_i	R_j	w_i	W_i
R1	0	0.017	0.024	0.074	0.073	0.188	0.084	0.292	0.143
R2	0.017	0	0.042	0.087	0.078	0.223	0.100	0.342	0.168
R3	0.015	0.016	0	0.073	0.066	0.171	0.180	0.350	0.172
R4	0.030	0.036	0.064	0	0.087	0.217	0.318	0.549	0.270
R5	0.022	0.031	0.051	0.085	0	0.189	0.304	0.502	0.247

The weights of the sub-requirements, shown in Table 5 and Figure 2, were determined in the same way.

Table 5 – Total relation matrix and sub-requirements' weights

R		D_r^i	R_r^i	$impw_r^i$	$impW_r^i$	w_r^i
R1	R11	0.294	0.245	0.734	0.306	0.044
	R12	0.323	0.375	0.835	0.348	0.050
	R13	0.351	0.338	0.830	0.346	0.049
R2	R21	0.224	0.214	0.662	0.212	0.036
	R22	0.157	0.211	0.607	0.194	0.033
	R23	0.274	0.224	0.706	0.226	0.038
	R24	0.124	0.097	0.470	0.150	0.025
	R25	0.214	0.254	0.684	0.219	0.037
R3	R31	0.122	0.134	0.506	0.162	0.028
	R32	0.217	0.202	0.647	0.208	0.036
	R33	0.214	0.243	0.676	0.217	0.037
	R34	0.199	0.175	0.611	0.196	0.034
	R35	0.243	0.217	0.678	0.217	0.037
R4	R41	0.045	0.053	0.313	0.095	0.026
	R42	0.055	0.071	0.355	0.108	0.029
	R43	0.317	0.285	0.776	0.236	0.064
	R44	0.194	0.212	0.637	0.194	0.052
	R45	0.185	0.174	0.599	0.182	0.049
	R46	0.194	0.173	0.606	0.184	0.050
R5	R51	0.371	0.285	0.810	0.262	0.065
	R52	0.199	0.203	0.634	0.205	0.051
	R53	0.092	0.147	0.489	0.158	0.039
	R54	0.103	0.135	0.488	0.158	0.039
	R55	0.234	0.219	0.673	0.218	0.054

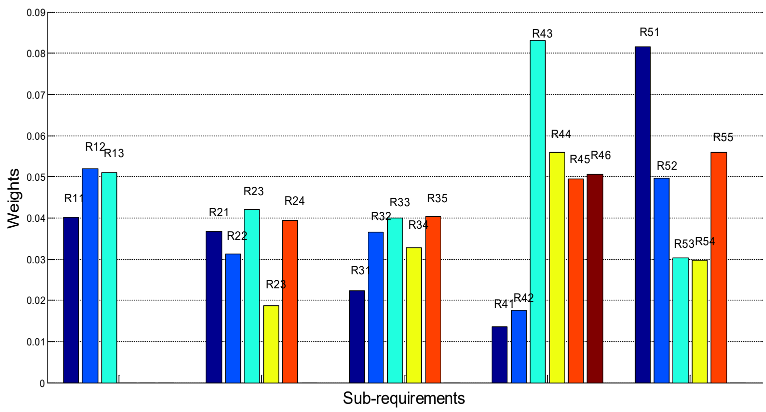

Figure 2 – Weights of importance of the sub-requirements

The initial estimations were transformed into the triangular IT2FS based on the equivalence shown in Table 6.

Table 6 – MABAC linguistic and triangular IT2FS variables for the rating of alternatives

Linguistic variable of influence	Triangular IT2FS
Very poor (VP)	((0,0,0;1),(0,0,0;0.8))
Poor (P)	((0,0.2,0.4;1),(0,0.1,0.3;0.8))
Medium (M)	((0.2,0.4,0.6;1),(0.1,0.3,0.5;0.8))
Good (G)	((0.4,0.6,0.8;1),(0.3,0.5,0.7;0.8))
Very good (VG)	((0.6,0.8,1;1),(0.5,0.7,0.9;0.8))

After the calculated weights of the sub-requirements and the formed model for ranking and the delivery of the bidder's initial project documentation (five bids) in accordance with the established requirements, the model was tested. Model testing was performed using the triangular IT2FS-MABAC method. This method was applied due to the fact that the offers are of a descriptive-qualitative nature, which is why the triangular IT2FS was applied in order to eliminate ambiguity in the project documentation offers. Hypothetically, the project teams submitted the initial project documentation, and the experts completed the initial assessment for each submitted offer. For each sub-requirement, experts for the selection of the short-range SAAM individually perform a qualitative assessment in the form of the following linguistic variables: very poor (VP), poor (P), medium (M), good (G), and very good (VG). Linguistic variables were adapted based on the Likert scale of ranking. The obtained estimates are grouped in Table 7.

Table 7 – Initial decision matrix (linguistic variables)

Criteria/Alt.		A1	A2	A3	A4	A5
R1	R11	3G+2VG	3M+2VG	5VG	5VG	VG+4G
	R12	2G+3VG	4G+VG	G+4VG	4VG+G	VG+4M
	R13	4G+VG	3G+2M	4VG+G	4VG+G	G+4M
R2	R21	2G+3VG	5M	3M+2G	M+4G	3M+2G
	R22	G+4VG	2M+3P	VP+4P	5VP	2M+3G
	R23	G+4VG	2M+3G	M+4G	5VP	3M+2G
	R24	4M+P	VP+2P+2M	M+4G	M+4P	4VP+P
	R25	2G+3M	3M+2G	VG+4G	M+4P	4P+M
R3	R31	3VG+2G	3G+2M	3G+3VG	G+4VG	G+4VG
	R32	2VG+3G	VG+4G	5VG	G+4G	5VG
	R33	M+4G	2M+P+2VP	G+4G	5VG	M+4P
	R34	2VG+3G	G+4M	5VG	5VG	M+4P
	R35	5G	2VG+3G	5G	2M+3G	G+4M
R4	R41	4G+M	2G+2M+P	4G+1VG	G+4M	5G
	R42	3M+2P	M+4G	M+4P	M+4P	5M
	R43	4M+G	5VG	4VG+G	3G+2VG	2M+3G
	R44	3M+2G	G+4M	3G+2M	G+4VG	5VG
	R45	P+4M	M+4P	3G+2M	G+4VG	G+4VG
	R46	5VG	G+4M	G+4G	5M	G+4VG
R5	R51	3G+2M	4VG+G	M+4P	5G	2M+3P
	R52	VG+4G	M+4P	G+4VG	G+4VG	G+4M
	R53	VG+4G	5VG	G+4VG	G+4VG	VG+4G
	R54	2G+2M+VG	G+4M	M+4G	G+4VG	G+4M
	R55	G+4VG	M+3G+VG	2G+3VG	G+4VG	G+4M

After the linguistic variables were transformed into the triangular IT2FS, the summary initial decision matrix was calculated. After that, the normalized triangular IT2FS decision matrix was calculated by formulas 24-25. The weighted IT2FS decision matrix was calculated by using formula 26. The border approximation area (BAA), the distance matrix from the BAA, was calculated respectively by using formulas 27 and 28.

The criterion functions for all alternatives - bids $\tilde{\tilde{S}}_j$ were calculated by using formula 29. The ranking values S_j were calculated by using formulas 10-13. Based on the obtained results, the project documentation was ranked. The obtained results are shown in Tables 8-9.

Table 8 – Summary IT2FS initial decision matrix $\tilde{\tilde{F}}$

Criteria/Alt.		A1	A2	A3	A4	A5
R1	R11	2.4,3.4,4.4; 1.9,2.9,3.9	1.8,2.8,3.8; 1.3,2.3,3.3	3,4,5; 2.5,3.5,4.5	3,4,5; 2.5,3.5,4.5	2.2,3.2,4.2; 1.7,2.7,3.7
	R12	2.6,3.6,4.6; 2.1,3.1,4.1	2.2,3.2,4.2; 1.7,2.7,3.7	2.8,3.8,4.8; 2.3,3.3,4.3	2.8,3.8,4.8; 2.3,3.3,4.3	1.4,2.4,3.4; 0.9,1.9,2.9
	R13	2.2,3.2,4.2; 1.7,2.7,3.7	1.6,2.6,3.6; 1.1,2.1,3.1	2.8,3.8,4.8; 2.3,3.3,4.3	2.8,3.8,4.8; 2.3,3.3,4.3	1.2,2.2,3.2; 0.7,1.7,2.7
R2	R21	2.6,3.6,4.6; 2.1,3.1,4.1	1,2,3; 0.5,1.5,2.5	1.4,2.4,3.4; 0.9,1.9,2.9	1.8,2.8,3.8; 1.3,2.3,3.3	1.4,2.4,3.4; 0.9,1.9,2.9
	R22	2.8,3.8,4.8; 2.3,3.3,4.3	0.4,1.4,2.4; 0.2,0.9,1.9	0,0.8,1.6; 0,0.4,1.2	0,0,0; 0,0,0	1.6,2.6,3.6; 1.1,2.1,3.1
	R23	2.8,3.8,4.8; 2.3,3.3,4.3	1.6,2.6,3.6; 1.1,2.1,3.1	1.8,2.8,3.8; 1.3,2.3,3.3	0,0,0; 0,0,0	1.4,2.4,3.4; 0.9,1.9,2.9
	R24	0.8,1.8,2.8; 0.4,1.3,2.3	0.4,1.2,2; 0.2,0.8,1.6	1.8,2.8,3.8; 1.3,2.3,3.3	0.2,1.2,2.2; 0.1,0.7,1.7	0,0.2,0.4; 0,0.1,0.3
	R25	1.4,2.4,3.4; 0.9,1.9,2.9	1.4,2.4,3.4; 0.9,1.9,2.9	2.2,3.2,4.2; 1.7,2.7,3.7	0.2,1.2,2.2; 0.1,0.7,1.7	0.2,1.2,2.2; 0.1,0.7,1.7
R3	R31	2.6,3.6,4.6; 2.1,3.1,4.1	1.6,2.6,3.6; 1.1,2.1,3.1	2.4,3.4,4.4; 1.9,2.9,3.9	2.8,3.8,4.8; 2.3,3.3,4.3	2.8,3.8,4.8; 2.3,3.3,4.3
	R32	2.4,3.4,4.4; 1.9,2.9,3.9	2.2,3.2,4.2; 1.7,2.7,3.7	3,4,5; 2.5,3.5,4.5	2,3,4; 1.5,2.5,3.5	3,4,5; 2.5,3.5,4.5
	R33	1.8,2.8,3.8; 1.3,2.3,3.3	0.4,1,1.6; 0.2,0.7,1.3	2,3,4; 1.5,2.53.5	3,4,5; 2.5,3.5,4.5	0.2,1.2,2.2; 0.1,0.7,1.7
	R34	2.4,3.4,4.4; 1.9,2.9,3.9	1.2,2.2,3.2; 0.7,1.7,2.7	3,4,5; 2.5,3.5,4.5	3,4,5; 2.5,3.5,4.5	0.2,1.2,2.2; 0.1,0.7,1.7
	R35	2,3,4; 1.5,2.5,3.5	2.4,3.4,4.4; 1.9,2.9,3.9	2,3,4; 1.5,2.5,3.5	1.6,2.6,3.6; 1.1,2.1,3.1	1.2,2.2,3.2; 0.7,1.7,2.7
R4	R41	1.8,2.8,3.8; 1.3,2.3,3.3	1.2,2.2,3.2; 0.8,1.7,2.7	2.2,3.2,4.2; 1.7,2.7,3.7	1.2,2.2,3.2; 0.7,1.7,2.7	2,3,4; 1.5,2.5,3.5
	R42	0.6,1.6,2.6; 0.3,1.1,2.1	1.8,2.8,3.8; 1.3,2.3,3.3	0.21.2,2.2; 0.1,0.7,1.7	0.2,1.2,2.2; 0.1,0.7,1.7	1,2,3; 0.5,1.5,2.5
	R43	1.2,2.2,3.2; 0.7,1.7,2.7	3,4,5; 2.5,3.5,4.5	2.83.8,4.8; 2.3,3.3,4.3	2.4,3.4,4.4; 1.9,2.9,3.9	1.6,2.6,3.6; 1.1,2.1,3.1

Criteria/Alt.		A1	A2	A3	A4	A5
R4	R44	1.4,2.4,3.4; 0.9,1.9,2.9	1.2,2.2,3.2; 0.7,1.7,2.7	1.6,2.6,3.6; 1.1,2.1,3.1	2.8,3.8,4.8; 2.3,3.3,4.3	3,4,5; 2.5,3.5,4.5
	R45	0.8,1.8,2.8; 0.4,1.3,2.3	0.2,1.2,2.2; 0.1,0.7,1.7	1.6,2.6,3.6; 1.1,2.1,3.1	2.8,3.8,4.8; 2.3,3.3,4.3	2.8,3.8,4.8; 2.3,3.3,4.3
	R46	3,4,5; 2.5,3.5,4.5	1.2,2.2,3.2; 0.7,1.7,2.7	2,3,4; 1.5,2.5,3.5	1,2,3; 0.5,1.5,2.5	2.8,3.8,4.8; 2.3,3.3,4.3
R5	R51	1.6,2.6,3.6; 1.1,2.1,3.1	2.8,3.8,4.8; 2.3,3.3,4.3	0.2,1.2,2.2; 0.1,0.7,1.7	2,3,4; 1.5,2.5,3.5	0.4,1.4,2.4; 0.2,0.91.9
	R52	2.2,3.2,4.2; 1.7,2.7,3.7	0.2,1.2,2.2; 0.1,0.7,1.7	2.8,3.8,4.8; 2.3,3.3,4.3	2.8,3.8,4.8; 2.3,3.3,4.3	1.2,2.2,3.2; 0.7,1.7,2.7
	R53	2.2,3.24.2; 1.7,2.7,3.7	3,4,5; 2.5,3.5,4.5	2.8,3.8,4.8; 2.3,3.3,4.3	2.8,3.8,4.8; 2.3,3.3,4.3	2.2,3.2,4.2; 1.7,2.7,3.7
	R54	1.8,2.8,3.8; 1.3,2.3,3.3	1.2,2.2,3.2; 0.7,1.7,2.7	1.8,2.8,3.8; 1.3,2.3,3.3	2.8,3.8,4.8; 2.3,3.3,4.3	1.2,2.2,3.2; 0.7,1.7,2.7
	R55	2.8,3.8,4.8; 2.3,3.3,4.3	2,3,4; 1.5,2.5,3.5	2.6,3.6,4.6; 2.1,3.1,4.1	2.8,3.8,4.8; 2.3,3.3,4.3	1.2,2.2,3.2; 0.7,1.7,2.7
$H\left(\tilde{f}_{ij}^{U}\right)=1, H\left(\tilde{f}_{ij}^{L}\right)=0.8, i=1,...,24; j=1,...,5$						

Table 9 – IT2FS and ‘crisp’ values of the closeness coefficient to the BAA and the rank of the alternatives

Candidates	$\tilde{\tilde{S}}_j$	$Rank\left(\tilde{\tilde{S}}_j\right)$	Ranking
A1	(0.035,0.039,0.044;1), (0.027,0.037,0.044;0.8)	1.943248956	2
A2	(-0.057,-0.057,-0.056;1), (-0.056,-0.057,-0.059;0.8)	1.570539829	5
A3	(0.085,0.088,0.091;1), (0.081,0.086,0.086;0.8)	2.141097582	1
A4	(0.030,0.019,0.010;1), (0.036,0.024,0.017;0.8)	1.877131511	3
A5	(-0.025,-0.026,-0.026;1), (-0.023,-0.026,-0.028;0.8)	1.694628858	4

A sensitivity analysis was done through changes in the weights of requests. The sensitivity analysis was carried out through 20 scenarios (Table 10). In each scenario, the weights of all sub-requirements within one requirement are increased (reduced) by 20%, and 40%, respectively. The weights of the other requirements and sub-requirements are increased (decreased) so that the sum of the criteria values is 1.

Table 10 – Sensitivity analysis of the results

$R_1 = R_{1old} \times 1.2$	$R_1 = R_{1old} \times 1.4$	$R_1 = R_{1old} \times 0.8$	$R_1 = R_{1old} \times 0.6$
$A3 > A1 > A4 > A5 > A2$	$\underline{A1 > A3 > A4 > A2 > A5}$	$A3 > A1 > A4 > A5 > A2$	$\underline{A3 > A1 > A4 > A2 > A5}$
$R_2 = R_{2old} \times 1.2$	$R_2 = R_{2old} \times 1.4$	$R_2 = R_{2old} \times 0.8$	$R_2 = R_{2old} \times 0.6$
$A3 > A1 > A4 > A5 > A2$	$\underline{A1 > A3 > A4 > A5 > A2}$	$A3 > A1 > A4 > A5 > A2$	$\underline{A1 > A3 > A5 > A4 > A2}$
$R_3 = R_{3old} \times 1.2$	$R_3 = R_{3old} \times 1.4$	$R_3 = R_{3old} \times 0.8$	$R_3 = R_{3old} \times 0.6$
$A3 > A1 > A4 > A5 > A2$	$\underline{A3 > A1 > A4 > A2 > A5}$	$\underline{A3 > A1 > A5 > A4 > A2}$	$A3 > A1 > A4 > A5 > A2$
$R_4 = R_{4old} \times 1.2$	$R_4 = R_{4old} \times 1.4$	$R_4 = R_{4old} \times 0.8$	$R_4 = R_{4old} \times 0.6$
$\underline{A3 > A1 > A5 > A4 > A2}$	$A3 > A1 > A4 > A5 > A2$	$\underline{A3 > A1 > A5 > A4 > A2}$	$\underline{A3 > A4 > A1 > A5 > A2}$
$R_5 = R_{5old} \times 1.2$	$R_5 = R_{5old} \times 1.4$	$R_5 = R_{5old} \times 0.8$	$R_5 = R_{5old} \times 0.6$
$\underline{A1 > A3 > A5 > A4 > A2}$	$\underline{A3 > A1 > A5 > A4 > A2}$	$A3 > A1 > A4 > A5 > A2$	$\underline{A3 > A4 > A1 > A5 > A2}$

The results in the table show that the ranking of the alternatives changed through 11 scenarios. In other scenarios, the ranking of the alternatives did not change. The correlation of the results was tested using Kendall's coefficient of concordance W. This coefficient represents a measure of the agreement between several judges (in this case 20 scenarios) who have rank ordered a set of entities (in this case five alternatives) (Field, 2005). The value of Kendall's coefficient of concordance for all 20 scenarios and 5 variables is 0.8635. The value of the coefficient of 0.8635 is extremely significant for a significance of 0.05. Thus, it can be concluded that there is a very high correlation (closeness) of ranks through the scenarios and that the results obtained using the hybridized fuzzy-DEMATEL-MABAC approach are credible.

Discussion

Based on the obtained results (Tables 3 – 4), it can be concluded that the requirement related to the ability to protect forces has the greatest weight (Petrović & Petrović, 2024). The next requirement in order of importance is the ability to protect forces, followed by: time capabilities, spatial capabilities and fire capabilities which represent the requirement that has the least weight - the least importance (Petrović & Petrović, 2024). It is obvious that, according to the experts, the most important ability to protect forces and force`s survival (R4) is the most important requirement when using a modern weapon system. In order to carry out a combat mission, it is necessary to ensure the survival of the forces. Bearing in mind the modest GDP and the limited capabilities of the military industry, the experts believe that when designing new weapons, the cost of the technological process, as well as the cost of use and maintenance, are very significant - requirement (R5). The importance of the time capabilities of (R3) is reflected in the modern conditions of Air Force and Air Defence warfare, which affect the need for high maneuverability of units with the ability to repel mass air strikes. The importance of the other two requirements, R1 and R2, is a bit lower than that of the others, but despite that their influence on the design of a new air defense missile system is extremely large.

The obtained results for the sub-requirements (Table 5 and Figure 2) indicate that the experts single out two sub-requirements during evaluation, while they evaluate the others almost equally. Sub-requirement R43 (autonomy in operation of combat platforms) - 0.064 and R52 (investment costs) have significantly greater importance than the others. This is justified by the fact that the SAAM for anti-aircraft operations, following the tendencies of the complexity of modern conflicts, must be able to react completely independently and in a timely manner to threats in the airspace. An extreme importance of operational autonomy is evident on the example of missile systems of older technological generations, composed of several subsystems. In the event that any of these subsystems is damaged or destroyed by enemy action, the system's operation would not be possible. It is also understandable that the price of the investment is of great importance, regarding that a complex asset like that is viewed as a long-term investment in the defense system. The experts placed slightly less importance on sub-requirements R44 (ability of passive sensors) -0.052 and R55 (possibility of linking with the existing surface to air assets) - 0.054 and R52 (operating costs) - 0.051 and R12 (size of the destruction zone of aerodynamic and ballistic targets) - 0.050. This is a consequence of the fact that there is a constant tendency to passivate the operation of the system, which reduces the total radiation time and thus enables safer work in terms of observation, detection and tracking of targets in the airspace. Also, the possibility of linking with the existing surface to air assets increases overall compatibility and excludes additional costs of procurement and training of staff. Also, SAAMs often require constant maintenance, training, and logistical support. High operating costs can strain a nation's budget, especially if these systems need to be kept at a high state of readiness at all times. Ensuring that operating costs are manageable helps maintain a sustainable defense posture over the long term. The destruction zone's size is crucial for air defense, directly affecting interception effectiveness. A larger zone increases the chances of neutralizing aerodynamic and ballistic threats by providing more engagement opportunities. It accommodates evasive maneuvers, enables simultaneous target management, and improves tracking of stealth aircraft or decoys. A broader zone also enhances adaptability to various attacks, ensures comprehensive coverage, and strengthens system integration. Ultimately, it optimizes resources and boosts overall defense reliability and success.

According to the experts, the least important sub-requirements are R24 (channel by missile) - 0.025, R41 (frequency agility of autonomous radars) - 0.026, R31 (fire maneuver) - 0.028, and R42 (pulse repetition frequency) - 0.029. Although rated much lower, sub-requirement R41 (frequency agility of autonomous radars) should not be forgotten because the ability of radars to work at different frequencies is crucial for the effectiveness of the SAAM because it increases their ability to detect and track different targets. Lower frequencies extend the detection range, aiding in spotting large objects such as aircraft. Higher frequencies improve resolution, enabling precise tracking of small or fast-moving targets such as missiles or drones. Low-frequency radars perform better in poor weather, while high frequencies are more vulnerable to interference. Multi-frequency radars resist countermeasures, enhancing reliability in combat. Higher frequencies also enable faster tracking of threats like incoming missiles. Overall, operating across different frequencies maximizes detection, resolution, and defense resilience. The weights of other sub-requirements are approximate. Based on the obtained data, it can be concluded that the ability to protect forces has the greatest importance. This is understandable because in combat operations, the human resource is the most important resource. Protecting forces in combat is crucial for maintaining capability and minimizing losses, ensuring operational continuity. It also boosts morale, which is a key to long-term success. Reducing manpower losses lowers training costs and shortens the time needed to regain readiness. Ultimately, sustained force protection increases the chances of success in combat. After the analysis of the obtained results of the weights of certain requirements and sub-requirements, a model was created for evaluating the initial project documentation of the respective bidders (project teams) for the design of the short-range SAAM. In the next step, the mentioned MCDM model was tested. It was assumed that five bidders applied for the competition and that they submitted the basis of the project proposal based on the created model. The obtained results are shown in Table 9. Based on the obtained results, it can be concluded that the offer number 3 is the best, while the offer of the project team number 2 is the worst. It can also be seen from the results that the MCDM model is successful and that there is a clear numerical difference between the bidders (alternatives) that ensures their ranking. In this way, by applying the IT2FS-COPRAS method, the MCDM model was successfully tested and it was shown that it works.

Conclusion

The paper shows the possibility of applying the IT2FS-DEMATEL-MABAC approach for the purpose of forming a model with which it is possible to evaluate the initial project documentation for designing the short-range SAAM. The IT2FS-DEMATEL approach was applied for the evaluation of requirements and sub-requirements and the formation of a model for the evaluation of the INITIAL project documentation. The IT2FS-MABAC approach was applied to test the model based on the estimated data for five providers of the initial project documentation. The application of the IT2FS was conditioned by the need to eliminate ambiguity in the obtained results. Based on the results obtained in the research, it can be concluded that this approach when defining the basic conditions - requirements that are necessary for the assessment of the initial project documentation for designing a short-range SAAM can have its scientifically based application.

There are numerous practical possibilities of applying the results of this research. Namely, in the future, based on the obtained results, it is possible to form a unique model with the help of which it is possible to design the production of SAAMs or similar combat systems. Also, this model can serve as a basis for choosing the optimal weapon system when equipping armed forces. Also, this model can serve as a basis for the modernization of certain weapon systems based on the estimated requirements for modernization. The MCDM decision-making model can also have a comprehensive practical application during the optimization of the decision-making process when solving other numerous problems in military units.

In the following research, it is necessary to consider the operationalization of tactical-technical requirements in order to create a wider scope of conditions that determine the ability of the project contractor to design a short-range SAAM in accordance with real current and future needs. Also, it is possible to improve the model through the application of other MCDM approaches that will include other MADM methods in different fuzzy theory conditions.

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Optimización del proceso de diseño de sistemas de misiles de artillería tierra-aire de corto alcance utilizando el enfoque triangular híbrido IT2FS-DEMATEL-MABAC

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

Resumen:

Introducción/objetivo: La posibilidad de optimizar el proceso de diseño de un sistema de artillería-misil tierra-aire de corto alcance (SAAM de corto alcance) mediante la aplicación del enfoque híbrido de toma de decisiones multicriterio (integración de los métodos DEMATEL y MABAC) en entornos difusos de intervalo triangular tipo 2, se muestra en este artículo. Mediante el análisis del contenido de la literatura, se seleccionaron los requisitos y subrequisitos táctico-técnicos. Además, se determinaron los pesos de estos requisitos y subrequisitos. Posteriormente, se creó un modelo de toma de decisiones multicriterio (MCDM) para la evaluación de diferentes proyectos iniciales de diseño de un SAAM de corto alcance, que también se probó en este artículo.

Métodos: El enfoque propuesto, que combina los métodos DEMATEL y MABAC, se modificó mediante conjuntos difusos de intervalo triangular tipo 2 (IT2FS). El método triangular IT2F-DEMATEL se aplicó para determinar los pesos de los requisitos y subrequisitos, mientras que el método triangular IT2FS-MABAC se aplicó para evaluar las alternativas (diseños iniciales del proyecto de un SAAM de corto alcance).

Resultados: Integración del enfoque triangular múltiple IT2FS-MCDM en un modelo único que se puede aplicar en el proceso de definición del proyecto de diseño inicial óptimo de un SAAM de corto alcance.

Conclusión: El artículo contribuye a la ciencia militar en la toma de decisiones relacionadas con el diseño de un SAAM de corto alcance.

Palabras claves: DEMATEL, MABAC, conjuntos difusos de intervalo triangular tipo 2, sistema de artillería y misiles tierra-aire de corto alcance.

Оптимизация процесса проектирования зенитно-ракетного комплекса малой дальности с использованием гибридного треугольного подхода IT2FS-DEMATEL-MABAC

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РУБРИКА ГРНТИ: 27.47.19 Исследование операций,
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ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: В данной статье представлены возможности оптимизации процесса проектирования зенитно-ракетного комплекса малой дальности с помощью гибридного многокритериального подхода к принятию решений (интеграция методов DEMATEL и MABAC) в нечеткой среде с треугольным *интервалом второго типа. Контент-анализ использовался для выбора тактических и технических требований и задач. В статье расставлены приоритеты требований, определены их весовые коэффициенты, а также разработана многокритериальная модель принятия решений (МКМПР) для оценки первоначальных проектов зенитно-ракетного комплекса противовоздушной обороны малой дальности. В статье также представлены результаты тестирования данной модели.*

Методы: Предложенный подход, сочетающий методы DEMATEL и MABAC, модифицирован с помощью нечетких множеств с треугольным интервалом второго типа (IT2FS). Треугольный метод IT2F-DEMATEL был применен для определения весовых коэффициентов требований и задач, а треугольный метод IT2FS-MABAC был применен для оценки альтернатив первоначальных проектных решений зенитно-ракетного комплекса малой дальности.

Результаты: Интеграция множественного треугольного подхода IT2FS-MCDM в единую модель, которая может применяться в процессе определения оптимального первоначального проекта зенитно-ракетного комплекса малой дальности.

Вывод: Данная статья вносит вклад в развитие военной науки в области принятия решений, связанных с разработкой зенитно-ракетного комплекса малой дальности.

Ключевые слова: DEMATEL, MABAC, нечеткие множества с треугольным интервалом второго типа, зенитно-ракетный комплекс малой дальности.

Оптимизација процеса дизајнирања артиљеријско-ракетног система за противваздухопловна дејства применом хибридног троугластог приступа ИТ2ФС-ДЕМАТЕЛ-МАБАК

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ОБЛАСТ: примењена математика, операциона истраживања, војне науке
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: У раду је приказана могућност оптимизације процеса дизајнирања артиљеријско-ракетног система за противваздухопловна дејства малог домета применом хибридног вишекритеријумског (интеграцијом метода ДЕМАТЕЛ и МАБАК) приступа у одлучивању у троугластом интервалном фази окружењу типа 2. Анализом садржаја извршена је селекција *тактичко-техничких захтева и подзахтева. Такође, обављена је приоритетизација захтева, одређене су релативне тежине захтева и подзахтева и креиран вишекритеријумски модел одлучивања (ВКО модел) за евалуацију почетних пројеката дизајнирања артиљеријско-ракетног система за противваздухопловна дејства малог домета. Извршено је и тестирање модела.*

Методе: Предложен модел ВКО комбинује методе ДЕМАТЕЛ и МАБАК модифковане помоћу троугластих интервалних фази скупова типа 2 (ИТ2ФС). Троугласти метод ИТ2ФС-ДЕМАТЕЛ примењен је за одређивање тежине захтева и подзахтева, док је троугласта метода ИТ2ФС-МАБАК примењена за евалуацију алтернатива – почетне пројектне документације за дизајнирање артиљеријско- ракетног система за противваздухопловна дејства малог домета.

Резултати: Интегрисање вишеструког ВКО приступа заснованог на троугластим ИТ2ФС у јединствени модел може се применити у процесу дефинисања оптималне почетне пројектне документације за дизајнирање артиљеријско-ракетног система за противваздухопловна дејства малог домета.

Закључак: Рад доприноси војној науци приликом доношења одлука у процесу дизајнирања артиљеријско-ракетног система за противваздухопловна дејства малог домета.

Кључне речи: ДЕМАТЕЛ, МАБАК, троугласти интервални фази скупови типа 2, артиљеријско-ракетни систем малог домета.

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