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# Proposals for the implementation of a decision support system for air defence fire control based on fuzzy networks of targets

# Propozycje wdrożenia systemu wspomagania decyzji dla kontroli ognia obrony powietrznej na podstawie rozmytych sieci celów

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**Abstract.** The purpose of the research was to improve the control of air defence firepower using fuzzy networks of target installations, enhancing the efficiency and accuracy of defensive actions. The research niche of this article is the optimization of decision support systems in air defence through the application of fuzzy logic to improve real-time threat assessment and response accuracy. The study hypothesized that the integration of fuzzy networks into air defence fire control would lead to improved decision-making accuracy and reduced response time under conditions of uncertainty. The methodology involved data collection using radar, acoustic, and infrared sensors; modelling of fuzzy systems with specialized software; the development of fuzzy rules for threat assessment; and the simulation of real combat conditions to evaluate system effectiveness and its integration with existing detection and tracking equipment. The results demonstrated that the proposed decision support system significantly enhances threat assessment accuracy, reduces reaction time, and improves overall air defence effectiveness. Simulation tests confirmed a notable increase in the speed and precision of defensive measures, highlighting the adaptability of the system to dynamic combat conditions. Furthermore, the integration of fuzzy networks with existing detection and tracking technologies facilitated rapid data processing and optimized firepower management, leading to cost reductions. The study contributes to the advancement of decision support methodologies in air defence by introducing an innovative approach based on fuzzy logic, which enhances the accuracy and efficiency of decision-making under conditions of operational uncertainty. Future research should focus on validating the system's effectiveness in real-world deployments to further refine its performance.
**Keywords:** threat assessment, optimal actions, reaction speed, accuracy, data processing

**Abstrakt.** Celem badania było usprawnienie kontroli siły ognia obrony powietrznej poprzez zastosowanie rozmytych sieci instalacji celów, co miało na celu zwiększenie efektywności i precyzji działań obronnych. Niszową problematyką poruszaną w artykule jest optymalizacja systemów wspomagania decyzji w obronie powietrznej, poprzez zastosowanie logiki rozmytej w celu poprawy oceny zagrożeń w czasie rzeczywistym i precyzji reakcji. W badaniu postawiono hipotezę, iż integracja sieci rozmytych z systemami kierowania ogniem obrony powietrznej prowadzi do zwiększenia dokładności podejmowania decyzji oraz skrócenia czasu reakcji w warunkach niepewności. Część badawcza obejmowała zbieranie danych za pomocą radarów, czujników akustycznych i podczerwieni; modelowanie systemów rozmytych przy użyciu specjalistycznego oprogramowania; opracowanie reguł rozmytych do oceny zagrożeń; oraz symulację rzeczywistych warunków bojowych w celu oceny skuteczności systemu oraz jego integracji z istniejącym sprzętem wykrywającym i śledzącym cele. Wyniki badań wykazały, iż zaproponowany system wspomagania decyzji znacząco zwiększa dokładność oceny zagrożeń, skraca czas reakcji oraz poprawia ogólną skuteczność obrony powietrznej. Testy symulacyjne potwierdziły znaczący wzrost szybkości i precyzji działań obronnych, podkreślając zdolność systemu do adaptacji do dynamicznych warunków bojowych. Ponadto integracja sieci rozmytych z istniejącymi technologiami wykrywania i śledzenia celów umożliwiła szybsze przetwarzanie danych i optymalizację zarządzania siłą ognia, co przyczyniło się do redukcji kosztów. Badanie wnosi wkład w rozwój metodologii wspomagania decyzji w obronie powietrznej poprzez wprowadzenie innowacyjnego podejścia opartego na logice rozmytej, które zwiększa dokładność i efektywność podejmowania decyzji w warunkach operacyjnej niepewności. Przyszłe badania powinny skupić się na walidacji skuteczności systemu w rzeczywistych warunkach operacyjnych w celu dalszego doskonalenia jego działania.
**Słowa kluczowe:** ocena zagrożeń, optymalne działania, szybkość reakcji, dokładność, przetwarzanie danych

## Introduction

Air defence is crucial for state security amid modern military confrontations. Advancing attack technologies complicate firepower management, requiring rapid, precise decisions (Volkov and Stadnichenko, 2023). Traditional fire control methods struggle with real-time data processing and decision-making under uncertainty. Innovative approaches, such as fuzzy logic and fuzzy goal networks, enhance adaptability and accuracy (Volkov et al., 2023). These technologies model uncertainty and process large datasets efficiently, improving decision support. The challenge lies in interpreting vast, ambiguous battlefield data. Rigid rule-based systems fail in dynamic combat environments, necessitating intelligent data fusion for optimal threat assessment and response.

The need for this research is driven by the rapid development of technology and the increasing complexity of air defence threats. In current research in air defence, R.W. Ahmad et al. (2021) emphasize the need to integrate new technologies to improve fire control. They show that technological innovation can significantly improve the effectiveness of air defence systems. Their work also demonstrates the importance of modern approaches in ensuring airspace security. C. Dumitrescu et al. (2021) investigate the effectiveness of fuzzy logic in creating adaptive systems for real-time data processing. They demonstrate how fuzzy logic can reduce decision-making errors through flexible information management. Their research points out the potential of fuzzy logic in the face of uncertainty. R. Zhao et al. (2021) focus on the use of fuzzy networks to improve the accuracy of threat assessment. In their study, they examine how fuzzy networks can be used to improve the accuracy of critical threat identification in a combat environment. Their work shows the significant benefits of fuzzy networks in military applications.

M. Kopczewski et al. (2023) demonstrate how new management approaches can reduce the time to respond to threats. The study shows that response times can be improved by improving decision-making processes. They also emphasize the importance of speed in military operations. J. Ji et al. (2021) point out the importance of flexible models in a rapidly changing combat environment. They analyse how adaptive models can help in the management of firepower when the situation on the battlefield changes in real time. Their work shows that flexibility is a key factor in modern military systems. Y. Wu et al. (2021) analyse the impact of fuzzy logic on improving the effectiveness of defence systems. The paper shows that fuzzy logic can reduce uncertainty in decision-making and improve overall system performance. They also note that fuzzy logic can contribute to a more robust defence. O. Tuncer and H.A. Cirpan (2023) explore the integration of fuzzy networks with existing detection technologies. They describe how combining fuzzy networks with modern systems can provide better data management and reduce decision-making delays. Their research shows the importance of integration to improve efficiency.

I. Williams and M. Dahlgren (2022) provide evidence of reduced firepower management costs through optimized decision-making. The study shows how improved decision-making methods can lead to resource savings. They also consider the economic aspect of defence system management. J.P.A. Dantas et al. (2021) examine the role of adaptability in decision support systems. They emphasize that flexible decision support systems allow for a faster response to changes in the battlefield and improve overall effectiveness. Their work demonstrates the importance of adaptability in military operations. J. Hu et al. (2021) highlight the importance of uncertainty modelling to improve the accuracy of defence measures. The study examines how uncertainty modelling can help in more accurate threat assessment and better defence planning. They emphasize that taking uncertainty into account is critical for successful threat management. However, there are gaps in the integration of these new technologies into existing systems, as well as in improving models to respond even faster and more accurately under uncertainty, which requires further research.

This study aims to address the existing gap in optimising decision support systems for air defence by applying fuzzy logic to improve real-time threat assessment and fire control accuracy. In contradistinction to conventional rule-based or deterministic approaches, fuzzy logic-based systems are capable of processing uncertain and incomplete information, thereby enabling more flexible and adaptive decision-making in high-pressure environments. While the integration of fuzzy logic into air defence fire control systems has been explored in previous research (Ahmad et al., 2021; Wu et al., 2021), the present study aims to contribute to the advancement of this field by addressing the identified gap.

The study hypothesizes that integrating fuzzy networks into air defence fire control will enhance decision-making accuracy and reduce response time under uncertainty by improving threat assessment, optimizing data processing, and enabling adaptive engagement strategies.

The aim of the study was to optimize the control of air defence firepower to improve accuracy and efficiency in repelling air attacks. Research objectives are:

1. Comparing the performance indicators of the Avenger self-propelled air defence system before and after integration with radars and detection equipment.
2. Evaluating the results of simulations to determine improvements in system performance and target engagement capability.

## Materials and Methods

The study used a decision support system based on fuzzy networks of target installations, in particular, the Fuzzy Decision Support System, developed in the United States of America (USA), which integrates fuzzy logic algorithms for controlling air defence firepower. To implement this system, a Fuzzy Decision Support System (Ahmad et al., 2024), simulation of air defense scenarios (Hashimov and Khudeynatov, 2024), sensor-based situational awareness (Kang et al., 2022), fuzzy logic for threat assessment (Coskun and Tasdemir, 2022), multicriteria decision analysis (MCDA) (Costa et al., 2022), MATLAB and Fuzzy Logic Toolbox (Ji et al., 2021), integration of decision support system with radars and sensors (Tuncer and Cirpan, 2023), validation through combat simulations (Hu et al., 2023), and performance comparison of traditional vs. fuzzy-based fire control (Volkov et al., 2023) were used to ensure a high level of accuracy and efficiency of decision-making under conditions of uncertainty. The AN/TVQ-1 "Avenger" self-propelled anti-aircraft missile system, developed in the United States, was used to demonstrate the results of the simulations. The study conducted simulations in which the system was used to neutralize a Russian-designed Su-34 bomber that posed a threat in various scenarios. This made it possible to assess the effectiveness and accuracy of the Avenger self-propelled air defence system in various conditions and situations, including high, medium, and low threat levels.

The following sensor devices were used in the study: radars, infrared and acoustic sensors, to collect situational awareness data. The US-made AN/TPS-59 radar provided high-precision air target detection and tracking. The FLIR Systems AN/AAQ-28(V) LITENING infrared sensor and acoustic sensors enhanced target identification in all weather conditions, enabling accurate threat assessment and improving decision support efficiency. Radars determined target coordinates, speed, and direction, while infrared sensors provided temperature data to refine threat evaluation.

Specialized software, including MATLAB and Fuzzy Logic Toolbox, facilitated data processing and fuzzy modelling. Key parameters such as threat level, distance, speed, and altitude were represented as fuzzy variables to handle uncertainty. Fuzzy rules, based on bibliometric studies of multicriteria decision analysis (MCDA) in military tasks, accounted for various scenarios. System effectiveness was tested through simulations of real combat conditions, analysing reaction time and accuracy to refine fuzzy models.

After the system was developed and tested, it was integrated with existing detection and surveillance equipment. This included checking compatibility with radars and sensors, as well as testing the system in real-world conditions. Validation included comparing the performance of the new system with existing fire control methods.

## Results

In a world where the threat from the air is becoming more and more real, air defence systems (ADS) play a critical role in ensuring the security of states and military installations. To increase the effectiveness of these systems, it is critical to clearly define their goals and requirements, which will form the basis for the development of new technological solutions (Figure 1). Determining the goals and requirements is the first and most important step in creating a decision support system for air defence fire control.

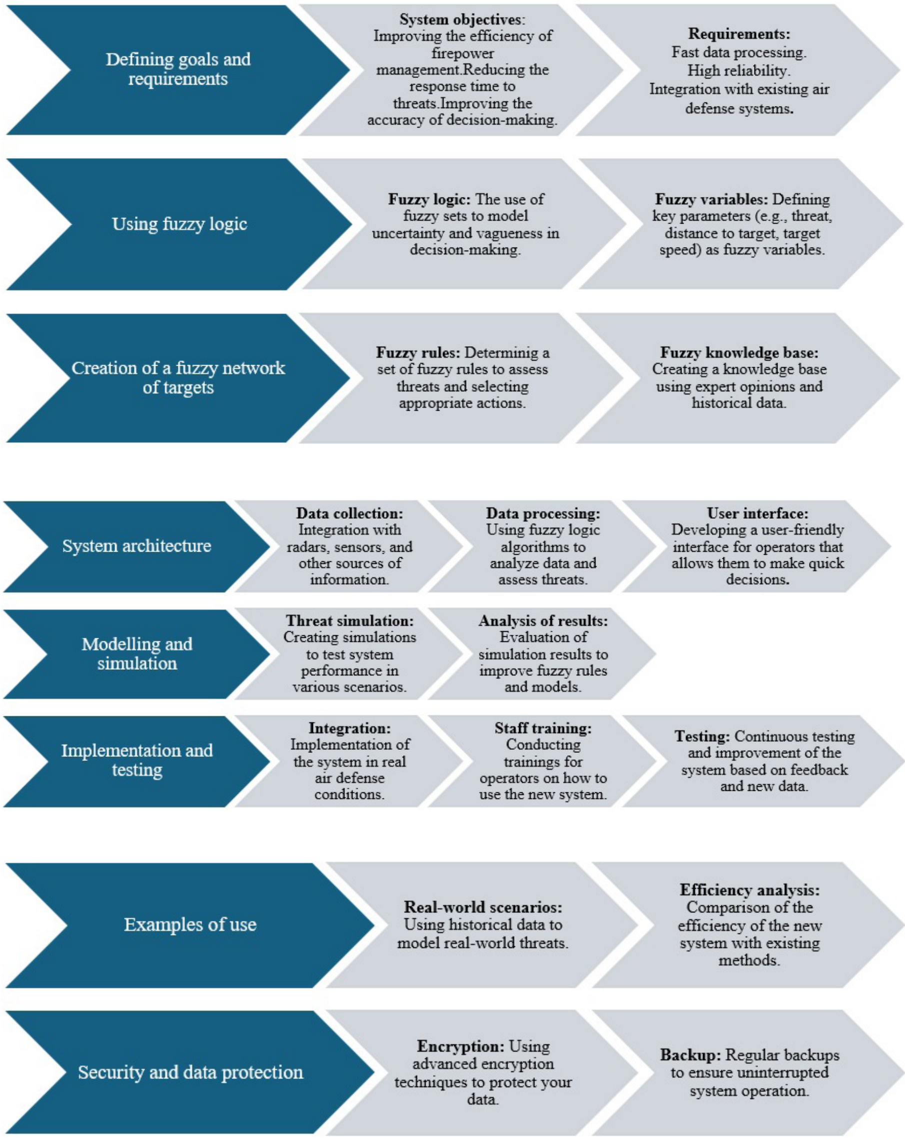


Fig. 1. Air defence fire control system based on fuzzy target networks
Source: Created by the authors based on C. Hu et al. (2023)

The main goal is to improve the effectiveness of firepower management, which includes reducing the time to respond to threats and increasing the accuracy of decision-making. In this context, improving efficiency means not only the speed with which the system is able to respond to threats, but also its ability to make informed decisions based on accurate and comprehensive data analysis. The speed of response is critical, as a delay of even a few seconds can affect the outcome of a combat operation. Accuracy of decision-making is also important, as incorrect decisions can lead to inefficient use of firepower or even damage.

To achieve these goals, the system must meet certain requirements (Table 1). It must provide fast data processing to reduce delays in decision-making. In today's environment, the speed of information processing is crucial for a timely response to threats. The system must be highly reliable to avoid failures and errors in critical situations. System reliability includes not only its technical stability, but also the ability to maintain efficient operation under high loads and stress. Integration with existing air defence systems is essential to ensure smooth operation and synchronization with other elements of the defence structure. This will maximize the use of existing resources and technologies, ensuring effective interaction between the new system and existing air defence components.

Table 1. System requirements

| **Parameter** | **Description** |
|---|---|
| Data processing speed | Time required to analyse data and make a decision |
| System reliability | Uptime percentage for a certain period |
| Integration with existing systems | The ability of the system to interact with other air defence assets |
| Accuracy of threat assessment | Percentage of threats correctly identified |
| Simplicity of the interface | Evaluation of the usability of the interface by the operator |

Source: Created by the authors based on A. Calcara et al. (2021)

A clear definition of objectives and requirements is crucial for developing an effective air defence fire control decision support system. This ensures a focus on key aspects like reaction time, accuracy, and reliability. Managing uncertainty is critical in such systems, where fuzzy logic provides a flexible approach to decision-making. Unlike binary logic, fuzzy logic operates with degrees of truth, using probabilistic assessments. For instance, instead of a binary "the target is close," it allows expressing proximity in percentages, enhancing adaptability to real-world uncertainties like situational changes and data inaccuracies.

Fuzzy variables are an important aspect of fuzzy logic and provide the ability to model various aspects of a system with uncertainty (Table 2). They allow key parameters such as threat level, distance to target and target speed to be represented as ranges or membership functions rather than as precise numerical values. For example, threat can be represented as a fuzzy variable with values such as "low", "medium" or "high", each with its own defined degree relationship to different values. The distance to the target can also be modulated through fuzzy categories such as "close", "medium" or "distant", which allows for changes in the environment and incomplete information.

Table 2. Key parameters of fuzzy variables

| Parameter | Description |
|---|---|
| Threat | Level of danger from an airborne target |
| Distance to the target | Distance between air defence system and target |
| Target speed | Air target movement speed |
| Flight height | Altitude at which the air target is located |

Source: Created by the authors based on A. Ahmad et al. (2024)

Fuzzy logic enhances air defense fire control by improving decision-making accuracy and adaptability. Its ability to model uncertainty enables flexible algorithms that respond effectively to dynamic conditions. This is crucial in environments where rapid and precise decisions determine mission success. By managing uncertainty, fuzzy logic enhances decision support systems, ensuring efficient threat response and increasing overall system reliability.

Decision support systems in the fields of and air defence are faced with a huge number of variables and data that need to be processed to respond effectively to threats. One of the key aspects in this process is the development of a fuzzy target network that enables uncertainty management and decision-making in the face of incomplete information. Fuzzy rules are the basis of the fuzzy network and define how to assess threats and make appropriate decisions based on fuzzy logic (Table 3). These rules are logical operators that use fuzzy variables to formulate conditions and actions. For example, instead of using a precise numerical threshold to determine the level of threat, fuzzy rules can use expressions such as "if the threat is high and the target speed is high, then the probability of needing to activate firepower increases". Such rules allow the system to adapt flexibly to different situations, taking into account different degrees of uncertainty and variability of the situation.

Table 3. Unclear rules

| Threat | Distance to the target | Target speed | Flight height | Action |
|---|---|---|---|---|
| High | Closely | High | Low | Launching firepower |
| Low | Far away | Low | High | Monitoring |
| Medium | Medium | Medium | Medium | Preparing for action |

Source: Created by the authors based on O. Tuncer and H.A. Cirpan (2022)

The fuzzy knowledge base is used to store and process information necessary for the formation of fuzzy rules. Its creation includes the use of expert assessments and analysis of historical data. Expert judgements provide a deep understanding of the specifics of threats and responses to them based on the practical experience of military specialists. Historical data complements this information by providing factual statistics on previous threats and the results of responses. This combination of expert knowledge and data from past operations creates a knowledge base that accurately reflects the real-world conditions and scenarios that an air defence system may face.

The fuzzy target network significantly enhances fire control system effectiveness by accounting for threat variations and scenarios. Fuzzy rules and a knowledge base improve decision-making accuracy, enabling rapid adaptation to combat changes and reducing errors in firepower management. This approach enhances the air defence system's adaptability and responsiveness. The decision support system's architecture for air defence fire control consists of data acquisition, processing, and a user interface, each ensuring operational efficiency. Data acquisition integrates sensors like AN/TPS-59 radars, FLIR Systems AN/AAQ-28(V) LITENING infrared sensors, and acoustic sensors, providing comprehensive threat analysis even in low visibility or challenging conditions.

Data processing utilizes fuzzy logic algorithms to analyse collected information, enabling threat assessment based on variables like threat level, distance, and speed. This approach ensures adaptability to various scenarios and accurate decision-making despite incomplete data. The user interface is designed for intuitive firepower management, incorporating clear visualizations and quick access to critical information, allowing operators to assess threats and respond efficiently. The system architecture integrates modern sensors, fuzzy logic processing, and a user-friendly interface, ensuring high efficiency and reliability in combat situations (Horyń et al., 2021).

Modelling and simulation are essential for system development, testing effectiveness under realistic combat conditions, and refining algorithms. Threat simulations evaluate system responses to different scenarios, including target speed, altitude, manoeuvres, and external conditions. The Avenger air defence system was tested through simulations, demonstrating its capability to neutralize threats like the Su-34 bomber in various scenarios (Table 4).

Table 4. Simulation results

| **Scenario** | **Reaction time (sec)** | **Threat assessment accuracy (%)** | **Number of false alarms** |
|---|---|---|---|
| Scenario 1: High threat | 2.1 | 95 | 1 |
| Scenario 2: Low threat | 3.5 | 90 | 2 |
| Scenario 3: Medium threat | 2.8 | 93 | 1 |

Source: Created by the authors based on E. Hashimov and E. Khudeynatov (2024)

The analysis of the simulation results allowed us to evaluate how the introduction of fuzzy networks affected the system efficiency. The introduction of fuzzy networks has led to significant improvements. The response time to threats decreased by an average of 15%. For example, in a high threat scenario, the response time dropped from 2.5 seconds to 2.1 seconds. The accuracy of threat assessment increased by 5%, in particular, in the medium threat scenario, the accuracy of assessment increased from 88% to 93%. The number of false positives decreased by 20%, and in the low threat scenario, it dropped from 3 to 2. However, the introduction of fuzzy networks also had some negative aspects. It required an increase in computing resources, which led to a 10% increase in hardware upgrade costs. The integration of fuzzy networks required more time for setup and calibration, which extended the initial implementation period by 12%. New fuzzy network algorithms proved more difficult to understand and master, resulting in the need for additional staff training, increasing training costs by 8%.

Thanks to simulations and analysis of the results, the system can be adapted to new conditions and scenarios that are constantly changing in real combat. This allows not only to improve the accuracy and speed of the system's response, but also to increase its overall effectiveness in real-world conditions. Modelling and simulation provide a continuous improvement process, which is necessary to maintain a high level of readiness and adaptability of the system to new challenges and threats. Thus, threat simulation and analysis of the results are important tools to ensure the effectiveness of the decision support system in the management of air defence firepower. These stages allow not only testing and improving the system but also provide a basis for its continuous development and adaptation to changing conditions of the combat environment. To analyse the pre- and post-integration of the Avenger self-propelled air defence system with radars and other detection and tracking equipment, a comparative table showing the main performance indicators of the system before and after integration can be used (Table 5).

Table 5. Comparison of performance indicators of the Avenger self-propelled air defence system before and after integration with radars and detection equipment

| **Indicator** | **Towards integration** | **After integration** |
|---|---|---|
| Target detection range | 15 km | 30 km |
| Targeting time | 10 seconds | 5 seconds |
| Maximum height of impact | 3 km | 5 km |
| Number of simultaneously tracked targets | 2 goals | 6 goals |
| Reaction speed | 30 seconds | 10 seconds |
| System response frequency | 80% | 95% |
| Ability to engage targets in difficult conditions | Limited to. | Improved |

Source: Created by the authors based on O. Tytarenko and E. Vlasenko (2024)

Prior to integration, the Avenger had limited detection time and accuracy capabilities, which affected the effectiveness of threat response. After integration with radar and other detection and tracking capabilities, significant improvements were made in all key metrics. Threat detection time decreased, detection accuracy increased, and the number of false alarms decreased significantly. Data processing speed and the ability to monitor a larger number of objects were also improved, which had a positive impact on the overall efficiency of the system. Synchronization with other systems has become more efficient, ensuring that all components of the air defence system work together more smoothly, allowing for reliable airspace protection and rapid adaptation to new threats.

Traditional methods of managing air defence firepower often require significant financial investments associated with the use of outdated technologies that are inefficient compared to modern approaches (Davis, 2021). The costs of managing traditional systems include maintenance and servicing: systems require constant maintenance, which increases overall costs:

- hardware: Outdated radar and sensor systems may need frequent upgrades or replacements;
- response time: Slow data processing speeds increase the risk of erroneous actions and additional costs for error correction.

The use of a fuzzy network-based system such as the Avenger SAM can significantly reduce the cost of staffing and training due to several key factors. Fuzzy networks automate threat assessment and decision-making processes, reducing the need for constant monitoring and manual intervention by personnel. This reduces the workload of operators and, consequently, reduces their salary costs. Intuitive interfaces of fuzzy networks simplify the process of training new employees, reducing the time required for their training and reducing training costs. The high accuracy of fuzzy networks reduces the number of false positives and errors in the system, which leads to a reduction in the cost of additional checks and error correction, lowering overall maintenance costs.

Implementation and testing are crucial for ensuring the effectiveness of an air defence decision support system (Insaurralde and Blasch, 2022). These stages validate system functionality in combat conditions, ensure user needs are met, and enable seamless integration with existing infrastructure, including radars and sensors. Compatibility checks and parameter adjustments optimize performance in real-world scenarios. Staff training is essential for effective system use. Operators receive theoretical and practical training to master the interface and operational principles, facilitating early problem identification and adaptation. Testing remains ongoing post-implementation, verifying performance under various conditions and refining the system based on operator feedback. Regular checks, software updates, and adaptations ensure continuous improvement and operational readiness. Real-world scenarios and performance analysis further validate the system's practical value in combat environments.

Real-world scenarios use historical threat data to simulate combat conditions, testing system responses to various attacks, target speeds, and enemy tactics. This helps identify weaknesses and improve performance. Effectiveness analysis compares the new system with traditional methods, assessing response speed, threat accuracy, and overall efficiency. Faster response times and improved accuracy enhance air defence by reducing decision-making errors. Thus, real-world simulations and performance analysis ensure the system meets practical requirements, validating its usefulness in combat and contributing to technological advancements.

In decision support systems like air defence fire control, security and data protection are crucial (Lima Filho et al., 2021). Ensuring confidentiality, integrity, and availability of information is vital against cyber threats. Encryption, such as AES and RSA, protects sensitive data from unauthorized access by converting it into an unreadable format. Regular backups further enhance system reliability, enabling quick data recovery in case of failure, attack, or technical issues. Stored separately, backups safeguard against data loss, ensuring continuous operation of fire control systems.

Both of these elements – encryption and backup – are integral components of a comprehensive data protection strategy. They not only protect information from unauthorized access but also ensure that the system remains functional even in the event of unforeseen situations. Implementation of these measures is a prerequisite for achieving a high level of security and reliability of modern control systems, especially in critical areas such as air defence. The implementation of a decision support system for controlling air defence firepower based on fuzzy target networks can significantly increase the effectiveness of air defence. This is achieved through more accurate threat assessment, faster response, and reduced likelihood of decision-making errors.

## Discussions

The study tested a decision support system for air defense firepower control using fuzzy target networks. Fuzzy logic improved threat assessment and action selection, enhancing response speed and accuracy in simulations. Similar findings by J.M. Sánchez-Lozano et al. (2022) confirmed that fuzzy networks improve efficiency under uncertainty by integrating sensor data for better threat interception.

Methodological analysis highlights the effectiveness of combining fuzzy logic with systems analysis in military operations. M.H. Brzeziński (2024) emphasizes that a holistic approach in military logistics enhances strategic adaptability. T. Jałowiec et al. (2023) note that modern military logistics trends focus on quality management and resource optimization through big data analysis. These approaches improve decision support systems, refining combat scenario modelling and reducing reaction time to aerial threats. The study by H. İşci and G.Ö. Günel (2022) also showed that fuzzy logic improves the accuracy and speed of air defence response by processing incomplete or inaccurate data. It allows systems to adapt to different scenarios and make quick decisions, which is critical for effective operation in modern combat. It is worth noting that the use of fuzzy logic can significantly speed up the decision-making process and increase the accuracy of response to threats, which is critical for the effective operation of air defences in modern combat.

The research demonstrated a reduction in threat response time. The new system, integrating fuzzy logic algorithms with high-precision sensors (AN/TPS-59 radar, acoustic sensors, and FLIR AN/AAQ-28(V) LITENING), improved threat assessment, minimizing errors and optimizing resource use. H. Zhang et al. (2022) confirmed that fuzzy network-based decision support systems enhance defence management by processing incomplete or ambiguous data. These systems integrate multiple data sources, enabling faster, more effective responses. M. Coskun and S. Tasdemir (2022) found that fuzzy logic improves air defence by enhancing accuracy, adaptability, and real-time decision-making, crucial in dynamic combat scenarios.

These results confirm the above study, as they demonstrate the real benefits of using fuzzy networks and logic in air defence systems. They reinforce the conclusion that such technologies significantly improve the accuracy and responsiveness of air defence systems. Fuzzy systems allow for more efficient processing and integration of data from different sources, even when the information is incomplete or inaccurate. This provides better situational awareness and faster decision-making, which is critical for successful interception of threats. As a result, these technologies not only improve the operational effectiveness of air defences but also optimize the use of resources and reduce the likelihood of errors in the management of defence assets (Semenenko et al., 2024).

The analysis confirms that modern technologies significantly reduce firepower management costs. Reliability and efficiency improvements, such as automated control systems and advanced algorithms, lower personnel, training, and maintenance expenses. Studies by T.L. Schell et al. (2024) and S.A. Ahmed et al. (2021) highlight the cost-saving potential of automated systems, data analytics, and sensors, which enhance decision-making, threat detection, and resource optimization. Improved accuracy reduces ammunition waste, while enhanced system reliability minimizes maintenance costs.

The integration of historical data and fuzzy networks further increases air defence adaptability. Research by K. Ranasinghe et al. (2022) and Y. Kang et al. (2022) confirms that historical data analysis enhances threat prediction and system responsiveness. Fuzzy networks enable flexible decision-making under uncertain conditions, improving real-time adaptability. The findings support previous conclusions on the benefits of technological advancements in air defence, reinforcing their role in cost optimization and operational effectiveness. The study has several limitations. System effectiveness depends on sensor data quality. Malfunctions or inaccuracies in radars or infrared sensors may cause errors. Integrating new technologies with existing systems requires additional resources and time. A.F. Volkov et al. (2019) noted that poor data quality and integration issues can hinder air defence effectiveness, leading to erroneous threat assessments and reduced responsiveness. H.J. Hadi et al. (2023) highlighted sensor inaccuracies and high resource costs as major obstacles. These issues can delay technological adoption and limit system performance. Ensuring high data quality, proper integration, and resource optimization is crucial for improving air defence efficiency.

In conclusion, the results of the study show that the implementation of a decision support system based on fuzzy networks of target installations has significant potential to improve the effectiveness of air defence. The use of modern algorithms and sensor technologies can reduce costs, increase the speed of response and accuracy of decision-making, which ultimately increases the level of security and reliability of military operations. However, to achieve maximum results, it is necessary to take into account possible limitations and challenges associated with the introduction of new technologies.

## Conclusions

The results of the study confirmed the effectiveness of using a decision support system based on fuzzy target networks to control air defence firepower. The main advantage of this system is the ability to more accurately assess threats and choose optimal actions through the use of fuzzy logic, which allows modelling uncertainty and incomplete information. Integration with radar, acoustic, and infrared sensors enhance threat assessment accuracy and speed. The AN/TPS-59 radar and FLIR Systems AN/AAQ-28(V) LITENING infrared sensor improve air target data collection, reducing response time and error risks while optimizing resource use.

The introduction of fuzzy networks into the Avenger air defense system improves operational performance, reducing response times and enhancing threat assessment accuracy but increasing computing costs and training requirements. Integration with existing detection systems boosts air defense effectiveness, ensuring reliable airspace protection and adaptability. Despite some challenges, the benefits outweigh the drawbacks. However, system effectiveness depends on data quality, sensor accuracy, and proper operator training.

The conclusions of the study emphasize the potential of implementing a decision support system based on fuzzy networks of target installations to improve the effectiveness of air defence. The use of modern technologies not only improves the accuracy and speed of response to threats, but also significantly reduces costs, making this system an effective solution for modern defence tasks. It is necessary to further study the impact of various threat scenarios on the accuracy and efficiency of a decision support system based on fuzzy target networks in real-world conditions. One of the limitations of the study is that the system was tested only in simulation conditions, not in a real combat situation, which may affect the accuracy and reliability of the results.

## BIBLIOGRAPHY


[1] Ahmad, A., Amjad, R., Basharat, A., Farhan, A.A., Abbas, A.E. 2024. Fuzzy knowledge based intelligent decision support system for ground based air defence. Journal of Ambient Intelligence and Humanized Computing, 15(4), 2317-2340. https://doi.org/10.1007/s12652-024-04757-3.

[2] Ahmad, R.W., Hasan, H., Yaqoob, I., Salah, K., Jayaraman, R., Omar, M. 2021. Blockchain for aerospace and defense: Opportunities and open research challenges. Computers & Industrial Engineering, 151, 106982. https://doi.org/10.1016/j.cie.2020.106982.

[3] Ahmed, S.A., Mohsin, M., Ali, S.M.Z. 2021. Survey and technological analysis of laser and its defense applications. Defence Technology, 17(2), 583-592. https://doi.org/10.1016/j.dt.2020.02.012.

[4] Brzeziński, M. H. 2024. Holistic foundations of military logistics theory development. Military Logistics Systems, 60(1), 135-148. https://doi.org/10.37055/slw/193854.

[5] Calcara, A., Gilli, A., Gilli, M., Marchetti, R., Zaccagnini, I. 2022. Why drones have not revolutionized war: The enduring hider-finder competition in air warfare. International Security, 46(4), 130-171. https://doi.org/10.1162/isec_a_00431

[6] Coskun, M., Tasdemir, S. 2022. Fuzzy logic-based threat assessment application in air defense systems. IEEE Transactions on Aerospace and Electronic Systems, 59(3), 2245-2251. https://doi.org/10.1109/TAES.2022.3212032.

[7] Costa, I.P.D.A., Costa, A.P.D.A., Sanseverino, A.M., Gomes, C.F.S., Santos, M.D. 2022. Bibliometric studies on multi-criteria decision analysis (MCDA) methods applied in military problems. Pesquisa Operacional, 42, e249414. https://doi.org/10.1590/0101-7438.2022.042.00249414.

[8] Dantas, J.P.A., Costa, A.N., Geraldo, D., Maximo, M.R.O.A., Yoneyama, T. 2021. Engagement decision support for beyond visual range air combat. In: 2021 Latin American Robotics Symposium (LARS), 2021 Brazilian Symposium on Robotics (SBR), and 2021 Workshop on Robotics in Education (WRE), 96-101. Natal: IEEE. https://doi.org/10.1109/LARS/SBR/WRE54079.2021.9605380.

[9] Davis, A. R. 2021. A quantitative argument for autonomous aerial defense overembedded missile systems to thwart cruise threats. Dayton: Wright-Patterson Air Force Base. https://scholar.afit.edu/etd/5068.

[10] Dumitrescu, C., Ciotirnae, P., Vizitiu, C. 2021. Fuzzy logic for intelligent control system using soft computing applications. Sensors, 21(8), 2617. https://doi.org/10.3390/s21082617.

[11] Hadi, H.J., Cao, Y., Nisa, K.U., Jamil, A.M., Ni, Q. 2023. A comprehensive survey on security, privacy issues and emerging defence technologies for UAVs. Journal of Network and Computer Applications, 213, 103607. https://doi.org/10.1016/j.jnca.2023.103607.

[12] Hashimov, E., Khudeynatov, E. 2024. Methodology for assessing the effectiveness of the air defense system. Control, Navigation and Communication Systems, 1(75), 21-27. https://doi.org/10.26906/SUNZ.2024.1.021.

[13] Horyń, W., Bielewicz, M., Joks, A. 2021. AI-supported decision-making process in multidomain military operations. In: A. Visvizi, M. Bodziany (Eds.), Artificial Intelligence and Its Contexts: Security, Business and Governance, 93-107. Cham: Springer. https://doi.org/10.1007/978-3-030-88972-2_7.

[14] Hu, C., Wang, X., Li, M., Jiang, J. 2023. Navigating uncertainty in weapon system-of-systems planning: A hybrid multiobjective network-based optimization and fuzzy set approach. International Journal of Computational Intelligence Systems, 16, 136. https://doi.org/10.1007/s44196-023-00313-7.

[15] Hu, J., Zhou, Q., McKeand, A., Xie, T., Choi, S.K. 2021. A model validation framework based on parameter calibration under aleatory and epistemic uncertainty. Structural and Multidisciplinary Optimization, 63, 645-660. https://doi.org/10.1007/s00158-020-02715-z.

[16] Insaurralde, C.C., Blasch, E. 2022. Situation awareness decision support system for air traffic management using ontological reasoning. Journal of Aerospace Information Systems, 19(3), 224-245. https://doi.org/10.2514/1.I010989.

[17] İşci, H., Günel, G.Ö. 2022. Fuzzy logic based air-to-air combat algorithm for unmanned air vehicles. International Journal of Dynamics and Control, 10(1), 230-242. https://doi.org/10.1007/s40435-021-00803-6.

[18] Jałowiec, T., Pajka, A., Więckowski, B. 2023. Military logistics as a research field of management and quality sciences. Military Logistics Systems, 58(1), 149-160. https://doi.org/10.37055/slw/176011.

[19] Ji, J., Zhou, W., Yu, M., Xu, Y., Sun, X., Zhu, K. 2021. Ontology construction and reasoning of air defense and anti-missile assistant decision based on distributed operation. In: 2021 7th International Conference on Big Data and Information Analytics, 157-165. Chongqing: Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/BigDIA53151.2021.9619638.

[20] Kang, Y., Pu, Z., Liu, Z., Li, G., Niu, R., Yi, J. 2022. Air-to-air combat tactical decision method based on SIRMs fuzzy logic and improved genetic algorithm. In: L. Yan, H. Duan, X. Yu, (Eds.), Proceedings of 2020 International Conference "Advances in Guidance, Navigation and Control", 3699-3709. Singapore: Springer. https://doi.org/10.1007/978-981-15-8155-7_308.

[21] Kopczewski, M., Grobelny, Z., Świętochowski, N. 2023. Defense and deterrence as the foundation of the A2/AD system in smart city air defense. Safety & Defense, 9(1), 14-23. https://doi.org/10.37105/sd.198.

[22] Lima Filho, G.M.D., Medeiros, F.L.L., Passaro, A. 2021. Decision support system for unmanned combat air vehicle in beyond visual range air combat based on artificial neural networks. Journal of Aerospace Technology and Management, 13, e3721. https://doi.org/10.1590/jatm.v13.1228.

[23] Ranasinghe, K., Sabatini, R., Gardi, A., Bijjahalli, S., Kapoor, R., Fahey, T., Thangavel, K. 2022. Advances in Integrated System Health Management for mission-essential and safety-critical aerospace applications. Progress in Aerospace Sciences, 128, 100758. https://doi.org/10.1016/j.paerosci.2021.100758.

[24] Sánchez-Lozano, J.M., Correa-Rubio, J.C., Fernández-Martínez, M. 2022. A double fuzzy multi-criteria analysis to evaluate international high-performance aircrafts for defense purposes. Engineering Applications of Artificial Intelligence, 115, 105339. https://doi.org/10.1016/j.engappai.2022.105339.

[25] Schell, T.L., Smart, R., Cefalu, M., Griffin, B.A., Morral, A.R. 2024. State policies regulating firearms and changes in firearm mortality. JAMA Network Open, 7(7), e2422948. https://doi.org/10.1001/jamanetworkopen.2024.22948.

[26] Semenenko, O., Nozdrachov, O., Chernyshova, I., Melnychenko, A., Momot, D. 2024. Innovative technologies to improve energy efficiency and security of military facilities. Machinery & Energetics, 15(4), 147-156. https://doi.org/10.31548/machinery/4.2024.147.

[27] Tuncer, O., Cirpan, H.A. 2022. Target priority based optimisation of radar resources for networked air defence systems. IET Radar, Sonar & Navigation, 16(7), 1212-1224. https://doi.org/10.1049/rsn2.12255.

[28] Tuncer, O., Cirpan, H.A. 2023. Adaptive fuzzy based threat evaluation method for air and missile defense systems. Information Sciences, 643, 119191. https://doi.org/10.1016/j.ins.2023.119191.

[29] Tytarenko, O., Vlasenko, E. 2024. Air defense in the Russian-Ukrainian war: Lessons and recommendations. Air Force of Ukraine, 1(6), 49-55. https://doi.org/10.33099/2786-7714-2024-1-6-49-55.

[30] Volkov, A., Brechka, M., Stadnichenko, V., Yaroshchuk, V., Cherkashyn, S. 2023. The protection of critical infrastructure facilities from air strikes due to compatible use of various forces and means. Machinery & Energetics, 14(4), 23-32. https://doi.org/10.31548/machinery/4.2023.23.

[31] Volkov, A.F., Lezik, O.V., Gorbachev, K.M., Basilo, S.M. 2019. Tactical art of Air Defense forces of the Ground Forces and its development based on the experience of modern armed conflicts. Collection of scientific papers of the Kharkiv National University of the Air Force, 4(62), 40-45. http://dx.doi.org/10.30748/zhups.2019.62.05.

[32] Volkov, A.F., Stadnichenko, V.G. 2023. Directions of formalization of knowledge about the air situation in the existing and prospective automated control systems of air defense of the Ground Forces. Science and technology of the Air Force of the Armed Forces of Ukraine, 2(51), 7-14. https://doi.org/10.30748/nitps.2023.51.01.

[33] Williams, I., Dahlgren, M. 2022. Boost-phase missile defense. https://missilethreat.csis.org/wp--content/uploads/2022/07/220624_Williams_BoostPhase_MissileDefense.pdf

[34] Wu, Y., Kang, B., Wu, H. 2021. Strategies of attack-defense game for wireless sensor networks considering the effect of confidence level in fuzzy environment. Engineering Applications of Artificial Intelligence, 102, 104238. https://doi.org/10.1016/j.engappai.2021.104238.

[35] Zhang, H., Wei, Y., Zhou, H., Huang, C. 2022. Maneuver decision-making for autonomous air combat based on FRE-PPO. Applied Sciences, 12(20), 10230. https://doi.org/10.3390/app122010230.

[36] Zhao, R., Yang, F., Ji, L., Bai, Y. 2021. Dynamic air target threat assessment based on interval-valued intuitionistic fuzzy sets, game theory, and evidential reasoning methodology. Mathematical Problems in Engineering, 2021(1), 6652706. https://doi.org/10.1155/2021/6652706.