ISSN 2669-2023 (print) / ISSN 2538-8959 (on-line) / **https://doi.org/10.47459/cndcgs.2026.157**

Evaluation of the Influence of Sensor Distance from Element C2 on the Effectiveness of Fire Control Using Operational Analysis Methods

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Abstract

This paper evaluates how the distance between air defence sensors and the command and control (C2) element influences fire-control effectiveness. Three deployment variants at 1, 7 and 20 km were assessed by means of operational analysis and the TOPSIS multi-criteria method using latency, connection reliability, situational awareness (SA), probability of kill (P_{kill}), survivability and logistical complexity. The baseline model favours the short-distance configuration, but sensitivity analysis shows that greater emphasis on survivability shifts the optimum towards the medium-distance variant. A separation of approximately 5-10 km provides the most robust operational compromise for contemporary air defence employment.

KEY WORDS: *air defence, command and control, sensors, fire control, TOPSIS, operational analysis, survivability*

Citation: Křišťál, M.; Hanuš, V. Evaluation of the Influence of Sensor Distance from Element C2 on the Effectiveness of Fire Control Using Operational Analysis Methods. In Proceedings of the Challenges to National Defence in Contemporary Geopolitical Situation, Brno, Czech Republic, 7-10 September 2026. ISSN 2538-8959, https://doi.org/10.47459/cndcgs.2026.157

1. Introduction

Command and control, or C2, systems are central to the combat use of air defence units. They connect sensors, command posts, communication networks and weapon systems into one functional structure. Through this structure, commanders can receive and process information, develop situational awareness, coordinate available resources and conduct effective fire control [1,2]. The performance of the C2 system therefore has a direct effect on the ability of an air defence unit to detect, identify, assess and engage airborne threats within the required time.

The quality, accuracy and speed of information entering the C2 element strongly influence the decision-making process. Reliable and timely data allow commanders and operators to assess threats correctly, assign targets to suitable weapon systems and avoid unnecessary or repeated engagements. In contrast, incomplete, delayed or incorrect information may lead to slower decisions, poor target classification, inefficient use of missiles and guns, or failure to engage a threat before it reaches its objective [3,4]. Information quality affects each stage of the command and control process, including detection, tracking, identification, threat evaluation, weapon assignment and engagement control.

One factor that can strongly affect the transfer of information between sensors and the C2 element is the physical distance between them. Greater distance may require additional communication nodes, relay stations, stronger transmitters or different network structures. It may also increase transmission delays, reduce data quality and create more points where communication can be interrupted. At the same time, distance influences bandwidth needs, signal strength, network stability and resistance to electronic attack or physical damage [1,5]. These factors are especially important in air defence, where even a small delay may affect the ability to engage fast-moving targets.

Sensor placement also creates an operational balance between protection and communication performance. Positioning sensors close to the C2 element may improve communication quality, reduce delays and simplify coordination. However, placing several important assets in the same area increases the risk that they will be detected, targeted and destroyed during a single attack. Excessive dispersion can improve survivability, but it may also reduce connection quality, increase delays and weaken situational awareness. This may result in slower threat assessment, less accurate fire control and reduced combat effectiveness [1,6].

The aim of this paper is to analyse how the distance between sensors and the C2 element affects fire-control effectiveness. The study applies operational analysis methods, including sensitivity analysis, to examine how changes in input values, assumptions and criteria weights influence the final results [3,7,8]. This approach helps test whether the conclusions remain stable under different operational conditions.

The paper seeks to support a clearer understanding of the relationship between sensor placement, communication performance, C2 functions and fire-control results. The findings may support planning decisions related to air defence formations, sensor deployment, communication design and the balance between system survivability and operational performance in present and future combat conditions.

2. Key Factors Influencing Data Transmission Between Air Defence Sensors and C2 system

The C2 system in air defence units represents an integrated set of elements that enables the collection, transmission, processing, and evaluation of information about the air situation and supports decision-making on the employment of firepower. For the C2 system to function effectively, information provided by sensors must be available in a timely, accurate, and reliable manner. The quality and speed of data transmission directly influence the length of the decision-making cycle, engagement success, and the overall combat effectiveness of the unit.

Air defence sensors and their role. Air defence sensors mainly include radar systems, electro-optical systems, passive sensors, and identification friend or foe systems [9–12]. Their primary tasks are to:

1. detect airborne targets;
2. measure their parameters (position, altitude, direction, speed);
3. identifying friend or foe;
4. providing data for SA [7,9–11,18].

The quality of data obtained from these sensors directly influences the accuracy of target trajectory prediction, the response time of weapon systems, and the ability to correctly prioritise threats.

Command and control system. The C2 element represents the central component responsible for information processing and fire control. In the context of air defence, it primarily involves the fusion of sensor data, the creation of the air situation picture, threat assessment, decision-making on the employment of firepower, target allocation, and coordination of units [2,13–16]. The effectiveness of the C2 system depends on several key factors, including the availability and quality of data, the stability and capacity of the communication network, the latency between detection and response, the ability of operators to make decisions within the required time frame, and the system's resistance to interference and attacks. These factors represent fundamental parameters used in the evaluation and analysis of C2 systems.

Factors affecting data transmission between sensors and C2 element. Data transmission between sensors and the C2 element is influenced by a number of technical and tactical factors. Based on consultations with domain experts and operational experience, several key factors have been identified.

Transmission latency. Latency represents the time interval between the detection of a target by a sensor and the availability of this information at the C2 element. It is influenced by several factors, including:

- the distance between the sensor and the C2 element;
- the transmission medium (radio link, optical link, or cable);
- the volume of transmitted data;
- interference or network congestion.

Higher latency prolongs the decision-making cycle (OODA loop [3]), thereby reducing the effectiveness of fire control, particularly when engaging fast and low-flying targets.

Connection reliability. Communication reliability can be characterised by several parameters, including:

- packet loss rate;
- probability of link failure;
- signal stability over time.

High packet loss or repeated communication failures degrade SA and may lead to delayed or incorrect decision-making.

Quality of situational awareness. The SA refers to the ability to maintain an accurate and up-to-date representation of the air situation [17]. The level of SA depends on several factors, including:

- data quality;
- time synchronisation of information;

- data fusion from multiple sensors;
- the continuity of information flows.

Degradation of SA directly reduces the effectiveness of fire control and increases the risk of an inadequate response to emerging threats.

The effect of distance between sensors and C2 element. The distance between air defence sensors and the C2 element significantly influences several operational and technical parameters of the system. In particular, it affects:

- transmission latency (greater distances generally lead to increased delays in information transmission);
- signal strength and communication stability (elements located at greater distances may be more susceptible to signal degradation or communication outages);
- the risk of simultaneous destruction of system elements (elements located close to each other are more vulnerable to detection and engagement by precision-guided munitions);
- the ability of the C2 system to maintain reliable communication during manoeuvres.

It is therefore necessary to find a compromise distance that:
– minimises information loss,
– maintains the decision-making cycle within acceptable limits,
– increases the survivability of system elements in combat conditions.

Operational analysis in the context of air defence. Operational analysis (OA) makes it possible to describe and quantify the relationships between technical parameters, tactical conditions, and combat outcomes. It enables:

1. the creation of mathematical models;
2. the simulation of various operational scenarios;
3. the determination of priorities and weights for evaluation criteria;
4. the optimisation of decision-making processes.

In the context of air defence, OA is particularly suitable for:
– evaluating unit deployment options,
– predicting the performance of sensor networks,
– analysing the stability of decisions under changing operational conditions.

An integral part of OA is sensitivity analysis, which allows the robustness of conclusions to be verified when input parameters or tactical conditions change.

3. Effectiveness Evaluation Criteria

The effectiveness of the combat use of the C2 system in air defence units can only be evaluated if clearly defined and measurable criteria are established. These criteria enable the comparison of different sensor deployment options in relation to the C2 element, identification of their strengths and weaknesses, and quantification of their impact on the overall performance of the system. The selection of criteria must reflect both the technical aspects of data transmission and the tactical conditions of combat, as well as the resulting fire effectiveness.

The following criteria are designed to cover the main areas influenced by the distance between sensors and the C2 element, namely information transfer, the quality of SA, response time, and the survivability of system elements. The individual criteria are derived from the factors identified later in this chapter and are further supplemented by additional indicators to support the selection of the most appropriate decision option. The following sections define the individual criteria used to evaluate the effectiveness of the analysed variants:

1. **Information transmission latency.** Information transmission latency is used as a cost criterion, meaning that lower values are preferred. Increased latency reduces the time available for decision-making and engagement, negatively affects the timeliness of SA, and may decrease the accuracy of fire-control solutions. Its value is primarily influenced by the sensor–C2 distance and the characteristics of the communication medium.
2. **Reliability and stability of the connection.** Connection reliability is used as a benefit criterion, meaning that higher values are preferred. Reduced reliability may cause packet loss, communication outages, and discontinuities in data flow, thereby degrading the air situation picture and delaying decision-making. This criterion is particularly important in environments affected by electronic warfare and during manoeuvre operations.
3. **Quality of situational awareness.** The SA is used as a benefit criterion, meaning that higher values are preferred. Its quality reflects the accuracy, timeliness, and completeness of the air situation picture and is influenced primarily by transmission latency, communication reliability, and the continuity of sensor-data updates. Degraded SA may reduce the effectiveness of target prioritisation and increase the risk of delayed or incorrect decision-making.
4. **Probability of successful engagement.** The P_{kill} expresses the likelihood that a target will be successfully neutralised or destroyed during an engagement and is therefore used as a benefit criterion, meaning that

higher values are preferred. Its relationship with sensor–C2 distance is indirect, as changes in distance affect engagement effectiveness primarily through their influence on latency, communication reliability, and SA. Consequently, greater sensor–C2 separation may reduce P_{kill} if the resulting degradation of data transmission limits the timeliness and accuracy of the fire-control process.

5. **Survivability of C2 elements and sensors.** In combat conditions, not only the functional performance of the system is important, but also its ability to withstand enemy detection and fire effects. The spatial separation between sensors and the C2 element influences:

- the risk of simultaneous destruction of C2 and sensor elements by a single strike;
- the reduction of detectability through spatial dispersion;
- the possibility of exploiting terrain masking and cover.

Higher dispersion generally increases the survivability of system elements by reducing their vulnerability to precision strikes. This criterion has gained increasing importance due to the growing threat posed by precision-guided munitions and intelligence, surveillance and reconnaissance (ISR) systems, including unmanned aerial platforms.

6. **Logistical and operational complexity.** Each deployment variant is associated with specific logistical and operational constraints that may affect its practical implementation. In particular, these include:

- complexity of movement and repositioning of system elements;
- requirements for communication equipment and supporting infrastructure;
- energy supply requirements;
- speed of deployment and redeployment.

The logistical feasibility of a given variant may significantly influence its usability in dynamic operational environments or during frequent manoeuvre operations.

The overall effectiveness of each deployment variant is determined by combining the results obtained for the individual evaluation criteria. In this study, these criteria are aggregated using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), which enables the calculation of evaluation scores and the ranking of the analysed variants.

4. Modelling and Methodology

The aim of this chapter is to present the procedure used to analyse, quantify and compare individual variants of sensor deployment in relation to the C2 element. The methodology is based on the principles of operational analysis (OA), which provides formal tools for modelling complex technical and tactical relationships, simulating different operational scenarios and performing multi-criteria evaluation.

In this work, operational analysis is applied to systematically assess how the distance between sensors and the C2 element influences fire control effectiveness and the overall combat capability of the air defence system.

The proposed methodology consists of several main steps: formulation of model assumptions, definition of variables and parameters, calculation of individual evaluation criteria, aggregation of results using a multi-criteria decision-making method, and sensitivity analysis.

Definition of model variables and parameters. To quantify the effects of the sensor–C2 separation, the following model variables and parameters are defined:

1. d – distance between the sensor and the C2 element (km);
2. $t(d)$ – data transmission latency as a function of distance d;
3. $p\_loss(d)$ – probability of data loss or communication failure;
4. $SA(d)$ – SA quality index;
5. $P\_kill(d)$ – estimated probability of successful engagement based on the quality of available data;
6. $Surv(d)$ – estimated survivability of the C2 element and sensors at a given level of spatial dispersion.

The relationships between these variables may be described using deterministic models (e.g., linear increase in latency with distance) or probabilistic models (e.g., exponential growth of packet loss probability with increasing distance).

Sensor deployment variants. For evaluation purposes, three simplified deployment variants (representing typical tactical configurations of sensor placement relative to the C2 element) have been defined:

1. Variant A – short sensor–C2 separation (approximately 1 km);
2. Variant B – medium sensor–C2 separation (approximately 5–10 km);
3. Variant C – long sensor–C2 separation (approximately 15–30 km).

For each variant, the values of the individual evaluation criteria will be calculated using the proposed model.

Mathematical and probabilistic models. The following mathematical and probabilistic models are used to describe the key parameters of the analysed system.

1. **Latency model.** Latency is a linear function of the distance d between the sensor and the C2 element

$$t(d) = t_0 + \alpha d.$$

where: t_0 – is the initial (technical) latency of the system: α – is the latency growth coefficient with respect to distance.

2. **Loss and failure model.** The probability of a packet loss or a communication failure is expressed using an exponential model

$$p_{\text{loss}}(d) = 1 - e^{-kd}.$$

where: k – is the coefficient expressing the sensitivity of the communication link to distance and interference; e – is the Euler's number ($e \approx 2.71828$).

3. **Situational awareness model.** The quality of SA is modelled as a composite index reflecting the combined influence of data transmission latency, communication reliability, and sensor-data update frequency. The SA quality index for a given sensor–C2 distance d is calculated as:

$$SA(d) = w_1[1 - t_{\text{norm}}(d)] + w_2[1 - p_{\text{loss}}(d)] + w_3 f_{\text{update}}(d).$$

where: $t_{\text{norm}}(d)$ is the normalised data transmission latency, $p_{\text{loss}}(d)$ is the probability of packet loss or communication failure, and $f_{\text{update}}(d)$ is the normalised frequency of sensor-data updates. The weighting coefficients w_1, w_2, and w_3 express the relative importance of the individual factors and satisfy the condition $w_1 + w_2 + w_3 = 1$. Higher values of $SA(d)$ indicate a more accurate, timely, and reliable representation of the air situation, whereas lower values reflect degradation caused by increased latency, reduced communication reliability, or a lower update frequency.

4. **Probability of successful engagement model.** The probability of successful engagement depends primarily on the quality of SA and the available response time. It can therefore be expressed as

$$P_{\text{kill}}(d) = f\big(SA(d), t(d)\big).$$

Survivability model. The survivability of system elements increases with greater spatial dispersion between sensors and the C2 element. In simplified form, survivability can be expressed as a function of distance

$$\text{Surv}(d) = h(d).$$

where $h(d)$ is a monotonically increasing function of the sensor–C2 distance, representing the assumption that greater spatial separation increases the survivability of system elements.

Multi-criteria decision-making method. To compare the analysed deployment variants, a multi-criteria decision-making method, such as the TOPSIS, will be applied.

The selected method enables:

1. criteria normalization;
2. incorporation of weights assigned to individual evaluation criteria;
3. calculation of evaluation scores for each variant;
4. ranking of the analysed variants according to their overall effectiveness.

The weights of individual criteria will be determined based on expert judgement, reflecting their relative importance for the operational effectiveness of the air defence system (for example, communication reliability may be assigned a higher weight than logistical complexity) [8].

Sensitivity analysis is used to verify the robustness of the obtained results. It examines how variations in key input parameters influence the final ranking of the analysed variants. The analysis includes changes in the weights assigned to individual evaluation criteria, such as increasing the importance of survivability, changes in model parameters, such as variations in the latency coefficient α, and an assessment of whether the ranking of deployment variants changes under modified conditions.

5. Evaluation of Variants Using Operational Analysis

In this chapter, the individual variants of sensor deployment relative to the C2 element are evaluated using the effectiveness criteria defined and presented in Chapter 4. The aim is to analyse how the effectiveness of the C2 system changes with varying sensor–C2 separation and to identify the variant that provides the optimal balance between data transmission speed, connection reliability, SA and element survivability.

The evaluation process consists of three main steps: the calculation of the values of individual criteria, the normalisation of the results and application of the selected multi-criteria decision-making method, and the determination of the ranking of the analysed deployment variants.

Based on the models described in Chapter 4, the values of the evaluation criteria, including latency, connection reliability, SA, P_{kill}, survivability, and logistical complexity, were calculated using sensor–C2 distances of approximately 1 km for Variant A, 7 km for Variant B, and 20 km for Variant C. The calculations were performed using a baseline system latency of $t_0 = 20\,\text{m}\,\text{s}^{-1}$, a latency growth coefficient of $\alpha = 3\,\text{ms}\,\text{km}^{-1}$, and a communication-link sensitivity coefficient of $k = 0.10$. The indices of $SA(d)$, probability of successful engagement $P_{\text{kill}}(d)$, and survivability $\text{Surv}(d)$ were derived as composite indicators based on the weighted influence of latency $t(d)$ and packet loss probability $p_{\text{loss}}(d)$.

Table 1.

Calculated values of the evaluation criteria for the analysed deployment variants

Criterion	**Variant A 1 km**	**Variant B 7 km**	**Variant C 20 km**
Latency $t(d)$ $[\text{ms}^{-1}]$	23	41	80
Packet loss $p_{\text{loss}}(d)$	0.095	0.503	0.863
SA (in the range 0-1)	0.95	0.78	0.42
P_{kill} (in the range 0-1)	0.92	0.83	0.58
Survivability (in the range 0-1)	0.25	0.65	0.90
Logistical complexity (in the range 0-1)	0.20	0.45	0.80

The values of latency and packet loss were calculated using the mathematical relationships defined above. The remaining criteria—situational awareness, probability of successful engagement, survivability, and logistical complexity—were determined by expert estimation on a normalised scale from 0 to 1.

The expert estimates were obtained through a questionnaire survey involving specialists in the field of air defence, command and control, and operational analysis from different organisations and workplaces. The values presented in Table 1 represent the arithmetic mean of the responses provided by the participating experts.

These estimates reflect the expected operational characteristics of the individual deployment variants, including communication reliability, information availability, spatial dispersion, vulnerability, coordination requirements, and logistical demands. They are not intended to represent universally valid or experimentally verified values. Their primary purpose is to demonstrate the applicability of the proposed evaluation model and to illustrate how quantitatively calculated and qualitatively assessed criteria can be integrated within a multi-criteria decision-making framework. In practical applications, the values should be further refined using a larger expert sample, experimental measurements, operational data, or simulation results.

The evaluation results are summarized in Table 1 and can be reproduced as follows:

1. **Comparison of latency, packet loss, and situational awareness:**
   - Variant A achieves the lowest latency and packet loss and the highest level of SA;
   - Variant C shows the opposite pattern, with the highest latency and packet loss and the lowest level of SA;
   - Variant B provides intermediate values for all three criteria.

2. **Probability of successful engagement:**
   - Variant A: highest probability of successful engagement. This is due to the lowest latency, the highest communication reliability, and the highest level of SA;
   - Variant B: slightly lower probability. This is caused by increased latency and a moderate reduction in communication reliability, while SA remains at an acceptable level;
   - Variant C: noticeably reduced probability of successful engagement. This results from high latency, increased packet loss, and degraded SA, which reduce the timeliness and accuracy of fire control.

3. **Survivability of C2 and sensors:**
   - Variant A: lowest survivability due to higher detectability and concentration of system elements;
   - Variant B: balanced solution with reduced concentration of signatures;

- Variant C: highest survivability due to greater spatial dispersion and lower probability of simultaneous strikes.

4. **Logistical complexity:**
   - Variant A: lowest logistical complexity;
   - Variant B: increased communication and coordination requirements;
   - Variant C: high requirements for communication infrastructure, coordination and synchronisation of system elements.

Each evaluation criterion has a different direction of preference (e.g., for latency the lower value is preferred, while for survivability the higher value is preferred). Therefore, the criteria should be first normalised to enable comparison on a common scale within the interval ⟨ 0;1⟩. Subsequently, weights should be assigned to the individual criteria according to their relative importance for the operational effectiveness of the air defence system.

Selected criteria weights and their justification. Determining the weights of individual criteria represents a fundamental step in multi-criteria decision-making. The assigned weights reflect the relative importance of individual factors influencing the overall effectiveness of the C2 system in air defence operations. [8]

In this work, the weights were determined based on:

1. tactical and technical requirements of air defence;
2. general principles of Theory of Engagement and Fire Control;
3. analysis of the impact of individual criteria on combat effectiveness;
4. the logic of fire control and the role of C2 within the OODA decision-making cycle.

The sensitivity analysis will determine whether the identified optimal variant remains stable across different scenarios or whether small changes in input parameters lead to a different solution.

Table 2.

Criterion weights used in TOPSIS and sensitivity analysis

Criterion	**Scenario 1: Performance**	**Scenario 2: Balance**	**Scenario 3: Survivability**
Latency	0.25	0.15	0.10
Connection reliability	0.25	0.20	0.15
SA	0.20	0.15	0.10
Probability of kill	0.20	0.15	0.10
Survivability	0.10	0.30	0.50
Logistical complexity	0.05	0.05	0.05

The rationale for the selected weights of individual criteria (restricted just to Scenario 1) is discussed below:

Latency (weight 0.25) — key to decision-making speed. Transmission latency directly affects:

1. the speed of the decision-making cycle;
2. the accuracy of target trajectory prediction;
3. the available engagement time for the weapon system.

Air defence systems frequently operate against fast-moving targets such as unmanned aerial vehicles or guided missiles. In such conditions, delays in information transmission and processing within the C2 system can significantly reduce the available reaction time and negatively affect engagement effectiveness. For this reason, latency represents one of the most critical parameters and was therefore assigned one of the highest weights in the evaluation. [6,12]

Connection reliability (weight 0.25). The reliability and stability of the communication link between the sensor and the C2 element are at least as important as transmission latency. Connection disruptions, including communication outages, packet loss, and signal degradation, may lead to degradation of the air situation picture or delayed decision-making. In combat conditions, particularly in environments affected by electronic warfare or jamming, the reliability of the communication link may become even more critical than latency itself. Loss of reliable data transfer can significantly reduce the effectiveness of the C2 process. For this reason, connection reliability was assigned a weight of 0.25 in the multi-criteria evaluation.

The situational awareness (weight 0.20) — the quality of the air picture. SA directly affects the ability of the C2 system to correctly identify, classify and prioritise threats. High-quality SA enables timely and accurate decision-making in the air defence engagement process. However, SA is not a completely independent criterion, as its quality is already partially influenced by latency and communication reliability. For this reason, SA was assigned a slightly lower weight than the previous two criteria.

Probability of successful engagement (weight 0.20) — operational outcomes. The probability of successful engagement represents the final operational effect of the air defence system during a fire engagement. From an operational perspective, this criterion is of primary importance because it reflects the ability of the system to neutralise incoming threats.

However, the value of P_{kill} is largely derived from other factors, particularly SA, transmission latency and communication reliability. Assigning an excessively high weight to this criterion could therefore lead to double counting of the influence of these parameters. For this reason, the weight assigned to the P_{kill} was set to 0.20, corresponding to the weight of the SA criterion.

C2 and sensor survivability (weight 0.10) — important but secondary factor. The survivability of C2 elements and sensors becomes particularly important in environments characterised by:

1. the presence of precision-guided munitions;
2. reconnaissance by unmanned aerial vehicles;
3. electronic warfare and jamming.

Higher survivability reduces the probability that the key system elements will be detected and destroyed during combat operations. However, survivability is not a direct parameter of fire control effectiveness. Rather, it reflects the long-term ability of the system to sustain combat operations. For this reason, survivability was assigned a lower weight compared to the primary criteria, while still remaining an important factor in the overall evaluation.

Logistical complexity (weight 0.05) — supporting criterion. Logistical factors are relevant primarily during the deployment of system elements, the movement and repositioning of units, and the sustainment of combat operations. These aspects influence the practical feasibility of individual deployment variants and may affect the ability of units to operate over longer periods. However, logistical complexity does not directly influence fire control effectiveness or the speed of the OODA decision-making cycle. For this reason, logistics was assigned the lowest weight in the evaluation, while still remaining a relevant supporting criterion.

Application of the multi-criteria method (TOPSIS). The TOPSIS method was used to calculate the overall effectiveness of the analysed variants. This method evaluates alternatives according to their relative distance from the ideal and negative-ideal solutions. The TOPSIS analysis was performed in Microsoft Excel using the standard calculation procedure described in the previous section. The decision matrix was normalised using vector normalisation, the normalised values were multiplied by the assigned criterion weights, and the distances of each variant from the ideal and negative-ideal solutions were subsequently calculated. Based on these distances, the coefficient of relative closeness to the ideal solution was determined for each deployment variant. The resulting TOPSIS scores and rankings for all three weighting scenarios are summarised in Table 3. [8]

Table 3.

TOPSIS scores and rankings for the three weighting scenarios

Variant	**Scenario 1 Ci***	**Rank**	**Scenario 2 Ci***	**Rank**	**Scenario 3 Ci***	**Rank**
A	0.820	1	0.527	2	0.328	3
B	0.574	2	0.579	1	0.601	2
C	0.180	3	0.473	3	0.672	1

Under Scenario 1, the highest coefficient of relative closeness to the ideal solution denoted by C_i^*, was achieved by Variant A (0.820), followed by Variant B (0.574) and Variant C (0.180). This indicates that, given the criterion weights specified for the performance-oriented scenario, Variant A represents the most favourable solution according to the applied multi-criteria evaluation. Although the TOPSIS method identified Variant A (1 km) as the most advantageous under Scenario 1, it should be noted that the mathematically optimal solution may not necessarily represent the most suitable configuration in real combat conditions. Variant A provides the lowest latency, the highest reliability of data transmission and consequently the highest values of SA and P_{kill}. However, the major drawback of this configuration is the extremely low survivability of sensors and C2 elements located in close proximity.

Such a configuration is highly vulnerable to:

- enemy ISR assets, particularly unmanned aerial vehicles;
- artillery, missile and precision-guided munition strikes,
- electronic warfare activities affecting communication and sensor systems.

In such a configuration, the simultaneous destruction of sensors and C2 elements by a single strike represents a realistic risk. This significantly limits the unit's long-term ability to continue combat operations and maintain a reliable command and control picture of the air situation. For these reasons, commanders may often prefer the compromise solution represented by Variant B (approximately 7 km). Although this variant is mathematically less effective than

Variant A in terms of data transmission performance, it provides significantly higher survivability of system elements due to their spatial dispersion, lower detectability and a reduced probability of simultaneous destruction. [1,2,6]

Variant B therefore represents a balanced compromise between communication performance, tactical security, and the long-term operational capability of the air defence unit. From the perspective of practical combat deployment, it can therefore be considered the most suitable solution. The discussion presented above focuses on Scenario 1, while the effects of the alternative weighting configurations represented by Scenarios 2 and 3 are examined in greater detail in the following sensitivity analysis.

6. Sensitivity Analysis

Sensitivity analysis examines how the resulting ranking of variants changes when the weights assigned to individual criteria are modified. In this work, the analysis focuses primarily on the weight of the survivability criterion, as it most clearly reflects the tactical perspective of the commander, particularly the balance between operational performance and the survivability of system elements. Three scenarios representing typical situations encountered in air defence operations were assessed:

Scenario 1 – corresponds to the original weighting used in the analysis and emphasises communication performance parameters such as latency, connection reliability, SA and P_{kill}. Survivability remains relevant but has a lower weight.

Scenario 2 – represents a balanced configuration in which the weight of survivability is increased to 0.30 while the weights of performance-related criteria are slightly reduced.

Scenario 3 – represents an extreme case in which survivability becomes the dominant criterion (weight 0.50), reflecting situations where the protection of sensors and C2 elements is considered the primary operational priority.

Scenario 1 – Original weights (performance-oriented). Variant A achieves the highest TOPSIS score due to its minimal latency, very high connection reliability and the highest values of SA and P_{kill}. Since the weight assigned to survivability in this scenario is relatively low, the reduced survivability resulting from the close proximity of sensors and C2 elements does not significantly affect the overall evaluation.

Scenario 2 – Balanced configuration (greater emphasis on survivability). After increasing the weight of the survivability criterion to 0.30, the ranking of variants changes as follows:

– **Variant B** (7 km) becomes the best-performing option, as it maintains good communication performance while offering significantly higher survivability than Variant A;
– **Variant C** remains in third place. Although it achieves the highest survivability due to the large separation of system elements, its effectiveness is reduced by high latency and lower communication reliability, which negatively affect SA and the probability of successful engagement.

Scenario 3 – Survivability-Oriented Configuration (Dominant Criterion). With a strong emphasis on survivability (0.50), the ranking of variants changes significantly:

– **Variant C** (20 km) becomes the best-performing configuration. The large separation between sensors and the C2 element ensures maximum dispersion and the highest survivability, even though it results in significantly higher latency and lower communication reliability;
– **Variant B** represents a compromise solution, maintaining acceptable communication performance while still providing relatively high survivability;
– **Variant A** ranks last in this scenario because the close proximity of sensors and the C2 element makes the system highly vulnerable to detection and destruction by enemy ISR assets and precision strikes.

7. Operational Implications for Air Defence Deployment

The results of the SA indicate that the selection of sensor–C2 distance cannot be based on one technical indicator alone. In practical employment, commanders must balance information latency, communication reliability, SA and the survivability of critical system elements.

For this reason, the analysed variants should be interpreted as deployment archetypes suitable for different tactical environments rather than as universally valid solutions. The preferred option changes according to the threat level, the characteristics of the terrain, the communication architecture and the commander's priority between short-term performance and long-term resilience:

Variant A is appropriate when the shortest possible reaction time is the dominant requirement and the threat of rapid detection or precision strike is limited.

Variant B is appropriate when the mission requires a balanced compromise between communication performance, flexibility of maneuver and survivability of the force.

Variant C is justified mainly in high-threat environments in which protection against enemy ISR and precision-guided munitions outweighs the penalty in latency and connection quality.

Implications for performance-oriented employment. A short sensor–C2 separation supports the fastest decision cycle and the highest quality of the air picture. This configuration may therefore be acceptable during short-duration engagements, in protected rear areas, or in situations where redundancy, deception and mobility reduce the danger of simultaneous destruction of system elements.

At the same time, Variant A should be regarded as only conditionally advantageous. If the enemy can rapidly locate emissions or attack concentrated nodes, the technical gains of low latency and high data quality may be offset by the operational risk of losing both sensing and coordination functions in a single strike.

For practical planning, this means that close placement of sensors and the C2 element requires strong protective measures, especially camouflage, emission control, pre-planned alternate positions and the ability to redistribute tasks immediately after disruption.

Without these protective measures, the short-distance configuration is more suitable as a temporary or situation-specific arrangement than as the default deployment pattern for air defence combat formations.

The analysis therefore confirms that technical superiority in one part of the C2 process does not automatically translate into superior operational utility in a contested battlespace.

Implications for balanced and survivability-oriented employment. Variant B preserves sufficiently good transmission quality for fire control while reducing the vulnerability created by the concentration of nodes in one area. This configuration supports maneuvers, mutual support, and the redistribution of signatures across the battlespace without imposing excessive technical and logistical demands. For this reason, it can be considered the most suitable baseline option for contemporary air defence units operating under persistent ISR pressure.

Variant C becomes relevant when the principal objective is preserving the force, complicating enemy targeting, and maintaining continuity of operations after an initial strike. However, such a deployment must be supported by redundant communication links, reliable time synchronization, and greater autonomy of subordinate elements. Otherwise, the increased latency and reduced communication reliability associated with wider dispersion may undermine the expected survivability benefits. From an operational-planning perspective, the main value of the analysis lies in showing where the decision boundary between Variants A, B and C shifts. The sensitivity analysis demonstrates that even a moderate increase in the importance of survivability is sufficient to move the preferred solution from A to B, which is highly relevant for commanders planning under uncertain threat assumptions. This means that medium-distance deployment should be treated as the reference configuration for most scenarios, while short and long separations should be selected only when supported by a clear tactical rationale, mission-specific intelligence and appropriate communication support.

Accordingly, the optimal sensor–C2 distance is not a fixed number but a function of mission tempo, enemy reconnaissance capability, expected precision-strike threat and the resilience of the communication architecture. This interpretation strengthens the practical applicability of the presented model for deployment planning and doctrinal discussion. [2,5]

8. Conclusions

The aim of this work was to assess how the distance between air defence sensors and the command and control (C2) element affects the effectiveness of fire control using operational analysis methods. Three deployment variants (A – 1 km, B – 7 km, C – 20 km) were compared and evaluated in terms of latency and reliability of data transmission, SA, P_{kill}, element survivability, and operational complexity.

The results showed that a shorter distance (Variant A) provides the best performance parameters, including low latency, high connection stability, and high values of SA and P_{kill}. However, this configuration also increases the vulnerability of the system due to the concentration of elements and the resulting low survivability. Conversely, a large distance (Variant C) improves survivability due to the spatial dispersion of sensors and the C2 element, but significantly degrades data transmission quality and reduces fire control effectiveness. Variant B represents the most balanced compromise, maintaining acceptable latency and information quality while significantly increasing the resilience and robustness of the system.

One of the main contributions of this work is the development of a practical evaluation framework linking technical data transmission parameters with the combat effectiveness of fire control. The framework enables a systematic comparison of deployment variants using the multi-criteria TOPSIS method. The results also showed high sensitivity to the weighting of evaluation criteria, confirming that the selection of the optimal deployment configuration is strongly influenced by the commander's priorities and the operational situation (performance versus survivability). From this perspective, the analysis identified a medium sensor–C2 separation (approximately 5–10 km) as the most robust solution, providing a stable compromise across different scenarios.

One of the main limitations of the presented analysis is that the applied models rely on simplified relationships and fixed parameters. In real operational conditions, these parameters depend on factors such as communication architecture, terrain, meteorological conditions, and particularly the intensity of electronic warfare. Another limitation is the relatively small number of analysed variants and the static nature of the evaluation. In practice, deployment configurations may change dynamically as the system reacts to losses, interference, and enemy maneuvers.

For these reasons, future research should focus on validating the proposed model using data obtained from real military exercises and on expanding the analytical framework through more advanced simulation approaches, such as Monte Carlo simulations or agent-based modelling.

The application of the TOPSIS method together with sensitivity analysis confirmed that the “optimal” deployment variant depends on operational priorities. However, from a practical operational perspective, a medium distance between sensors and the C2 element (approximately 5–10 km) appears to provide the best balance between fire control effectiveness and the survivability of the system in modern battlefield conditions.

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