Advances in Military Technology
Vol. 20, No. 2, 2025, pp. 349-360
ISSN 1802-2308, eISSN 2533-4123
DOI 10.3849/aimt.01981

Multi-Criteria Optimization of Complex Technical Systems

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The manuscript was received on 18 March 2025 and was accepted after revision for publication as an original research paper on 21 June 2025.

Abstract:

The wide functionality and high structural complexity of modern technical systems necessitate the search for new, universal methods for their optimization. The article proposes a multi-criteria optimization method, which allows ranking competitive configurations of complex technical systems in terms of formalized and non-formalized expression of optimality criteria.

Keywords:

complex technical systems, optimization, criterion, structure, objective function, scalarization.

1 Introduction

In today's conditions of global challenges and intensive development of technologies, ensuring the effective functioning of complex technical systems (CTS) is becoming one of the key tasks in many industries, in particular in military affairs and border security systems [1-6]. Most modern military combat systems are complex technical systems that operate in conditions of high uncertainty, dynamic changes in the situation, and increased requirements for speed of response. It is evident that under such functional requirements, optimizing the structure and functions of these systems is a challenging task since it includes a whole set of competing criteria aimed at increasing efficiency, reliability, and responsiveness [7]. An additional challenge in optimizing modern CTS is the deep integration of information and analytical tools. While this integration significantly enhances functional capabilities, it also complicates management at the intra-system organizational level due to nonlinear

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interactions, emergent behaviors, and the system's adaptability to external conditions [8]. Fig. 1 shows an example of the evolution of the system's functional capabilities, which is formed by integrating the resources of individual subsystems within a standard information model, which provides distributed autonomous system management, subsystem load balancing, etc.

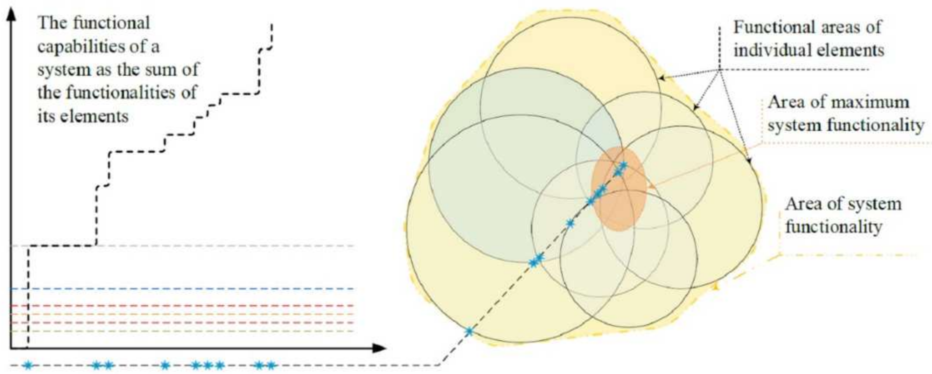


Fig. 1 Functional space of a CTS

This necessitates an efficient basic structural organization and adaptive algorithms for functioning that can ensure optimal resource allocation, rapid action planning, and coordination between different subsystems. This can be achieved by combining flexible algorithms for intra-system control and dynamic system reconfiguration based on the current state of the environment and key goals of the system [9]. The basis of these processes can be a multi-criteria optimization approach that allows synthesizing sets of optimal functional models to achieve a global target or weighted goal.

One example of a complex technical system is the information and technical support system (ITS) for protecting the state border of Ukraine [10], which is currently under development. Conceptually, this process involves expanding the technical infrastructure for data collection while simultaneously incorporating software services for analysis, such as clustering, classification, generalization, and forecasting. All this is accompanied by the integration of cybernetic and technical elements in various network infrastructure models [3]. Today, ITS includes infrastructure solutions (video surveillance systems, intelligent barriers, motion detectors), mobile monitoring tools (unmanned aerial vehicles, patrol vehicles), as well as automated data processing systems (video analytics systems, risk assessment and forecasting systems, decision support systems). Solving the problem of optimizing the structure and functionality of such a system requires an integrated approach [11, 12]. The solution space should encompass only those configurations that simultaneously guarantee complete control zone coverage, minimize resource consumption, and maximize threat detection efficiency. In addition, the optimization model should provide for operational changes in input data and requirements, regardless of the level of formalization of criteria and indicators.

This study aims to substantiate the method of dynamic optimization of CTS systems based on applying multi-criteria optimization models in a deterministic state space.

2 Problem Formulation

The basis of the monitoring system is a network of sensors, surveillance equipment, elements of the communication infrastructure, and local computing nodes. The main goal of solving the problem is to optimize the structure (set and connections of components) and adjust the operating parameters of the network. The basis of the objective function is to ensure the required level of efficiency in detecting and processing information about potential threats at the border with minimal resource consumption and taking into account operational restrictions. This should be achieved by selecting (activating) the optimal number of sensors and gauges and uniformly loading the information and communication infrastructure nodes. The limitation of the activation of sensors and nodes is the bandwidth and reliability of the communication network. The optimal system structure will be considered to be a set of elements that provides maximum functionality (reliability, sensitivity, area of reliable coverage, etc.) with minimal resource consumption (number of sensors, load of computing nodes) and given parameters of the communication network (bandwidth, delay, power of preprocessing algorithms) [10].

A set of criteria characterizes the effectiveness of this CTS, and its components are elements of the network structure; that is, they all affect the system's effectiveness to varying degrees according to all criteria [3, 8]. Given this, the optimization problem is solved in two stages. In the first stage, sets of system configurations are formed that meet the requirements of the key optimality criterion for the leading efficiency indicator. We will assume that the non-key criterion's efficiency indicators are distributed non-monotonically and linearly independent in the CTS's resulting state space. This means that an increase or decrease in efficiency for the key criterion can be achieved by different combinations of indicators for other criteria.

3 Basic Materials and Results

The effectiveness of the multi-criteria approach largely depends on the quality and accuracy of the formed partial criteria. One of the classical optimization methods can be used to determine the optimal configuration of the system by a separate criterion. In the case of a monitoring system in border protection, the solution to the optimization problem will be the optimal set and spatial distribution of sensors that provide the maximum probability of detecting violations in the control zone with minimal resource consumption and a uniform distribution of the likelihood of detection throughout the control zone. Given that the sensors are connected to the network through a system of communication nodes, the activation or change in the sensitivity of individual sensors can occur dynamically. The system's efficiency changes depending on external conditions (time of day, weather, etc.). Therefore, the solution to the optimization problem must contain entire sets of competing system configurations. To choose one of them, it is necessary to consider additional criteria and solve the multi-criteria optimization problem. The basis of its solution is a set of criteria and computational models for the dynamic assessment of the current values of indicators of individual criteria.

The initial data was formed by averaging the efficiency indicators of four configuration options for the state technical control system for 2024. The conditional cost of the system in different configurations was determined based on market prices of equipment as of December 2024 and the length of the control area. Several single-criteria optimization problems were solved for these initial data, and a set of system configurations was obtained that had different efficiencies according to four criteria

(Tab. 1). The criteria used are characterized by both formalized (quantitative) and non-formalized (linguistic) indicators.

Tab. 1 System configuration options

Criterion	System configuration				
	x_1	x_2	x_3	x_4	x_5
Probability of detection – Z_1	0.78	0.76	0.83	0.85	0.79
Cost (CU) (con. units) – Z_2	900	700	1 200	1 300	1 100
Automation – Z_3	2	1	4	3	5
Reaction rate (seconds) – Z_4	50	100	10	30	5

Thus, it is necessary to choose from five system configuration options, which differ in the set of elements, the level of automation, and the set of additional functions. All this affects the system's efficiency in a given configuration according to one of four criteria Z_1-Z_4.

What complicates the task is that the criteria are given in different forms:

- Z_1 – probability of detection, formalized, quantitative in the range [0, 1],
- Z_2 – cost, formalized, quantitative in the range [0, +∞),
- Z_3 – automation, non-formalized, linguistic (formalization: "low" – 1, "below average" – 2, "average" – 3, "above average" – 4, "high" – 5),
- Z_4 – reaction rate formalized, quantitative in the range [0, +∞).

If necessary, taking into account the priority of criteria Z_1-Z_4, they may be given weighting factors.

In addition to the fact that heterogeneous values characterize the criteria (Tab. 1), they also contain inconsistent values. The basis of this inconsistency is the different physical content of the indicators and, as a consequence, different "directions" of their optimization. For some criteria, maximization of values (Z_1, Z_3) is desirable; for others, minimization (Z_2, Z_4), which should be taken into account when forming a multi-criteria optimization model.

To formulate the problem mathematically, we introduce several notations:

$X = \{x_i\}, i = 1, 2, \cdots, n$ – the set of all possible variants of the system,

$Z\{x_i\} = \{Z_1(x_i), Z_2(x_i), \cdots, Z_m(x_i)\}$ – the vector criterion characterizing the system configuration x_i,

$Z_m(x_i)$ – the partial quality criterion characterizing the system x_i,

$\Upsilon = \{\gamma_j\}, j = 1, \cdots, m$ – the set of normalized weight coefficients,

$\delta_m(x_k, x_l)$ – the relative assessment of the superiority of the system in the configuration x_k over the system in the configuration x_l according to the criterion $Z_m(x)$,

$\varphi_m(x_k, x_l)$ – the intensity of advantages of the system in the configuration x_k over the system in the configuration x_l according to the criterion $Z_m(x)$,

$L_m(x_k, x_l)$ – the intensity of losses of the system in the configuration x_k of the system in the configuration x_l according to the criterion $Z_m(x)$,

$W_m\left[Z(x_i)\right]$ – the relative advantage of the system configuration x_i compared to other system configurations according to the criterion $Z_m(x)$,

$\overline{E}_j(x_k)$ – the average intensity of system losses in the configuration x_k by the criterion $Z_m(x)$ relative to other configurations,

$\overline{H}_j(x_k)$ – the average intensity of system advantages in the configuration x_k by the criterion $Z_m(x)$ relative to other configurations,
$d_i(x)$ – the average scalar deviation from the optimal value in the space of intensities of losses and advantages of the system configuration.

Considering the introduced concepts, multi-criteria optimization of the system consists of the following. From the known set of possible configurations of the system $X = \{x_i\}, i = 1, 2, \cdots, n$, which is formed based on the vector criterion, $Z\{x_i\} = \{Z_1(x_i), Z_2(x_i), \cdots, Z_m(x_i)\}$ it is necessary to find the configuration that corresponds to the best-weighted estimate in the space of intensities of losses and gains

$$d_{\min}(x) = \min_{x_i \in X} \sum_{Z_j \in Z} \left\{ d\left[Z_j(x_i) \right] \cdot \gamma_j \right\} \tag{1}$$

Calculating this function allows us to find the system configuration with the best weighted score for all vector criteria. The algorithm for its calculation includes the following stages:

- formation of the set of x_i all possible configurations of the system,
- calculation (estimation) and formalization of efficiency indicators using vector criteria $Z\{x_i\}$,
- normalization of vector values $\{Z_1(x_i), Z_2(x_i), \cdots, Z_m(x_i)\}$,
- calculation of relative estimates of the advantages of configurations $\delta_m(x_k, x_l)$ and their intensities $\varphi_m(x_k, x_l)$,
- calculation of relative estimates of configuration losses $L_m(x_k, x_l)$,
- calculation of projections $\varphi_m(x_k, x_l)$ in the space of intensities of advantages and disadvantages,
- determination of $d_{\min}$, and selection of the most advantageous system configuration.

Each criterion characterizes a certain local quality of an alternative system configuration, such as the probability of detection, reliability, cost, speed, etc. If the requirements are not expressed in the same units of measurement, they are reduced to a dimensionless form with the same measurement scales. This can be done by dividing the value of each criterion by the unit of the corresponding scale, but more complex methods are effective, for example, by introducing the function

$$f_i(x) = \frac{Z_i(x) - Z_i^{\max}}{Z_i^{\max} - Z_i^{\min}} \tag{2}$$

With such normalization, the contribution of a single criterion's "local quality" to the "global quality" depends on how much the local quality changes on the admissible set. This approach to normalization is part of the principle of uniform optimality. It is a reasonable basis for calculating the functions of evaluating the advantages and the intensity of advantages of different system configurations within a single indicator. To this end, for a pair of configurations, (x_k, x_l) the function of the relative advantage of the system in the configuration x_k over the system configuration x_l by the criterion is calculated Z_m.

$$\delta_m(x_k, x_l) = \begin{cases} \dfrac{Z_m(x_k) - Z_m(x_l)}{Z_m^{\max} - Z_m^{\min}} & , Z_m(x_k) - Z_m(x_l) > 0 \\ 0 & , Z_m(x_k) - Z_m(x_l) \le 0 \end{cases} \tag{3}$$

Normalization of values by $\left(Z_m^{\max} - Z_m^{\min}\right)$ is one of the possible options, which in this case (construction of sensor networks) and in this formulation is convenient since there is no need to consider the sign of the result and the obtained values belong to the interval [0, 1]. This is because the quality criteria are heterogeneous quantities with value scales that differ by several orders of magnitude (probability, cost, coverage area, coverage uniformity, etc.). Still, the relative variation of the values has different orders of magnitude. Because of this, normalization by the range of values (except for cases when the values vary from zero) will not be equivalent to a "local" contribution.

Eq. (3) is derived from the assumption that maximizing the values of indicators is desirable according to partial criteria (maximum value of the probability of detection, higher level of automation). In the other case, when the minimum value according to partial criteria (minimum cost, minimum reaction speed) is ensured, Eq. (3) is transformed into the form

$$\delta_m(x_k, x_l) = \begin{cases} -\dfrac{Z_m(x_k) - Z_m(x_l)}{Z_m^{\max} - Z_m^{\min}} & , Z_m(x_k) - Z_m(x_l) \le 0 \\ 0 & , Z_m(x_k) - Z_m(x_l) > 0 \end{cases} \tag{4}$$

The results of calculating the relative assessment of the advantage of the system in the configuration x_k over the system in the configuration x_l by the criterion $Z_m(x)$ are given in Tab. 2.

Tab. 2 Relative estimates of the advantages of system configurations

x_k	x_l									
	$\delta_1(x_k, x_l)$					$\delta_2(x_k, x_l)$				
	x_1	x_2	x_3	x_4	x_5	x_1	x_2	x_3	x_4	x_5
x_1		0.03	0	0	0		0	0.50	0.67	0.33
x_2	0		0	0	0	0.33		0.83	1.00	0.67
x_3	0.06	0.08		0	0.05	0	0		0.17	0
x_4	0.08	0.11	0.02		0.07	0	0	0		0
x_5	0.01	0.04	0	0		0	0	0.17	0.33	
	$\delta_3(x_k, x_l)$					$\delta_4(x_k, x_l)$				
x_1		0.50	0	0	0		0.53	0	0	0
x_2	0		0	0	0	0		0	0	0
x_3	0.50	0.75		0.25	0	0.42	0.95		0.21	0
x_4	0.33	0.67	0		0	0.21	0.74	0		0
x_5	0.60	0.80	0.20	0.40		0.47	1.00	0.05	0.26	

The value of the intensity of the advantage of a configuration x_k over the system in the configuration x_l by criterion $Z_m(x)$ shows how intense the advantage of the selected configurations within one criterion is relative to the advantages of the selected configurations by other criteria. The formula calculates the intensities of the advantages of system configurations:

$$\varphi_m\left(x_k, x_l\right)=\begin{cases}\dfrac{\delta_m\left(x_k, x_l\right)-\delta_m\left(x_l, x_k\right)}{\delta_m^{\max}} & , \delta_m\left(x_k, x_l\right)-\delta_m\left(x_l, x_k\right)>0 \\ 0 & , \delta_m\left(x_k, x_l\right)-\delta_m\left(x_l, x_k\right) \leq 0\end{cases} \quad (5)$$

Eq. (5) is key in this method, derived from considerations similar to those used in fuzzy set theory regarding nonlinear activation functions.

The results of calculating the intensity of the advantage of the system in the configuration x_k over the system in the configuration x_l according to the criterion $Z_m(x)$ are given in Tab. 3.

Tab. 3 Intensity of advantage of system configurations

x_k	x_l									
	$\varphi_1(x_k, x_l)$					$\varphi_2(x_k, x_l)$				
	x_1	x_2	x_3	x_4	x_5	x_1	x_2	x_3	x_4	x_5
x_1		0.24	0	0	0		0	0.50	0.67	0.33
x_2	0		0	0	0	0.33		0.83	1	0.67
x_3	0.57	0.80		0	0	0	0		0.17	0
x_4	0.78	1	0.22		0.67	0	0	0		0
x_5	0.12	0.36	0.45	0		0	0	0.17	0.33	
	$\varphi_3(x_k, x_l)$					$\varphi_4(x_k, x_l)$				
x_1		0.63	0	0	0		0.53	0	0	0
x_2	0		0	0	0	0		0	0	0
x_3	0.63	0.94		0.31	0.25	0.42	0.95		0.21	0.05
x_4	0.42	0.83	0		0	0.21	0.74	0		0
x_5	0.75	1	0	0.50		0.47	1	0	0.26	

The intensities of advantages, unlike their estimates, give a more complete picture of the dominance of a specific configuration of the system in terms of efficiency within all criteria. These data are sufficient to rank the configurations in terms of efficiency by the average indicators of the intensity of advantages. However, to expand the search space for effective configurations of the system, it is better to introduce another indicator – the intensity of the loss of the configuration x_k to the system with the configuration x_l by the criterion $Z_m(x)$, which is calculated by inversion $\varphi_m\left(x_k, x_l\right)$:

$$L_m\left(x_k, x_l\right)=1-\delta_m\left(x_k, x_l\right) \quad (6)$$

 DOI 10.3849/aimt.01981

The feasibility of such a transformation is due to the possibility of a more convenient interpretation of the space of average intensities of advantages and disadvantages. Tabs 4-7 show the results of the calculations.

Tab. 4 Intensity of loss of system configurations by criterion $Z_1(x)$

Configuration x_k	**Configuration** x_l					$\bar{E}_1(x_k)$
	x_1	x_2	x_3	x_4	x_5	
x_1		0.76	1.00	1.00	1.00	0.94
x_2	1.00		1.00	1.00	1.00	1.00
x_3	0.43	0.20		1.00	1.00	0.66
x_4	0.22	0.00	0.78		0.33	0.33
x_5	0.88	0.64	0.55	1.00		0.77
$\bar{H}_1(x_l)$	0.63	0.40	0.83	1.00	0.83	

Tab. 5 Intensity of loss of system configurations by criterion $Z_2(x)$

Configuration x_k	**Configuration** x_l					$\bar{E}_2(x_k)$
	x_1	x_2	x_3	x_4	x_5	
x_1		1.00	0.50	0.33	0.67	0.63
x_2	0.67		0.17	0.00	0.33	0.29
x_3	1.00	1.00		0.83	1.00	0.96
x_4	1.00	1.00	1.00		1.00	1.00
x_5	1.00	1.00	0.83	0.67		0.88
$\bar{H}_2(x_l)$	0.92	1.00	0.63	0.46	0.75	

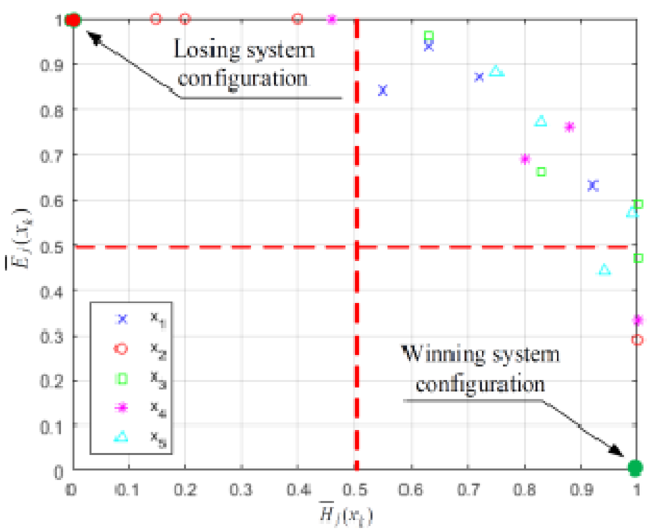
Tab. 6 Intensity of loss of system configurations by criterion $Z_3(x)$

Configuration x_k	**Configuration** x_l					$\bar{E}_3(x_k)$
	x_1	x_2	x_3	x_4	x_5	
x_1		0.38	1.00	1.00	1.00	0.84
x_2	1.00		1.00	1.00	1.00	1.00
x_3	0.38	0.06		0.69	0.75	0.47
x_4	0.58	0.17	1.00		1.00	0.69
x_5	0.25	0.00	1.00	0.50		0.44
$\bar{H}_3(x_l)$	0.55	0.15	1.00	0.80	0.94	

The obtained data makes it possible to construct projections of configurations in the normalized metric space of average loss intensities in terms of various criteria for the entire set of CTS configurations (Fig. 2).

Tab. 7 Intensity of loss of system configurations by criterion $Z_4(x)$

Configuration x_k	***Configuration*** x_l					$\overline{E}_4(x_k)$
	x_1	x_2	x_3	x_4	x_5	
x_1		0.47	1.00	1.00	1.00	0.87
x_2	1.00		1.00	1.00	1.00	1.00
x_3	0.58	0.05		0.79	0.95	0.59
x_4	0.79	0.26	1.00		1.00	0.76
x_5	0.53	0.00	1.00	0.74		0.57
$\overline{H}_4(x_l)$	0.72	0.20	1.00	0.88	0.99	



Z_j	$\overline{H}_j(x_k)$	$\overline{E}_j(x_k)$
Z_1	0.63	0.94
	0.4	1.00
	0.83	0.66
	1	0.33
	0.83	0.77
Z_2	0.92	0.63
	1	0.29
	0.63	0.96
	0.46	1
	0.75	0.88
Z_3	0.55	0.84
	0.15	1
	1	0.47
	0.8	0.69
	0.94	0.44
Z_4	0.72	0.87
	0.2	1.00
	1	0.59
	0.88	0.76
	0.99	0.57

Fig. 2 Projection of system configurations in the space of distribution of average intensities $\overline{H}_j(x_l)$, and $\overline{E}_j(x_k)$

The obtained criterion estimates give a complete idea of the "value" of a particular configuration for the implementation of the system, considering all the criteria, regardless of the form of their presentation and the scale of absolute values. The obtained assessment of the quality of the system configuration is vectorized and contains several competitive states that can be visually assessed as the best (Fig. 2). To eliminate ambiguity, it is necessary to perform scalarization [10]. This can be done by calculating the average distance from the point [1, 0] in the space of the distribution of average intensities for each configuration [13]

$$d_k = \sum_{Z_j \in Z} \left\{ \sqrt{\left[1 - \bar{H}_j(x_k)\right]^2 + \left[\bar{E}_j(x_k)\right]^2} \cdot \gamma_j \right\} \tag{7}$$

where γ_j is the vector of criterion weights. If the criteria have the same weight or are not applied, it is considered that $\gamma_j = 1/m$.

Eq. (7) [13] is a tool for comparing different configurations of a complex technical system by assessing their overall “closeness” to the idealized state in the space of averaged and weighted intensities of the criteria. Considering that the criteria for evaluating technical systems are of different types, the improvement of expression (7) consists in introducing the weight coefficients of these criteria γ_j.

The minimum average distance (7) will correspond to the best system configuration, weighted by all criteria. Fig. 3a shows the results of calculating the minimum distance for different CTS configurations.

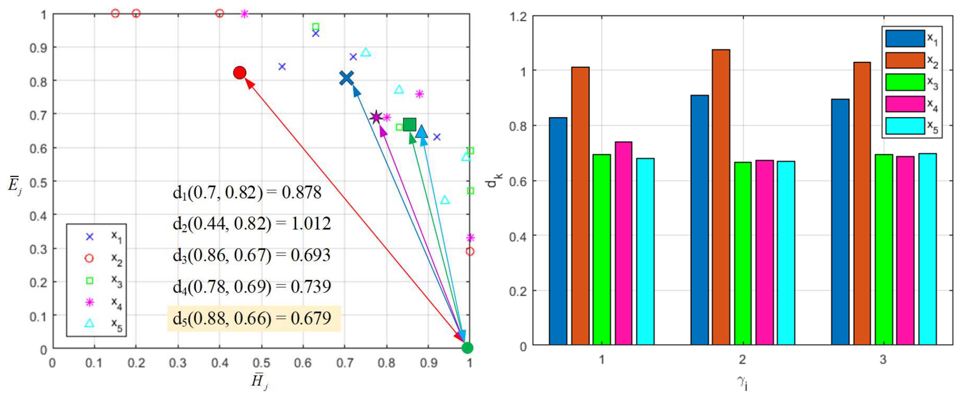


Fig. 3 Average distance (a) in the space of distribution of average intensities; (b) bar chart in group form for three sets of weights

Using different weighting factors for the criteria in Eq. (7) when calculating the average distance (Tab. 8) significantly affects the criterion significance of the system configurations.

Tab. 8 Average distances for different sets of weighting factors

	d_k											
γ_i	0.25	0.25	0.25	0.25	0.34	0.18	0.30	0.18	0.35	0.22	0.21	0.22
x_1	0.88				0.91				0.89			
x_2	1.01				1.07				1.03			
x_3	0.69				0.66				0.69			
x_4	0.74				0.67				0.69			
x_5	0.68				0.67				0.70			

As seen from Tab. 8, a slight redistribution of weight coefficients leads to changes in the priority of system configurations (Fig. 3). However, this does not affect the main trend – the groups of outsiders and leaders retain their relative positions. The first and second configurations are the worst in all three cases, while the third, fourth, and fifth configurations compete.

4 Conclusions

The obtained results confirmed the possibility of constructing a unified state space in multicriteria optimization problems. The proposed approach can serve as a reliable foundation for developing dynamic reconfiguration algorithms for complex technical systems in response to changing external conditions or internal system factors. The value of the achieved result lies in the absence of strict requirements regarding the number and formalism of partial optimality criteria, due to the normalization process of the vector criterion at the initial stages of state space formation.

The use of the weight coefficient vector and the basic principles of its formation are beyond the scope of this study. It is a powerful tool for managing state projections in the space of intensities of losses and gains and requires additional research.

For cases where all criteria are maximized or minimized, it is advisable to use well-known methods of mathematical programming [12].

The study proposes a multi-criteria optimization method that can be used to optimize the use of engineering and technical systems of the State Border Guard Service of Ukraine. The method allows ranking competing configurations of complex technical systems in terms of formalized and non-formalized expression of optimality criteria. This is particularly relevant to border security systems, which are complex technical systems that operate in conditions of high uncertainty and dynamic changes.

The optimization of the application of modern technologies in the border protection system allows for: significantly increasing situational awareness and the effectiveness of border protection; minimizing human losses, and adapting the border infrastructure to the conditions of hybrid warfare.

Examples of modern high-tech means used or implemented in the State Border Guard Service of Ukraine include: the Triton combat complex for visual and technical surveillance; optical-electronic surveillance system; unmanned aerial vehicles for aerial reconnaissance; “Bukovel-AD” mobile electronic warfare complex, and modern technical means of border control (thermal imagers, optics, sensor systems, etc.).

By applying the proposed multi-criteria optimization method, the State Border Guard Service of Ukraine can optimize the structure and functions of these systems, ensuring the required level of efficiency in detecting and processing information about potential threats at the border with minimal resource consumption and taking into account operational restrictions.

Further research will be aimed at developing a method for solving the inverse problem – the formation and selection of a set of states of a complex technical system based on constraints in the space of intensities of advantages and disadvantages. This will allow the logical completion of developing a model of optimal configuration and adaptation of the CTS when external conditions change and internal system disturbances occur.

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