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Анализ комплексных показателей назначения при принятии компромиссного решения с использованием векторной оптимизации в многокритериальных задачах

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Аннотация. В статье рассматриваются вопросы, связанные с выбором оборудования для систем контроля радиочастотного спектра в условиях многокритериальности и противоречивости требований к их характеристикам. Анализируются подходы к определению весовых коэффициентов, позволяющих агрегировать разнородные показатели, такие как точность пеленгования, диапазон частот, быстродействие, помехоустойчивость и другие, в единый интегральный критерий. Основное внимание уделено трём группам показателей назначения: комплексным, экономическим и технико-экономическим. Для каждой из них выявлены особенности формирования и ограничения при практическом применении. Показано, что использование только технических или только экономических критериев не даёт полной картины, необходимой лицу, принимающему решение. Наибольшую ценность представляют технико-экономические показатели, позволяющие связать достигаемый технический эффект с затратами различного вида. Однако, как отмечается в работе, применение таких критериев, как отношение эффекта к затратам, требует дополнительного анализа зависимости между этими величинами. При линейном характере связи использование подобных критериев оправдано, в противном случае необходимо приводить сравниваемые варианты к сопоставимому виду или привлекать экспертные оценки. Результаты могут быть полезны специалистам, занимающимся модернизацией и развитием систем радиоконтроля, а также тем, кто участвует в тендерных процедурах по выбору подобного оборудования.

Ключевые слова: многокритериальные задачи, векторная оптимизация, компромиссное решение, комплексные показатели назначения, системы радиоконтроля, технико-экономическая эффективность, весовые коэффициенты, принятие решений

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Research article

Analysis of complex assignment indicators when making a compromise solution using vector optimization in multi-criteria tasks

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Abstract. The article discusses issues related to the choice of equipment for radio frequency spectrum monitoring systems in conditions of multiple criteria and conflicting requirements for their characteristics. The approaches to determining weighting coefficients are analyzed, which make it possible to aggregate heterogeneous indicators such as bearing accuracy, frequency range, speed, noise immunity, and others into a single integral criterion. The main attention is paid to three groups of indicators of purpose: complex, economic, and techno-economic. For each of them, the peculiarities of formation and limitations in practical application are revealed. It is shown that using only technical or only economic criteria does not provide the complete picture needed by the decision maker. The most valuable technical and economic indicators are those that make it possible to link the achieved technical effect with various types of costs. However, as noted in the paper, the application of criteria such as the ratio of effect to cost requires additional analysis of the relationship between these values. If the relationship is linear, the use of such criteria is justified, otherwise it is necessary to bring the compared options to a comparable form or involve expert assessments. The results may be useful to specialists involved in the modernization and development of radio monitoring systems, as well as to those who participate in tender procedures for the selection of such equipment.

Keywords: multi-criteria tasks, vector optimization, compromise solution, complex assignment indicators, radio monitoring systems, technical and economic efficiency, weighting factors, decision-making

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Introduction. In today's increasingly intense information warfare environment, the use of radio frequency spectrum (RFS) monitoring systems (hereinafter referred to as RFSMS) plays a crucial role in ensuring the security of both the state and various sectors of activity.

In general, the effectiveness of the RFSMS can be characterized by the following indicators:

- 1) the ability to quickly and accurately detect the source of unwanted radio emissions (RE),
- 2) classify the technical parameters of such an RE,
- 3) make a decision on further work with the RE.

The RFSMS system must be highly productive and effective, and in order to make a decision on its development, renewal or modernization, and the search for current (alternative) and promising design options, it is possible to use a multi-criteria analysis method (MCA), which, from

several proposed RFSMS alternatives, will allow one to find solutions that best satisfy all criteria or represent an optimal compromise between them.

RFSMS [2] are complex systems that are characterized by such features as: 1) emergence (integrity), 2) the presence of heterogeneous connections, 3) robustness, therefore, it is practically impossible to select the required system without taking into account many characteristics, but only using the intuition of the decision maker (DM).

To conduct a multi-criteria analysis, it is necessary to determine the parameter weights (weighting coefficients), since only with their help it is possible to ensure the unification (aggregation) of various indicators, such as frequency range, direction finding accuracy, speed, the possibility of panoramic analysis and direction finding, work with databases, reliability, placement requirements, etc., into a single aggregate (integral) indicator and ultimately make a final decision.

The purpose of the article is to analyze and systematize existing approaches to assessing weights when conducting a generalized quantitative analysis of existing RFSMS, as well as to identify components that will influence the choice of methodology for determining weighting coefficients.

In compromise decision-making problems solved using vector optimization, there are always conflicting criteria, whereby improving one leads to a deterioration in the other, or vice versa. The situation is even worse when the criteria are not only contradictory but also irreducible (expressed in different units of measurement).

Thus, the vector optimization problem is one of making a compromise decision, taking into account the performance indicators that characterize the main parameters of the emergency response system, defining the primary tasks it is designed to perform. These indicators play a significant role in assessing the quality of equipment when finding the best solutions.

Let us consider the designation indicators by which it is proposed to evaluate the weighting coefficients when making a compromise decision: 1) complex designation indicators, 2) economic complex designation indicators, 3) technical and technical-economic designation indicators.

Complex purpose indicators. Complex designation indicators are indicators presented in the form of a product of the quality indicators of any system K_i , in our case the RFSMS:

$$K_I = K_1 K_2 \dots K_n \quad (1)$$

and the quotient obtained by dividing some indicators by others:

$$K_{II} = \frac{K_1 K_2 \dots K_m}{K_{1+m} K_{m+2} \dots K_n}, \quad (2)$$

where K_i — technical parameters, economic, social and time indicators. When assessing the effectiveness of the emergency response system, the article proposes to use the following general indicators [3]: the size of the zone (territory) of operation, the nature of use, the functions performed, the performance of the systems, design limitations during production and installation, cost, minimization of damage from the purchase, the time from order to commissioning, the expected social significance of the purchased emergency response system.

The use of these generalized indicators will allow us to consider several quality indicators and, based on them, formulate a generalized performance indicator. These indicators make it clear that each must be assessed across all proposed SRFSMS.

Let us analyze and divide the complex indicators for the appointment of the SRFSMS into three groups:

- 1) indicators, all components of which are not presented in monetary terms;
- 2) indicators, all components of which are expressed in monetary terms;
- 3) indicators, some of whose components have a monetary expression, while the other part is not presented in monetary form.

The indicators of the 1st group characterize technical efficiency and are formed by combining the technical characteristics of the RFSMS.

To evaluate the effectiveness of the RFSMS, it is necessary to develop a set of technical parameters that characterize its operation, such as its intended purpose (radio emission measurement or direction finding), operating mode, installation location, tasks, the existing electromagnetic environment (EME), prospects for the development of radio technologies in the region, and much more. We will highlight the first group of indicators (technical parameters) characterizing the capabilities and functionality of the RFSMS:

- 1) operating frequency range – characterizes the frequency range in which the system is capable of finding, detecting and monitoring RE;
- 2) sensitivity of the receiving device (the threshold for detecting the radioactive source by reception) – characterizes the minimum level of RE at which the system is able to detect it;
- 3) dynamic range (of the receiving device of the RFSMS) characterizes the difference between the minimum and maximum signal levels of the RE, which the receiving device can correctly process, detect or measure without distortion;
- 4) resolution (frequency or time), where the first determines how closely spaced in frequency the irradiated radiation sources can be recorded as separate ones, and the second determines the minimum time interval within which the system is able to record the irradiated radiation sources;
- 5) The measurement error of the main parameters of the RE characterizes the accuracy and reliability of the data received by the system;
- 6) directional characteristics (for direction-finding antennas), this is the ability of the system to distinguish signals that come from close angular directions and the error in the angle at which the system determines the RE;
- 7) bandwidth (frequency range scanning speed) characterizes the number of signals that the system is capable of processing per unit of time;
- 8) probabilistic characteristics of detection of RE:
 - probability of detection (P^d) : the probability that the system will detect a radioactive source of a certain type/level within its coverage area,
 - probability of false alarm (P^f) : the probability that the system will “detect” an RE where it does not exist,
 - probability of correct classification : the probability of correct determination of the type of radioactive source (modulation, affiliation, etc.), if the system is provided with a classification function;
- 9) reaction time (detection and processing of the RE) is the time interval between the appearance of a signal from the RE until its recording;
- 10) bandwidth (spectral window) is the frequency band within which monitoring can be carried out simultaneously (relevant for broadband systems);
- 11) resistance to interference and overload, this is the ability of the system to operate in conditions of high interference, both intentional and unintentional, and to prevent overload of the input paths;
- 12) operational reliability and fault tolerance, this is the probability of failure-free operation, resistance to external factors;
- 13) automation and integration, this is the level of automation of the processes of direction finding, detection, measurement, identification and classification of radio signals, the ability to integrate into other systems (for example, into frequency resource management systems, into radio environment analysis programs);
- 14) the spatial control zone (coverage), as a rule, depends on the height of the antennas, the power of the radio waves, the geographical features of the region and the frequency of the signal;
- 15) power consumption and infrastructure requirements, it is necessary to take into account the manufacturer’s requirements for power supply, cooling, dimensions and weight of the equipment.

The indicators of the 2nd group include: the payback period of capital investments, the comparative efficiency coefficient, minimizing the damage from the purchase of the RFSMS, and an analysis of indicators determined by the difference between costs and effects.

Economic complex indicators of destination. The most common economic indicators are indicators of the effect-cost ratio or the difference W-E.

Since effects and costs are measured on a common scale of value, their application does not require additional research. Let us list the main types of economic effects and costs. The economic effect of the RFSMS is determined by the sphere and period of its manifestation, as well as the volume of output. Depending on the sphere of manifestation, the following types of effect are distinguished: effect at the producer (in the sphere of production of new systems); effect at the consumer (in the sphere of operation of the RFSMS); and state (national economic) effect.

In this article, we only consider the effect that the consumer will experience when he begins to use the RFSMS.

The economic effect for the consumer characterizes the efficiency of the emergency response system if it reflects only the interests of the consumer enterprise.

The economic effect of the emergency response system can be determined over various time intervals: annual economic effect; economic effect for the entire service life of the systems.

In this case, we assume that the effect is the savings in current costs for the compared options i and j, obtained during the payback period T of capital investments. The costs are capital investments $\Delta K = K_{\circ j} - K_{\circ i}$. Then, to determine the more effective option, the following formula can be used:

$$\sum_{t=1}^T (C_{yi} - C_{yj})_t = K_{yi} - K_{yj} \quad (3)$$

where C_{yi} , C_{yj} are current costs for the compared options in the t -th year excluding depreciation charges.

The meaning of formula (3) is that with a more capital-intensive option, the amount of savings on operating costs over time T should be no less than the capital investment. Otherwise, the condition for the payback of capital investments will be written as

$$\frac{\dot{Y}}{W} = \frac{\sum_{t=1}^T (C_{yi} - C_{yj})}{K_{yj} - K_{yi}} = 1 \quad (4)$$

Formula (4) can be represented graphically on a chart (Figure 1). This chart shows the dependence of costs and benefits on time for two options for selecting the RFSMS (I and II).

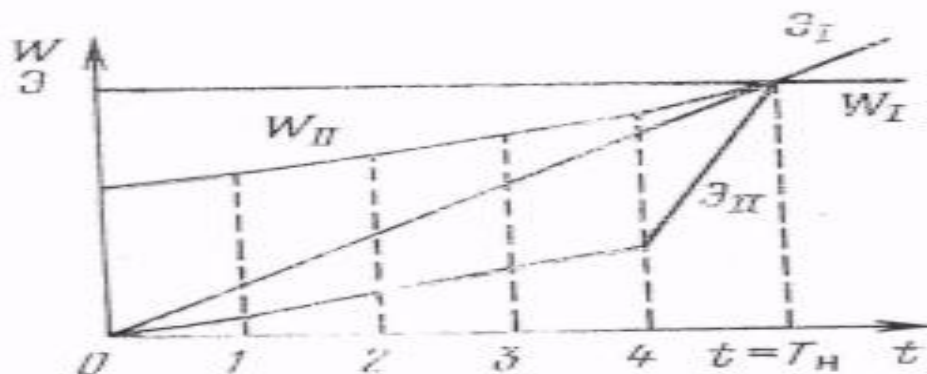


Figure 1. Dependence of costs and effects on time

In the first case, capital investments W_I are constant, and savings on operating costs increase linearly over time.

Both E_{II} and W_{II} vary nonlinearly with time. Although in both cases the ratio $E/W = 1$ at $t = T_n$, the results of these examples cannot be considered equivalent. This is due to the fact that

although the effect obtained over time T_n is the same in both cases, it is distributed unequally over time. The same applies to capital investments. To identify the best technical solution, it is necessary to take the time factor into account in the analysis.

When using cost criteria such as E/W , it is necessary to consider the dependence of E and W on the degree of achievement of the goal q . The degree of achievement can be considered, for example, the performance of the RFSMS, which is characterized by the speed of panoramic spectral analysis of signals at a given resolution and dynamic range.

Figure 2 shows the nonlinear dependencies $E(q)$ and $W(q)$. It follows from the figure that the ratio E/W depends significantly on q . When comparing the i -th and j -th systems, the efficiency condition for the i -th system has the form $E > W$. This condition is satisfied for the range of values $q^*_1 < q < q^*_2$. When $q < q^*_1$ and $q > q^*_2$ The i -th system turns out to be less efficient - than the j -th. Thus, given the nonlinear nature of the dependencies $E(q)$ and $W(q)$, in order to select the most efficient option for technical solutions, it will be necessary to study the relationship in a specific area.

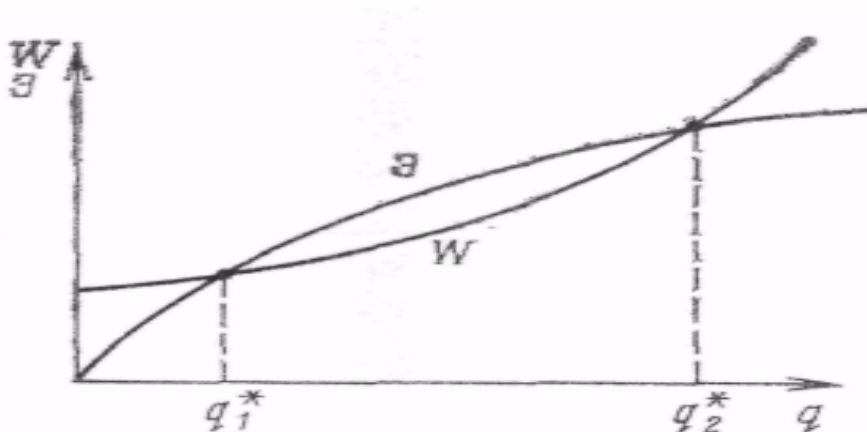


Figure 2. Nonlinear dependencies $E(q)$ and $W(q)$.

These studies address economic indicators that do not provide complete information for making decisions on the supply of the RFSMS.

The third group of indicators are technical and economic ones and therefore are of greatest interest when selecting optimal options for new emergency response systems. These indicators include: costs per unit of produced systems and the ratio of the technical effect of a given type to costs.

Regardless of the type of complex purpose indicator, when using them, it is still necessary to conduct a certain analysis. The main elements of this analysis are: establishing the meaning and content of the quantities E and W ; determining the dependencies of the effect and costs on time; analyzing the dependencies of E and W on the degree of goal achievement when applying the - compared RFSMS.

Technical and technical-economic indicators of the purpose. The technical complex designation indicators are:

$$K_{IT} = K_{1T} K_{2T} \dots K_{nT} \quad (7)$$

$$K_{It} = \frac{K_{1t} K_{2t} \dots K_{mt}}{K_{(m+1)T} \dots K_{nt}} \quad (8)$$

where K_{it} is the i -th particular technical quality indicator.

Although the K_{IT} and K_{IIT} indicators generalize a number of specific indicators, they are of a local nature, as their formation does not take into account economic quality indicators. This does not mean that technical integrated performance indicators are completely unsuitable. However, when using them, it is necessary to consider the economic and social significance of the specific K_{it} indicators.

Let's analyze this using some examples.

The operating frequency range of a radio receiver built into the RFSMS is the range of possible tuning frequencies within which its basic characteristics are ensured. For smooth tuning, the frequency range is defined by the limiting frequencies $f_{0 \min} - f_{0 \max}$. The relative range is characterized by the overlap coefficient

$$k_P = f_{0 \min} / f_{0 \max} \quad (9).$$

This parameter is used to compare the proposed RFSMS; the receivers used in such equipment must have a high coverage factor.

However, the economic significance of the overlap coefficient k_P in the whole system of the SCCRHS in the general case is not the same.

Let us assume that when comparing two variants of the proposed RFSMS, the condition $k_{P1} = k_{P2}$ is satisfied, where $k_{P1} = f_{0 \min 1} / f_{0 \max 1}$ and $k_{P2} = f_{0 \min 2} / f_{0 \max 2}$. The equality $k_{P1} = k_{P2}$ can be ensured by various combinations of parameters $f_{0 \min}$ and $f_{0 \max}$.

The economic consequences of implementing these relationships will depend on the receivers used in the RFSMS. For example, the importance of the frequency band will depend on the wavelength range used (decameter or meter).

Another important characteristic of the radio receiver in the RFSMS is the dynamic range and the intersection points for second- and third-order intermodulation.

Intermodulation in a receiver is the occurrence of interference at the output of a radio receiver when two or more interfering signals with frequencies outside the main and side channels are applied to its input. This type of interference is called intermodulation.

In the general case, the excess of the useful signal over the intermodulation components of the n -th order:

$$\Delta_n = P_1 - P_n = (IP_n - P_{in}) - n(IP_n - P_{in}) = (n-1)(IP_n - P_{in}) \quad (10)$$

n -th order intermodulation is determined by the formula:

$$D_n = (IP_n - P_{pr})n - 1/n \quad (11)$$

Ensuring the required operating frequency range, dynamic range for n -th order intermodulation, and n -th order intermodulation components will be associated with different costs of selecting a receiving device for the RFSMS. Therefore, when using generalized indicators such as the overlap coefficient k_P , intermodulation components Δ_n , dynamic range D_n for a technical and economic assessment of the compared RFSMS, additional analysis will be required.

In this case, it will be necessary to bring the compared options into a comparable form according to individual parameters K_{IT} (in the example under consideration, according to the parameters k_P , Δ_n , D_n) or to evaluate their significance using expert assessment methods.

When conducting additional analysis, the reliability of the data obtained may not correspond to the actual data.

Therefore, without dwelling further on technical complex quality indicators, we will consider the characteristics of similar technical and economic indicators. In practice, indicators such as E_t / W or W / E_t are widely used, where E_t is the technical effect and W is the economic costs of one type or another. Such indicators include:

- the volume of output per unit of capital investment;
- costs associated with servicing the unit of the RFSMS;
- operating costs per measurement or direction finding of a radiation source.

As indicated in [4], the efficiency of the RFSMS for performing certain tasks can be compared using the ratio

$$E_1 / E_2 = (G_1 / C_1) / (G_2 / C_2), \quad (12)$$

where G_1, G_2 – results of using the proposed RFSMS options 1 and 2; C_1, C_2 – costs of creating and operating the specified RFSMS.

It is also possible to evaluate using indicators such as:

$$E' = G - C \text{ and } E'' = G / C \quad (13)$$

In practice, indicators of the G / C type are considered more "convenient" than the $E' = G - C$ indicator, since the latter can only be used if G and C have the same dimensionality (the same

units of measurement). However, both the first and second indicators have shortcomings. Suppose that G and C are expressed in monetary terms. It would seem that the E' criterion can be used in this case. However, when applying it, costs C are subtracted from the result G . If G is the economic effect and C is the discounted costs, then such a subtraction will in some cases be invalid. This is due to the different structures of the indicators of economic effect and costs.

For example, if the payback period formula is used, the costs are additional capital investments. The economic benefit is the savings on operating costs. In this case, adding and subtracting the benefits and costs is impossible.

G / C indicator has certain advantages over the $E = G - C$ indicator, since when using it, the effect and cost indicators can have different dimensions. The disadvantage of such criteria is that the same value of E' can be obtained with different combinations of G and C . When comparing two types of RFSMS using this criterion, the following conditions can be met: $E'_1 = E'_2$; $G_1 \gg G_2$; $C_1 \gg C_2$. The choice of a more effective option is associated with one or another degree of uncertainty

Conclusion. According to the presented results, the selection of comprehensive performance indicators is crucial when conducting a detailed analysis of the RFSMS tender proposals. The outcome of the selection process will largely depend on the selection of these indicators to make the right decision. Having analyzed the three types of indicators, it can be concluded that the most appropriate approach is to conduct an analysis based on technical and economic indicators, as they are interrelated and not isolated.

It seems that when using criteria like G / C , it is necessary to identify the relationship $G = f(C)$. If this relationship is linear, their use will be justified. Otherwise, it will be necessary to either compare the options in terms of effect or cost, or determine their importance using expert methods.

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