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NEW METHODS OF CALCULATING THE GENOME OF STRUCTURE AND THE FAILURE CRITICALITY OF THE COMPLEX OBJECTS' ELEMENTS

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There are considered two new methods of analysing the contribution of separate elements into the efficiency of a complex object. The first one is based on the introduction of a new notion – "the genome of structure" applied for calculating the structural significance of the monotonous and non-monotonous systems. The second method allows estimation of a more general indicator – failure criticality of the element. This method is based on a combined method of a fuzzy logic conclusion and on the methods of the experiment planning theory. The failure criticality of the complex objects' elements is expressed by a vector property for which evaluating there is used a number of partial indicators, which may have both quantitative and qualitative character and for their measurement there may be used different types of scales. The resulting indicator of the element failure criticality is presented in the form of a polynomial which accounts both the influence of the separately taken indicators and the influence of the indicators' aggregations (of 2, 3, etc.). Calculation of the polynomial coefficients is made on the basis of processing the expert information and the corresponding linguistic variables quantitatively measured by fuzzy numbers.

Keywords: genome of structure, failure criticality, complex object, multi-criteria analysis, theory of experiment planning, linguistic variable

1. Introduction

Due to the increase of the structural and functional complexity of the analysed objects and systems in the theory of reliability in recent time, ever growing popularity is given to the methods, which account not only the numeric values of the indicators of the constituent elements' reliability but also more general evaluations of the elements' failures influence on the objects' functioning. There are two the most recognised indicators: the structural significance of the element and the failure criticality of the elements [1]. Both these elements cannot be fully determined by the element's properties only and must be determined in the frame of the complex object (CO) containing the given object. Ranging the elements according to these indicators makes possible to concentrate efforts on perfecting of the assemblies which play a key role in supporting the complex objects functioning.

2. The Genome of Structure and Its Application for Determining the Structural Significance of the Element

To research the reliability of the CO connected with its structural formation, we use the following structural functions: the function of reliability, safety, vitality, minimum failures' sections obtained by orthogonalising the monotonous and non-monotonous functions of the algebra of logic (FAL), replacing the logical arguments in FAL for the probabilities of their verity and the corresponding logic operations for the arithmetic ones.

In papers [2-4] there is introduced the notion of *the genome of structure*, presenting by itself the vector $\chi = (\chi_0, \chi_1, \chi_2,\ldots,\chi_n)$, which components are the coefficients of the polynomial of the function of the minimum sections of failure of the structure containing homogenous elements. And if $\chi_0 = 0$ and the sum component of the vector equal 1, the polynomial of failure $T(Q)=\chi_0+\chi_1Q+\chi_2Q^2+\ldots+\chi_nQ^n$ describes the structure of the monotonous CO. If $\chi_0 = 0$ and the sum component of the vector equals 0, the CO is a non-monotonous one and the polynomial of failure does not retain «1» (i.e. $T(Q) = 0$). If $\chi_0 = 1$, the CO is non-monotonous and the polynomial of failure does not retain «0» (i.e. $T(Q) = 1$). Besides, the genome of structure of the monotonous systems holds different topological properties of the structure: the degree of the junior polynomial member equals the smallest power among the minimum sections of the structure failures; the coefficient with the junior polynomial member is always positive and equals the number of the minimum sections of the failures of the smallest power; the degree of the polynomial senior member equals the number of connections within the structure; the number of alternations of the signs «+» and «-» in the polynomial is bigger or equals the number of the structure internal knots.

With the help of the genome of structure we can calculate the integral evaluations of the significance and contribution of separate elements into the structural reliability of the CO employing the probability and fuzzy-possibility approaches for both the monotonous and non-monotonous structures.

While employing the probability approach, for the case of a homogenous structure (with the same probability of the CO elements' failures) calculation is performed under the formula $F_{\hom ogen}(\chi)=(\chi_0,\chi_1,\chi_2,...,\chi_n)\cdot(1,\frac{1}{2},\frac{1}{3},...,\frac{1}{n+1})^T$, for the case of a non-homogenous structure (with different probabilities of the systems elements' failures) calculation is performed under the formula $F_{non-\hom ogen}(\chi)=(\chi_0,\chi_1,\chi_2,...,\chi_n)\cdot(1,\frac{1}{2},\frac{1}{2^2},...,\frac{1}{2^n})^T$.

In case of a fuzzy-possibility description of the system elements' failures [2-4], to calculate the indicator of possibility of the structure failure we must integrate the polynomial of the failure possibility $T(\mu)=\chi_0+\chi_1\mu+\chi_2\mu^2+...+\chi_n\mu^n$ as much as possible

$$F_{possib}(\chi)=\sup_{\mu\in[0,1]}\min\{T(\mu),g(\mu)\}=\sup_{\alpha\in[0,1]}\min\{\alpha,P(\{\mu\,|\,T(\mu)\geq\alpha\})\}.$$

Before calculating we should define the degree of the possibility and, desirably, its distribution function $g(\mu)$. In case of the monotonous homogenous structures, the function of the possibility degree distribution is $g(\mu)=1-\mu$.

For the non-monotonous homogenous structures, when the polynomial of the failure possibility does not retain «0» and «1» ($T(0)=1$, $T(1)=0$), the function of the possibility degree distribution is $g(\mu)=\mu$.

If the polynomial of the possibility of the non-monotonous structure failure does not retain «1» ($T(1)=0$), the possibility degree is $P(\{\mu\,|\,T(\mu)\geq\alpha\})=P(H_\alpha)=\sup_{A\subseteq H_\alpha}|A|=\sup\{\mu^{\max}-\mu^{\min}\}$, where $\mu^{\max}=\sup\{\mu\,|\,T(\mu)\geq\alpha\}$ and $\mu^{\min}=\inf\{\mu\,|\,T(\mu)\geq\alpha\}$.

If the polynomial of the possibility of the non-monotonous structure failure does not retain «0» ($T(0)=1$), the possibility degree is $P(\{\mu\,|\,T(\mu)\geq\alpha\})=P(H_\alpha)=\sup_{A\subseteq H_\alpha}|A|=\sup\{1-(\mu^{\max}-\mu^{\min})\}$, where $\mu^{\max}=\sup\{\mu\,|\,T(\mu)\leq\alpha\}$ and $\mu^{\min}=\inf\{\mu\,|\,T(\mu)\leq\alpha\}$.

Graphical interpretation of defining the integral indicator of the failure possibility for the described cases is given in figure 1, 2.

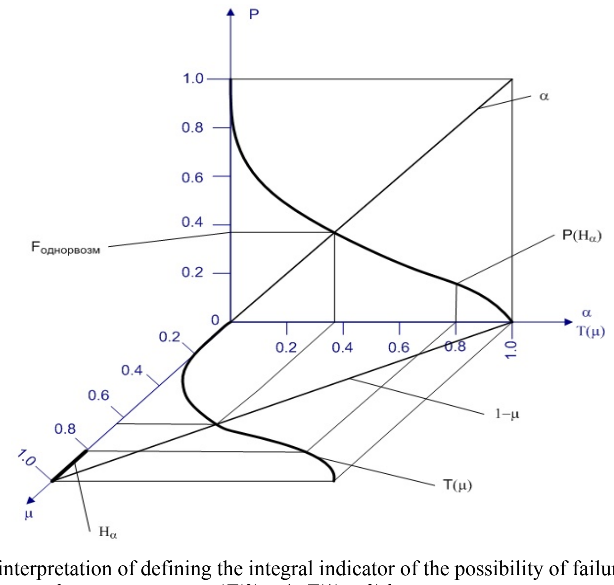

Figure 1. Graphical interpretation of defining the integral indicator of the possibility of failure of the monotonous and non-monotonous ($T(0)=1$, $T(1)=0$) homogenous structures

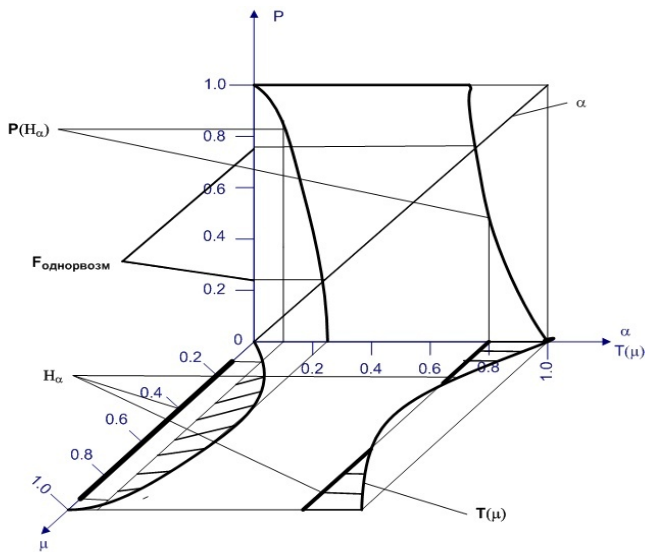

Figure 2. Graphical interpretation of defining the integral indicator of the possibility of failure of the non-monotonous (either ($T(1) = 0$, or $T(1) = 0$) homogenous structures

The suggested method may be used for calculating the significance of the positive and negative elements' contributions into the structural failure of the CO. To calculate the degree of significance of the i-th element in the structural construction, the following polynomial should be employed:

$$\xi_i(Q_1,Q_2,...,Q_n) = T(Q_1,Q_2,...,Q_n)\big|_{Q_i=1} - T(Q_1,Q_2,...,Q_n)\big|_{Q_i=0},$$

where $T(Q_1,Q_2,...,Q_n)\big|_{Q_i=1}$ is the polynomial of failure in the case of the i-th element coming out of order, $T(Q_1,Q_2,...,Q_n)\big|_{Q_i=0}$ is the polynomial of failure in the case of the i-th element running smoothly.

The polynomials for calculating the positive and negative elements' contributions have the following form:

$$B_i^+(Q_1,Q_2,...,Q_n) = T(Q_1,Q_2,...,Q_n)\big|_{Q_i=1} - T(Q_1,Q_2,...,Q_n),$$
$$B_i^-(Q_1,Q_2,...,Q_n) = -(T(Q_1,Q_2,...,Q_n) - T(Q_1,Q_2,...,Q_n)\big|_{Q_i=0}).$$

Each of the considered polynomials $\xi_i(Q_1,Q_2,...,Q_n)$, $B_i^+(Q_1,Q_2,...,Q_n)$, $B_i^-(Q_1,Q_2,...,Q_n)$ may be confronted to a corresponding genome χ_ξ^i, χ_+^i, χ_-^i, by which employment we can calculate the elements' significance and contributions into the structural formation according to the above formulae, for example, non-homogenous probability estimations: $\alpha_i = \chi_\xi^i \cdot (1,\frac{1}{2},\frac{1}{2^2},...,\frac{1}{2^n})^T$, $\beta_i^+ = \chi_\xi^i \cdot (1,\frac{1}{2},\frac{1}{2^2},...,\frac{1}{2^n})^T$, $\beta_i^- = \chi_-^i \cdot (1,\frac{1}{2},\frac{1}{2^2},...,\frac{1}{2^n})^T$.

Thus, with the help of the genomes χ_ξ^i, χ_+^i, χ_-^i, we can calculate the elements' significance and contribution into the CO structural formation by using both the possibility and the probability estimations.

The calculated characteristics of the CO elements' significance and contributions into the structural failure (reliability) have independent value and, moreover, they may be considered as one of the indicators of the elements' failure criticality. And, as the above analysis has shown [2-4], the given indicator takes interval values.

3. Determining the Failures Criticality: Problem Definition

The failure criticality of the complex objects' elements is a vector property for which evaluating there is used a number of partial indicators, such as [1]: degree of damage of the failure consequences; probability of failure; resistance of the element to the external unfavourable factors; degree of reserving;

controllability of the element state; length of the failure risk probability period; possibility of the failure localization.

The above indicators may have both quantitative and qualitative character and for their measurement there may be used different types of scales [1]. In the most general case, the failure criticality of the CO elements is estimated by the set of indicators $F = \{f_i,\ i = 1,...,m\}$, each of which presents a linguistic variable. An example of a linguistic scale conformably to one of the partial indicators is given in the second column of Table 1.

Table 1. A linguistic scale conformably to the indicator "Control of the element state"

Indicator	Scale	Terms
Controllability of the element state	1. The element state is not controlled	1. Low
	2. Periodic control is performed	2. Less than average
	3. Constant control without prediction is performed	3. Average
	4. Periodic control with prediction is performed	4. Higher than average
	5. Constant control with prediction is performed	5. High

Detecting critical elements on the basis of their ranging according to the degree of the failures' criticality, presents a task of a multi-criteria choice. For resolving such tasks there have been developed different methods [2-6] usually connected with the scaling of the vector criterion and with convolutions of different types. It is using of convolutions that conditions the main disadvantages of the given methods, namely:

- determining of the used in the convolutions weight coefficients of partial elements, is attended by serious difficulties of getting and processing of expert information; as a result, weight coefficients are badly connected with the real role of partial indicators of criticality at the generalized estimate of the object elements' criticality property;
- there is not accounted the non-linear character of the indicators' influence on each other and on the generalized indicator of the failure criticality of the CO element;
- in building the integral indicator there occurs smoothing of the partial indicators values of the elements' failure criticality.

4. Method of Calculating the Failures' Criticality: Problem Solution

The given paper suggests a combined method solving the task of the multi-criteria failure criticality analysis of the CO elements' failure under the condition of substantial uncertainty, based on a combined method of a fuzzy logic conclusion and of the methods of the experiment planning theory [10-14]. The essence of the suggested method lies in the following.

Let us consider a linguistic variable f_i = "controllability of the element state". It may take value from a set of simple and composite terms $T(f_i) = \{$"*Low*", "*Less than average*", "*Average*", "*Higher than average*", "*High*"$\}$ (see Table1). For formal presentation of the linguistic variables' terms we can use fuzzy numbers of the (L-R) type. Then, the values of the indicator "controllability of the element state" can be presented at a certain 100 points scale (see Figure 3).

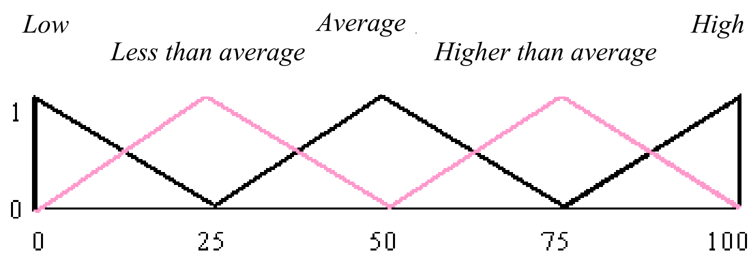

Figure 3. Indicator's presentation at a certain 100 points scale

Similarly, we can describe possible values of other partial indicators.

A generalized view of a decision-maker at the estimated failure criticality of the CO element is formed on the basis of the simultaneous analysis of several indicators with the corresponding values of terms.

Let us introduce for the resulting indicator a linguistic variable "Failure criticality of the CO element" which may take the following values $T(f^{\text{res}})=\{$"*Low*", "*Less than average*", "*Average*", "*Higher than average*", "*High*"$\}$. The experts' opinions about the influence of the partial indicators of the element failure criticality on the resulting estimate of criticality, in the general form are described by the following production rules: P_j: "If $f_1 = A_{1j}$ and $f_2 = A_{2j}$ and … and $f_m = A_{mj}$, then $f^{\text{res}} = A_j^{\text{res}}$", where $A_{ij} \in T(f_i)$, $A_j^{\text{res}} \in T(f^{\text{res}})$.

The resulting indicator of the element failure criticality can be presented in the form of the polynomial $f^{res} = \lambda_0 + \sum_{i=1}^{m}\lambda_i f_i + \sum_{i=1}^{m}\sum_{j=1}^{m}\lambda_{ij} f_i f_j + \ldots + \lambda_{12\ldots m} f_1 f_2 \ldots f_m$, which takes in account both the influence of the separately taken indicators (through the values of the coefficients λ_i) and the influence of the indicators' aggregations of two (λ_{ij}), three (λ_{ijk}), etc.

To build the resulting indicator, it is necessary to transfer the values of all partial indicators f_i to the scale [-1, +1]. With this purpose, possible boundary values of the linguistic variable f_i are marked as -1 и +1; with this, point "0" corresponds to the middle of the scale (in conformity to the physical meaning of the given indicator). Coding of the current value of the linguistic variable f_i is performed by $\breve{f}_i = (f_i - \bar{f})/h$, where f_i is the value of the indicator at the scale of the linguistic variable; $\bar{f} = (f_i^{\max} + f_i^{\min})/2$ is the middle point of the variable scale; $h = (f_i^{\max} - f_i^{\min})/2$ is the interval of varying; $f_i^{\max}, f_i^{\min}$ are the boundary values of the variable. The result of coding is presented on Figure 4.

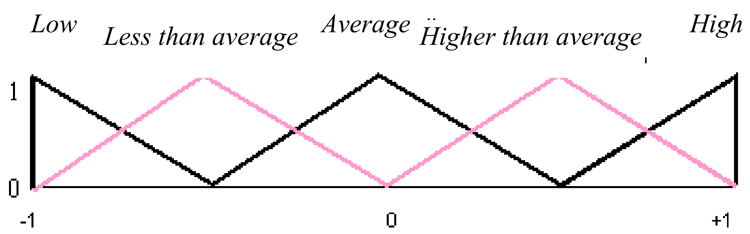

Figure 4. The result of indicator coding

Further, it is necessary to build a matrix of questioning in the expert's professional language at the boundary values of the indicators f_i. In case $m = 3$ the questioning matrix has the form presented in Table 2.

Table 2. The questioning matrix in case $m = 3$

Statement	f_1	f_2	f_3	f^{res}
1	*Low*	*Low*	*Low*	*Bad (B)*
2	*High*	*Low*	*Low*	*Less than average (LA)*
3	*Low*	*High*	*Low*	*Bad (B)*
4	*High*	*High*	*Low*	*Average (A)*
5	*Low*	*Low*	*High*	*Less than average (LA)*
6	*High*	*Low*	*High*	*Higher than average (HA)*
7	*Low*	*High*	*High*	*Average (A)*
8	*High*	*High*	*High*	*Good (G)*

Thus, for example, the second line of the table presents the following expert's judgment: 'If the indicator f_1 has the value "*High*", the indicator f_2 has the value "*Low*", the indicator f_3 has the value "*Low*" then the resulting indicator f^{res} is estimated as "*Less than average*".

Then, we form an orthogonal plan of the expert questioning [10-13], which for the case $m = 3$ is presented in Table 3.

Table 3. The orthogonal plan of the expert questioning for the case $m = 3$

	f_0	f_1	f_2	f_3	f_1f_2	f_1f_3	f_2f_3	$f_1f_2f_3$	f^{res}
1.	1	-1	-1	-1	1	1	1	-1	*B*
2.	1	1	-1	-1	-1	-1	1	1	*LA*
3.	1	-1	1	-1	-1	1	-1	1	*B*
4.	1	1	1	-1	1	-1	-1	-1	*A*
5.	1	-1	-1	1	1	-1	-1	1	*LA*
6.	1	1	-1	1	-1	1	-1	-1	*HA*
7.	1	-1	1	1	-1	-1	1	-1	*A*
8.	1	1	1	1	1	1	1	1	*G*

Let f^{res} may take the values presented on Figure 5. For building an integral indicator with substance coefficients we'll perform an operation of dephasification of the linguistic values of the variable f^{res}, for which we shall put each term in correspondence with its fuzzy number mode ("*Bad*" – 0,2; "*Less than average*" – 0,45; "*Average*" – 0,55; "*Higher than average*" – 0,75; "*Good*" – 1).

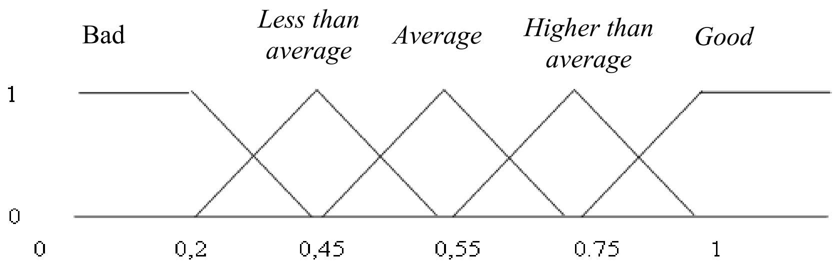

Figure 5. Values of f^{res}

Calculation of the polynomial coefficients is performed according to the rules adopted in the theory of experiment planning [10-13], for which we calculate the average scale products of the corresponding columns of the orthogonal matrix by the vector of the diphase values of the resulting indicator. The received results are given below in Table 4.

Table 4. The results of the average scale products calculation

$f_0 \times f^{\text{res}}$	$f_1 \times f^{\text{res}}$	$f_2 \times f^{\text{res}}$	$f_3 \times f^{\text{res}}$	$f_1 \times f_2 \times f^{\text{res}}$	$f_1 \times f_3 \times f^{\text{re}}$	$f_2 \times f_3 \times f^{\text{res}}$	$f_1 \times f_2 \times f_3 \times f^{\text{re}}$	*Polynomial values*
0,2	-0,2	-0,2	-0,2	0,2	0,2	0,2	-0,2	0,20
0,45	0,45	-0,45	-0,45	-0,45	-0,45	0,45	0,45	0,45
0,2	-0,2	0,2	-0,2	-0,2	0,2	-0,2	0,2	0,20
0,55	0,55	0,55	-0,55	0,55	-0,55	-0,55	-0,55	0,55
0,4	-0,4	-0,4	0,4	0,4	-0,4	-0,4	0,4	0,40
0,75	0,75	-0,75	0,75	-0,75	0,75	-0,75	-0,75	0,75
0,55	-0,55	0,55	0,55	-0,55	-0,55	0,55	-0,55	0,55
1	1	1	1	1	1	1	1	1,00
Polynomial coefficients	λ_0	λ_1	λ_2	λ_3	λ_{12}	λ_{13}	λ_{23}	λ_{123}
Polynomial values	0,5125	0,175	0,0625	0,1625	0,025	0,025	0,0375	0

Thus, the convolution of the indicators in our case has the following form:

$$f^{\text{res}} = 0{,}5125 + 0{,}175 f_1 + 0{,}0625 f_2 + 0{,}1625 f_3 + 0{,}025 f_1 f_2 + 0{,}025 f_1 f_3 + 0{,}0375 f_2 f_3 .$$

If we do not perform the dephasification of the resulting indicator values, the suggested method allows building a functional dependence of the failure criticality indicator on f_i with fuzzy coefficients $\lambda_0, \lambda_1, \lambda_2, ..., \lambda_{12...m}$. Though, in the given case it is reasonable to use arithmetic operations on the fuzzy trapeziform numbers introduced in the paper [13].

5. Example of Calculating the Failure Criticality

To examine the suggested approach, let us consider an example made in paper [1] and compare the results of ranging the CO elements according to the degree of criticality by the suggested method with the method of marking out Pareto layers presented in paper [1].

As a vector of criticality, we'll take a two-component vector $\vec{f} = (f_1, f_2)$. We need to range 10 elements $X = \{x_i, i = 1,...,10\}$, having the following criticality estimates: $\vec{f}(x_1) = (0.1, 0.1)$, $\vec{f}(x_2) = (0.6, 0.1)$, $\vec{f}(x_3) = (0.8, 0.1)$, $\vec{f}(x_4) = (1, 0.1)$, $\vec{f}(x_5) = (0.1, 0.4)$, $\vec{f}(x_6) = (0.4, 0.4)$, $\vec{f}(x_7) = (0.6, 0.4)$, $\vec{f}(x_8) = (0.1, 0.6)$, $\vec{f}(x_9) = (0.8, 0.6)$, $\vec{f}(x_{10}) = (0.1, 0.8)$. The results of marking out Pareto layers with the use of the classic relation of domination by Pareto on the set $X = \{x_i, i = 1,...,10\}$ are presented on Figure 6.

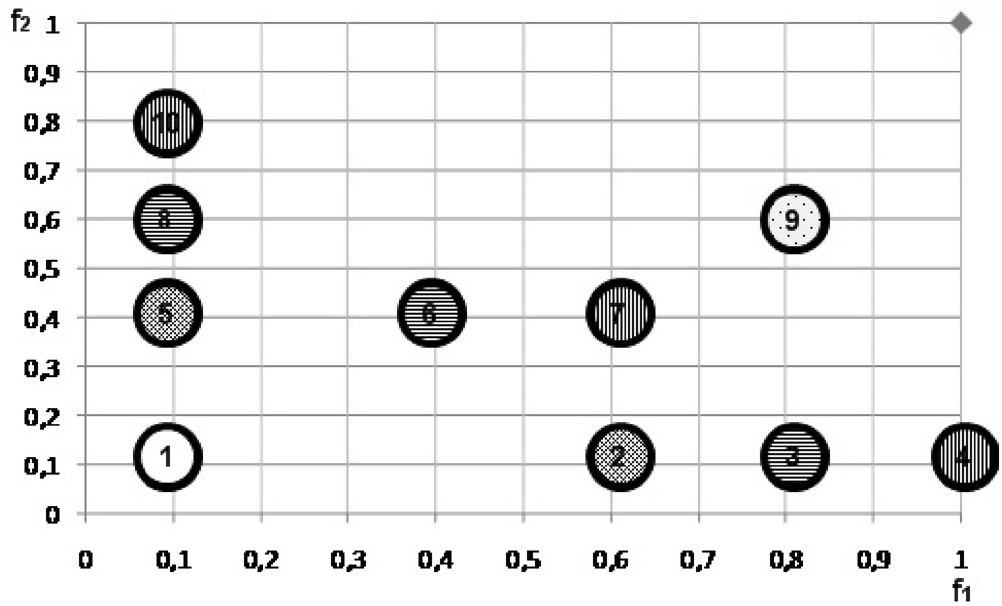

Figure 6. The results of marking out Pareto layers

Here, Pareto layers consist of the following elements: $X_1^{nd} = \{x_1\}$, $X_2^{nd} = \{x_2, x_5\}$, $X_3^{nd} = \{x_3, x_6, x_8\}$, $X_4^{nd} = \{x_4, x_7, x_{10}\}$, $X_5^{nd} = \{x_9\}$. For ranging the elements according to the criticality degree, we have used in each layer [1] a linear indicators' convolution of the type $f^{\text{res}}(x_i) = \lambda_1 f_1(x_i) + \lambda_2 f_2(x_i)$. Let the coefficients of the criticality indicators' significance be of the same value $\lambda_1 = \lambda_2 = 0.5$. Then, the result of ranging of the set $X = \{x_i, i = 1,...,10\}$ is as follows: $x_1 \prec x_5 \prec x_2 \prec x_8 \prec x_6 \prec x_3 \prec x_{10} \prec x_7 \prec x_4 \prec x_9$, which is presented on Figure 7.

It is easy to note that in case of using the suggested method, the elements x_6, x_7 in the corresponding Pareto layers $X_3^{nd} = \{x_3, x_6, x_8\}$, $X_4^{nd} = \{x_4, x_7, x_{10}\}$ at different combinations of the significance coefficients λ_1, λ_2, as the result of their ranging, will be always dominated by the given layers' elements. It means that in solving the tasks of ranging and determining the critical elements in Pareto layers, the elements x_6, x_7 will under no condition be admitted as most critical or less critical.

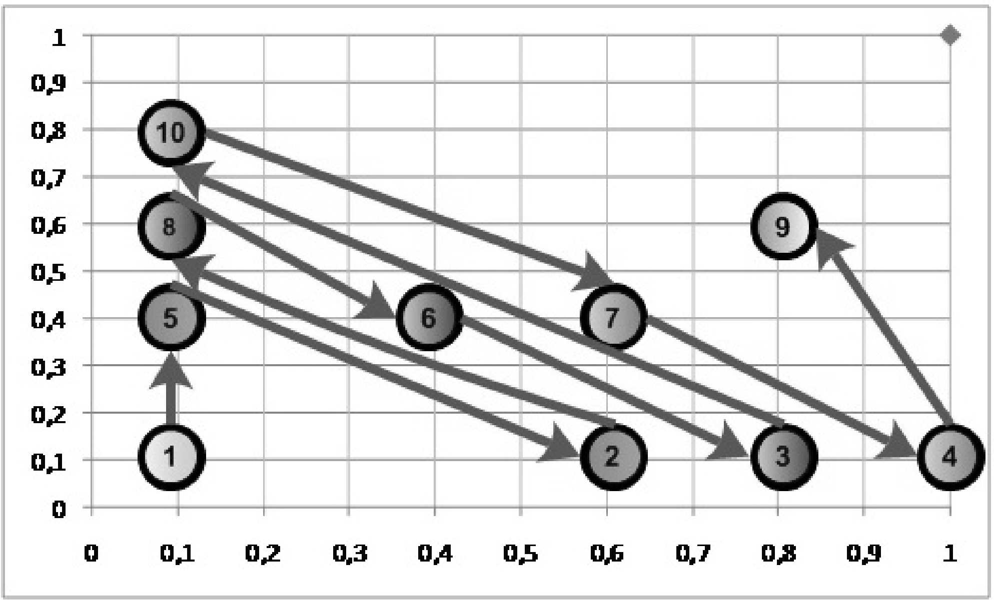

Figure 7. The result of ranging of the set $X = \{x_i, i = 1,...,10\}$

Let us perform the ranging of the CO elements according to their criticality degree by the suggested combined method. We'll show that we can mark out from the Pareto layers the elements x_6, x_7 as well as any others. Let the orthogonal plan of the expert questioning be presented in Table 5.

Table 5. The orthogonal plan of the expert questioning

f_0	f_1	f_2	f^{res}	$f_1 \times f_2$
1	-1	-1	0,1	1
1	1	-1	0,9	-1
1	-1	1	1	-1
1	1	1	1	1
$f_0 \times f^{\text{res}}$	$f_1 \times f^{\text{res}}$	$f_2 \times f^{\text{res}}$	$f_1 \times f_2 \times f^{\text{res}}$	*Polynomial values*
0,1	-0,1	-0,1	0,1	0,100
0,9	0,9	-0,9	-0,9	0,900
1	-1	1	-1	1,000
1	1	1	1	1,000
Polynomial coefficients	λ_0	λ_1	λ_2	λ_{12}
Coefficients' values	0,75	0,2	0,25	-0,2

Having processed the data of the expert questioning according to the above method we'll get the following equation describing the expert's judgment: $f^{\text{res}} = 0,75 + 0,2 f_1 + 0,25 f_2 - 0,2 f_1 f_2$. The results of calculating the integral indicator of the elements' failure criticality are shown on Figures 8 and 9.

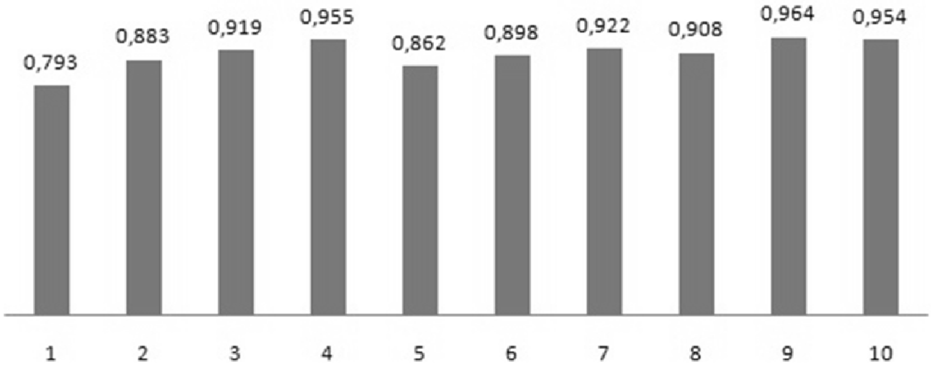

Figure 8. The results of calculating the integral indicator of the elements' failure criticality

The received results of ranging the CO elements according to the criticality degree are similar to the above ranging, shown on Figure 7. Here, the elements x_6, x_7 in the corresponding Pareto layers $X_3^{nd} = \{x_3, x_6, x_8\}$, $X_4^{nd} = \{x_4, x_7, x_{10}\}$ have turned out the least critical by the expert's opinion.

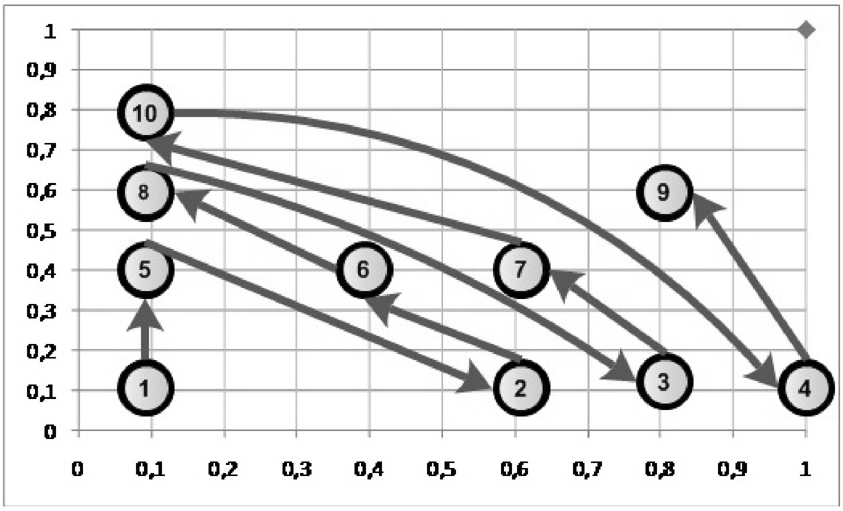

Figure 9. The results of ranging the CO elements according to the criticality degree

6. Conclusions

Advantages of the suggested approach to the analysis of the elements' contribution into the CO efficiency:

1. Introduction of the notion of the genome of structure allows evaluation of the elements' structural significance for both the monotonous and non-monotonous systems.
2. Using both quantitative and qualitative (fuzzy, inexact, interval) information about the elements' failure influence on the CO functioning substantially increases the trustworthiness the conclusions and decisions made in the CO design and management.
3. In the frame of the suggested method, there is performed formalization of the expert information, presented in the natural for the expert language, by means of introducing linguistic variables, which allow adequate reflecting of an approximate word description of objects and phenomena even in those cases when a determined description is either lacking or impossible in principle.
4. The suggested method of the failures' criticality analysis allows formalizing the expert's (group of experts') experience in the form of prediction models in a multi-dimension space and taking into account complex simultaneous influence of several factors on the resulting criticality indicator of the CO.

Due to this, there is revealed the non-linear character of the particular indicators' influence on the integral indicator of the failures' criticality and there is increased the trustworthiness of the decision-making results.

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