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MATHEMATICAL MODEL OF CONSTRUCTION OF THE COMPLEX INDEX OF SAFE OPERATION OF HOISTING MACHINES

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Application of modern methods of the theory of fuzzy sets and the theory of decision-making to a problem of construction of an integral index of safety in multicriteria spatio-textual signs on the basis of axiomatically entered concept of sufficiency is considered. The ways of constructing a complex index of safety in the production of lifting machines using computer algorithms that allow a qualitatively new level to solve the problem of processing a large amount of information necessary to improve the reliability of the estimates. The proposed method can be adapted for specific objects by expanding or changing the multi-criteria space of particular features that characterize the safety of operation of these objects in real conditions.

Keywords: safety, hoisting machine, integral indicator, private security metrics, sufficiency

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МАТЕМАТИЧЕСКАЯ МОДЕЛЬ ПОСТРОЕНИЯ КОМПЛЕКСНОГО ПОКАЗАТЕЛЯ БЕЗОПАСНОСТИ ЭКСПЛУАТАЦИИ ГРУЗОПОДЪЕМНЫХ МАШИН

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Рассматривается применение теорий нечетких множеств и принятия решений к построению интегрального показателя безопасности в многокритериальном пространстве частных признаков на основе аксиоматически вводимой концепции достаточности. Предложены пути построения комплексного показателя безопасности при грузоподъемных работах с использованием компьютерных алгоритмов, которые обрабатывают большое количество информации для повышения достоверности получаемых оценок. Метод может быть адаптирован для конкретных объектов путем трансформации многокритериального пространства частных признаков, характеризующих безопасность эксплуатации объектов в реальных условиях.

Ключевые слова: безопасность, грузоподъемная машина, интегральный показатель, частные показатели безопасности, достаточность.

Introduction. The analysis of safety of operation of hoisting machines shows that at the existing economic situation and the increasing requirements to maintenance of works, the measures applied now in the considered direction do not give satisfactory results. One of the ways to solve the problem is the use of automated systems that can facilitate and simplify the work of structures that ensure the safety of operation of hoisting machines. The need to create such systems was emphasized by the Board of Gosgortekhnadzor of Russia. At the same time, the developed systems should not only display the state of safety, but also contribute to the development of recommendations to improve its level at facilities. The authors propose to build an information-analytical algorithm for predicting possible emergencies at enterprises operating cranes, lifts and towers as an element of such system.

Main directions of ensuring the safety of operation of hoisting machines. The most important areas are:

supervision and control of equipment condition;

timely repair and maintenance of equipment;

training of specialists working with hoisting machines and control over their qualification level.

The analysis of the current state of problem solving in these areas shows the presence of significant shortcomings [1, 2], in particular, the lack of consistency and disparate solution of individual issues. The advantage of a systematic approach to ensuring the safety of the operation of hoisting machines is in the links between the main directions mentioned above, in contrast to the current situation, when all efforts to solve the problem are applied in isolation within each direction without taking into account their mutual influence. To implement the system approach, it is necessary to develop an integral (complex) indicator that can be used to predict the safety of operation of a particular object after a certain training, taking into account the concept of sufficiency set out below.

The concept of sufficiency in ensuring the safety of facilities. Problems of safety improvement can be solved by classical methods of optimization of known criteria. Usually, to assess safety an indicator is formed on the basis of supervision and control measures. However, with the help of a single indicator, it is difficult to justify decisions due to the difficulties of formulating a target functional that takes into account all factors affecting the safety of the object's operation. In this case, the problem becomes multi-criteria with a known set of solutions, among which it is necessary to find the best. Such problems are solved using modern decision-making theory [3].

The problem of improving safety with a complex of conflicting requirements imposed on objects, some of which can not be represented in the form of numerical indicators, is quite complex. In addition, in the case of multi-criteria safety assessment, the question of indicators (their number, significance, measurement methods, etc.) is debatable. Obviously, the set of criteria should cover all the essential aspects of the objects. The higher the indicator of the positive side of the safety of operation of the object and, accordingly, the lower the negative side, the better. However, this provision is not always true, and can be expanded by introducing the concept of sufficiency [4]. This concept assumes the existence of limits in safety indicators, exceeding which is meaningless, since it does not lead to a real result, and in some cases reduces the safety due to the presence of initially unaccounted factors (uncontrolled indicators).

From the mathematical point of view, the concept of sufficiency is that when certain conditions (sufficiency conditions) that determine the correctness of the statement *P* are met, it becomes obviously true. Therefore, the concept of sufficiency in this case includes the formulation of conditions under which the statement that the object is operated safely becomes true. The set and formulation of sufficiency conditions depends on the specifics of the object, the conditions of its operation and the requirements imposed on it [4]. We assume that for each of the m indicators characterizing the safety of the object operation, there is a given threshold value d_i. Then the excess of this value by the estimates $x_{i\nu}$ and $x_{i\mu}$ for the analyzed objects is a necessary and sufficient condition of equivalence from the point of view of the required level of safety:

$$a_\nu \sim a_\mu \Leftrightarrow x_i^\nu \geq d_i, \qquad x_i^\mu \geq d_i, \qquad i = 1, \dots, m.$$

This condition is a variant of the mathematical formulation of the concept of sufficiency, and the boundary d_i introduced in this way will later be called the level of sufficiency for each of the indicators. Obviously, in practical terms, the key thing here is to determine the levels of sufficiency (indicators threshold values) on the basis of qualitative and quantitative analysis of the safety of operation of the object.

Construction of an integral indicator in the criterion space. In the case of multi-criteria safety assessment, an excessively large number of indicators reduces the effectiveness of monitoring, as complex (system) analysis of information becomes difficult. In this regard, it is advisable to aggregate the indicators, i.e. to build one integral indicator that adequately conveys all the required information about the initial set of criteria [5]. The problem of aggregation is solved by constructing a hierarchical structure of indicators. At each level of the hierarchy, the number of private indicators, as a rule, should not exceed 10. The formed integral indicator in this case will be flexible enough to be able to include (or exclude) an additional set of indicators without significantly changing its structure [6]. Here it is expedient to use the principle of generalized criterion, when a metrized multiplicative relation of linear order is given on a set of partial indices [5].

Let us have a set $A = \{a_1, a_2, \ldots, a_n\}$ of objects, the level of safety of operation of which must be evaluated in a multicriteria space Re^m, characterized by a set of partial indicators $K = (k_1, k_2, \ldots, k_m)$. The set of objects A is displayed in the criterion space Re^m as a set of points forming a matrix of estimates:

$$X = \|x_{ij}\|_{n,m},$$

where $x_{ij} = k_j(a_i)$ — assessment of safety of operation of the object a_i on a scale of a private indicator k_j; n — number of objects in the set A; m — number of indicators (scales of estimates) in the set K, on which the relation of the metrized multiplicative linear order is set [5].

To take into account the introduced concept of sufficiency and uncertainty of tne number of indicators, we map the initial indicators $K = (k_1, k_2, \ldots, k_m)$ to the indicators $R = (r_1, r_2, \ldots, r_m)$ by forming special membership functions $y_{ij} = r_j(a_i)$:

$$y_{ij} = 0, \text{ if } x_{ij} \le g_j;$$
$$y_{ij} = f(x_{ij}, g_j, d_j), \text{ if } g_j \le x_{ij} \le d_j;$$
$$y_{ij} = 1, \text{ if } x_{ij} \ge d_j.$$

The function $f(x_{ij}, g_j, d_j)$ varies from 0 to 1.

This mapping allows us to introduce an integral exponent representing some function Z of the formed fuzzy exponents r_j and blurred (in the sense of L. A. Zadeh [7]) ratio S on pairs of training objects specified as points on the z axis. The position of points on the z axis uniquely depends on the coefficient vector $B = (b_1, \ldots, b_m)$. This allows us to define the function Z as a linear combination of estimates y_{ij} with a vector of coefficients $B = (b_1, \ldots, b_m)$, called convolution coefficients [8, 9]:

$$Z = \sum_{j=1}^{m} b_j r_j, \qquad z_i = \sum_{j=1}^{m} b_j y_{ij}, \qquad i = \overline{1,n}.$$

The components of the convolution coefficient vector are subject to the condition [8]:

$$b_j \ge 0, \sum_{j=1}^{m} b_j = 1.$$

The main problem is to construct the relation S and reasonably define the vector $B = (b_1, \ldots, b_m)$.

The method of determining the convolution coefficients. To determine the components of the vector $B = (b_1, \ldots, b_m)$, some finite set P of so-called training objects must be given, the level of safety of operation of which is objectively known and can be estimated by a numerical indicator. This makes it possible to form a kind of objectively approximating existing training matrix of paired relationships between these objects [10]:

$$Q = \|q_{rk}\|_{p,p}.$$

The size of a square symmetric matrix Q is determined by the number "p" of the training objects in question from the set P, and its q_{rk} elements are the known squares of the distances between the r-th and k-th training objects on the security preference axis.

To construct the relation *S* on pairs of training objects, we define the square of the distance between the *r-th* and *k-th* training objects on the *z* axis by the formula:

$$s_{rk}(B) = (z_r - z_k)^2 = \left[\sum_{j=1}^{m} b_j \left(x_{rj} - x_{rj}\right)\right]^2.$$

Then the observed structure of the relationships between training objects on the *z* axis with a fixed vector *B* is determined by a square symmetric matrix:

$$S(B) = \left\| s_{rk} \right\|_{p,p}.$$

The correspondence of the structure of relationships between training objects, specified by the matrix *Q*, and the structure of relationships observed on the axis of indicators *z*, determined by the matrix *S(B)*, is estimated using the functional:

$$J(B) = \sum_{r=1}^{p-1} \sum_{k=r+1}^{p} \left[s_{rk}(B) - q_{rk}\right]^2.$$

The function *Z**, defined by the vector *B**, for which the value of the functional *J(B*)* is minimal, is an integral (complex) indicator of safety of the object. The solution to the problem of extremization of the functional *J(B)* belongs to the class of problems of minimization of smooth functions on the simplex and is considered in detail in [8, 9]. Taking into account the introduced concept of sufficiency, the maximum possible value of the integral safety indicator is equal to one. This corresponds to the equality of the unit of all private safety indicators, included in the integral indicator, i.e. implementation of all necessary and sufficient conditions under which the operation of the object becomes absolutely safe. The degree of proximity of the integral indicator to the unit shows the level of complex implementation of safety requirements for all private indicators. This allows us to determine not only the current state of safety, but also to predict the behavior of the object in case of changes in individual private indicators, and to manage these indicators [11, 12].

Example of construction of hierarchical structure of safety indicators of hoisting machines operation. When constructing a hierarchical structure, the following can be attributed to the ordinal indicators of the top level:

supervision and control over the equipment condition;
repair and maintenance of hoisting machines;
training of specialists and control over the level of knowledge.

The following criteria should be specified for the construction of private security indicators at the second and subsequent levels of the hierarchy:

supervision and control over the technical condition of cranes, hoists and towers;
fast and timely repair of devices that ensure the safety of machines;
training of specialists of all areas related to the operation of hoisting equipment.

The approximate structure of indicators for the three levels of the hierarchy is shown in Fig. 1.

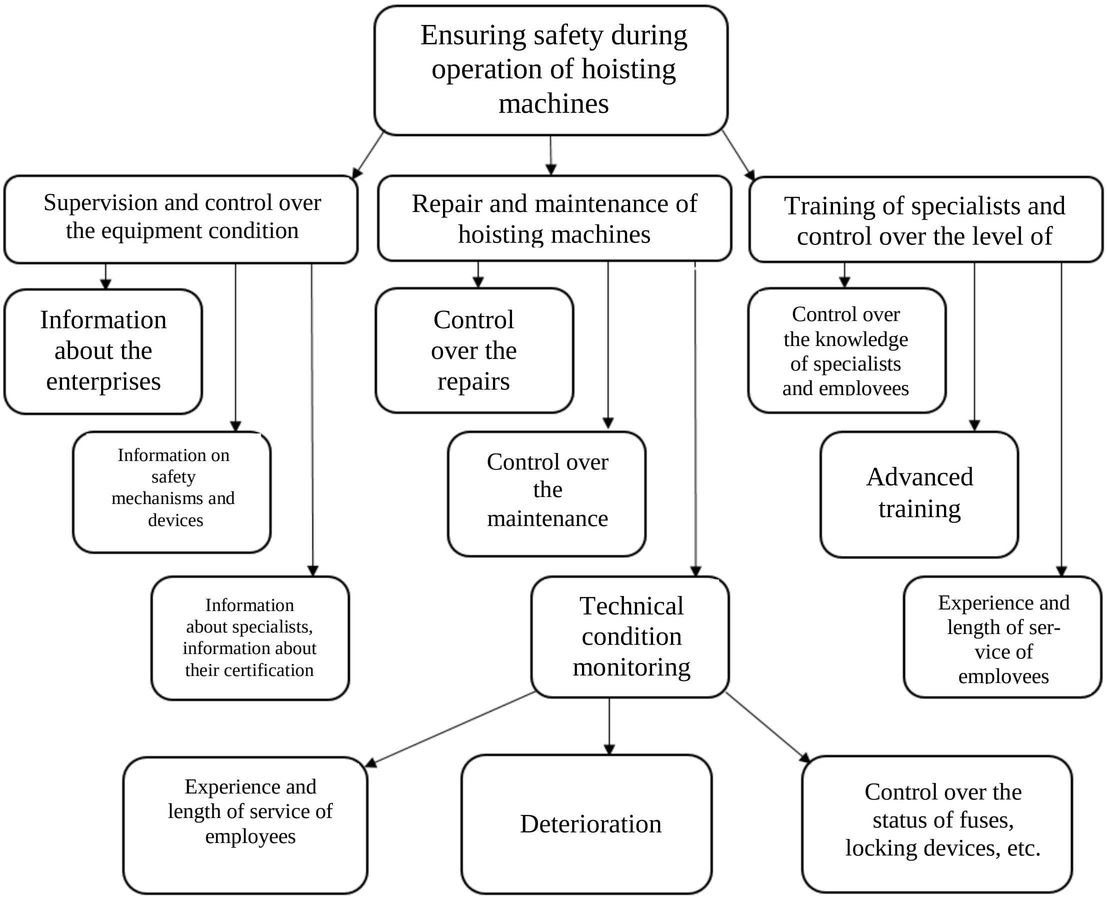

Fig. 1. Hierarchical structure of criteria for monitoring

Conclusion. The developed model for constructing a comprehensive indicator of safety of hoisting machines operation allows you to determine the level of current safety of the analyzed objects range from 0 (critical safety) to 1 (complete or absolute safety). The model is quite universal and can be used to assess the safety of other objects with appropriate changes in the hierarchical structure of safety indicators. In addition, the model allows you to automatically adapt the generated indicator to changing conditions by changing the training set of objects and conduct continuous monitoring of safety. To do this, it is necessary to monitor changes in the process of operation of private safety indicators at the lower levels of the hierarchical structure.

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