Reliability of human-machine interaction in distributed information environments. Models for morphological analysis and optimization of group activities

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***Abstract*—The problem of designing group activities of operators in distributed information environments is considered. An optimization model is proposed for choosing the option of assigning functions to a group of operators for the basic model of the algorithm for executing an application in the form of an event graph. The model can be used in decision support systems by the operator-manager of critical control systems.**

***Keywords*—ergonomics, ergatic system, human-operator, human-machine, reliability, modeling, information technology, critical system, group activity**

I. Introduction

Fundamental changes in computer control tools and methods [1] for complex distributed objects, such as energy systems, oil and gas transportation systems, transport and research systems [2-5], training systems [6-9] have fundamentally changed the work of people in distributed information environments. The technology of interaction between operators and control objects through complex information models has changed and become more complicated [1, 10]. The share of group activities has increased when operators jointly implement the specified control technologies, despite the fact that they may be located at a great distance from each other [1, 10]. With the increase in the technical and organizational complexity of such ergatic control systems, the cost of operator's errors, failures and malfunctions of information technology equipment also increases [1, 2, 10, 11]. With the introduction of computer-aided decision support methods and artificial intelligence, the role of a person does not decrease, but also increases significantly [1, 3, 10], especially in the context of combating cybercriminals and various cyber-attacks on information systems [12].

II. Problem Statement

The main goal of the ergonomic support of complex control systems is to minimize the risks caused by the erroneous actions of people-operators [3, 10, 13-16], by taking into account engineering-psychological and ergonomic restrictions, the individual characteristics of operators and by "adapting" technology to a person [16-18].

In recent years, emphasis from studying and solving problems of the so-called "physical" ergonomics (anthropometric, physiological, etc. problems) shifted to solving problems of providing cognitive comfort for operators and tasks of "organizational" ergonomics [2, 3, 11, 16-eighteen]. This implies the taski of determining the number of personnel, the qualifications of people, the distribution of functions between operators and the design of methods for interaction between operators.

This task of the prompt organization of operator interaction is especially acute in cases related to non-standard or emergency situations, as well as in the tasks of managing security incidents. The operator-manager, who takes over the organization of the elimination of the problem situation, must quickly distribute the functions between individual operators. In this case, the requirements [18-20] should be taken into account:

- Maximizing the probability of error-free execution of the application (elimination of the problem situation);
- Restrictions on the timing of activities;
- Opportunities for organizing joint activities (forming a team or group of operators compatible with each other):
    - technologically (means of labor, communication channels, information models, etc.) [18-20];
    - psychologically [26, 27];
    - other.

Various network methods can be used to simulate the activities of operators, e.g.[13, 21]; but the most convenient tool is a functional network (FN) [18-20], which allows not only description of the activity but also evaluation of its reliability characteristics.

To assess the reliability of the activity, mathematical models and a software-modeling complex were developed [22-24], and a number of optimization tasks were solved, including distribution of functions between operators [25]. However, the issues of organizing group activities are not fully resolved in the ergonomics of automated control systems [27-29].

In this regard, the objective of this work is to determine the problem of forming a group of compatible operators working in a single information space, who are assigned to perform discrete algorithmic activities to execute applications arriving at random times (with the distribution of individual operations between specific operators) in order to maximize the probability of error-free execution under constraint on mathematical expectation of runtime.

III. RESULTS.

A. *The principle of formalizing the problem situation of group activity optimization*

To set the optimization problem, we suggest the following approach:

- Describe in natural language the sequence of work to complete the application.
- Following the identified logic, develop a FS model that describes the activities for the implementation of the application (work schedule).
- Make the transition from the work graph to the event graph (as events we use events consisting in the fact that some operation was performed correctly or performed with some violation (Fig. 1 demonstrates an example of the transition from the work graph to the event graph).
- Considering the possibility of alternative assignments of operators to separate operations (with different probabilities of transition from state to state and different runtime characteristics), build on the basis of an event graph a model of semi-Markov decision-making process (SMDMP) for assigning operators to perform individual operations (taking into account their compatibility in a group).
- Formalize the optimization problem for SMDMP (for example, if we are talking about maximizing the probability of error-free execution with a restriction on the mathematical expectation of execution time, then this will be the task of "maximizing the probability of absorption of the process into a given state, while limiting the time spent before absorption".

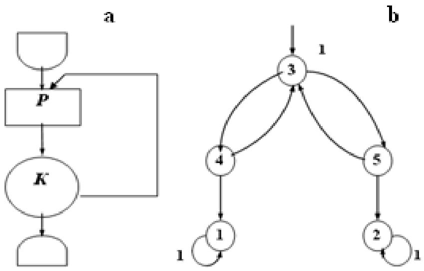

Fig. 1. An example of the process model for implementing the simplest application: *a* - work graph; *P* - work operation; *K* - operation control; *b* – graph of events [18.25].

B. *Model for designing group activities*

Let us select the absorbing vertices among the SMDMP vertices (let in the general case their number is r, in the simplest case - 2, i.e., "error-free" and "with error") and number them starting from 1. Let the vertices 1, 2, ... r_l are the vertices with acceptable outcomes. For non-absorbing vertices, we define the probabilities of finding the process in these initial states: $a = (a_{r+1}, a_{r+2}, \ldots, a_n)$, so that

$$\sum_{i=r+1}^{N} a_i = 1, \quad (1)$$

where N is the number of states, r – the number of absorbing states.

We assume that K is the set of all operators. K_0 is the cardinality of K. At each vertex i there can be K_i of alternative assignments. Each variant is associated with a set of transitions from vertex i to vertex j when choosing the k-th solution, $k \in K_i$. with corresponding probabilities and transition times.

Thus, the k-th solution corresponds to the assignment of the operator $k \epsilon K_i \epsilon K$ to the stage of the technological process, which corresponds to state i of the SMDMP.

$P_{ij}^{(k)}$ is the probability of the transition of the process from state i to state j when choosing the k-th alternative. Wherein:

$$\sum_j p_{ij}^{(k)} = 1 \; at \; all \; i \; and \; all \; k \in K_i \qquad (2)$$

$T_{ij}^{(k)}$ is the average time of transition from state i to state j when choosing the k-th alternative. Then the average time of the i-th work with the k-th solution, $T_i^{(k)}$, is defined as:

$$T_i^{(k)} = \sum_j P_{ij}^{(k)} * T_{ij}^{(k)} \qquad (3)$$

In reliable design, it is most often necessary to maximize P_r - the probability of absorption in the r-state (or in states of the r-type):

$$P_r = \sum_l \sum_{i=r+1}^{N} \sum_{k \in K_i} P_{ir_l}^{(k)} * x_i^{(k)} \qquad (4)$$

Here $x^{(k)}_i$ defines a solution: $x^{(k)}_i > 0$ if the k-th alternative is selected at the i-th vertex, and $x^{(k)}_i = 0$, if another solution is chosen. It is also necessary:

- Describe the presence of dependent vertices (if the operations that correspond to the states $l, v, \ldots, n$, are performed by the same person).
- Introduce a limit on average execution time.
- Introduce auxiliary Boolean variables $\delta^{(k)}_i$ (to ensure the uniqueness of solutions and the formation of conditions for the dependence of the vertices: here k is the operator, i is vertex of the SMDMP).

Based on the technical and technological characteristics of the system and psychological characteristics of people, we introduce the compatibility matrix (dimension K_0xK_0) to describe the possibility of their joint work:

$$[C_{nl}] = \begin{bmatrix} c_{11} & c_{12} & \ldots & \ldots & c_{1K_0} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ c_{K_0 1} & c_{K_0 2} & \ldots & \ldots & c_{K_0 K_0} \end{bmatrix} \qquad (5)$$

Its elements characterize the compatibility of people when working in the system:

$$c_{nl} = \begin{cases} 1, \; if \; n-th \; and \; l-th \; operators \; can \; be \; used \; together, \; or \; n = l; \\ 0, \; if \; n-th \; and \; l-th \; operators \; cannot \; be \; used \; in \; perfomance \; together. \end{cases} \qquad (6)$$

To analyze the formation of groups of operators, that may be assigned to execute the application together, we use the concepts of generating functions and combinations.

Combinations of n different objects $A_1, A_2, \ldots A_n$ on i without repetition can be obtained as coefficients α_i of the generating function:

$$F(s) = \sum_{i=0}^{n} \alpha_i s^i = (1 + A_1 s)(1 + A_2 s) \ldots (1 + A_n s) \qquad (7)$$

The number of these combinations is determined by the coefficient $\mu_i = C_n^i$ of the enumerator:

$$F_*(s) = \sum_{i=0}^{n} \mu_i s^i = (1+s)^n \qquad (8)$$

As an example, we give a combination of four objects for $i=1,2,3,4$:

$$\begin{aligned} F(s) = \sum_{i=0}^{4} \alpha_i s^i &= (1 + A_1 s) * (1 + A_2 s) * (1 + A_3 s) * (1 + A_4 s) = \\ &= s^0 + (A_1 + A_2 + A_3 + A_4) s^1 + \\ &+ (A_1 A_2 + A_1 A_3 + A_1 A_4 + A_2 A_3 + A_2 A_4 + A_3 A_4) s^2 + \\ &+ (A_2 A_3 A_4 + A_1 A_3 A_4 + A_1 A_2 A_4 + A_1 A_2 A_3) s^3 + \\ &+ (A_1 A_2 A_3 A_4) s^4 \end{aligned}$$

The values of α_i ($i=1,2,3,4$) are defined as follows:

$\alpha_1 = A_1 + A_2 + A_3 + A_4$;

$\alpha_2 = A_1A_2 + A_1A_3 + A_1A_4 + A_2A_3 + A_2A_4 + A_3A_4$;

$\alpha_3 = A_1A_2A_3 + A_1A_2A_4 + A_1A_3A_4 + A_2A_3A_4$; $\alpha_4 = A_1 A_2A_3A_4$.

Hence, it is obvious that the group of i operators is one of $C_{K_0}^i$ combinations of elements of the set K_0 with i elements.

Thus, possible groups of i operators can be defined as coefficients of the generating function for s^i.

$$F(s) = \sum_{i=0}^{K_0} \alpha_i s^i = (1 + k_1 s)(1 + k_2 s) \ldots (1 + k_{K_0} s), \qquad (9)$$

where s is any real number.

In the general case, a combination of operators from the set K_0 with respect to i operators may be defined as:

$$k_{h_1} \, k_{h_2} \, \ldots k_{h_i} , \qquad (10)$$

where: $h_1 = 1,2,3,\ldots,K_0$; $h_2 = 2,3,4,\ldots,K_0$; $h_i = i, i+1, i+2, \ldots, K_0$; $i=1,2,\ldots,K_0$

We put the sequence $G=\{g_j\}$ of K_0 elements in accordance with all combinations (10)

$$g_j = \begin{cases} 1, \; if \; in \; combination \; (16) \; \exists \; h_l = j; \\ 0, \; otherwise \end{cases} , \qquad (11)$$

where $j=1,2,\ldots,K_0$; $l=1,2,\ldots,i$.

Thus, for example, for four groups of three person-operators ($k_2k_3k_4$, k_1,k_3k_4, $k_1k_2k_4$, $k_1k_2k_3$), the following sequences is formed:

$q_1=\{0,1,1,1\}$; $q_2=\{1,0,1,1\}$; $q_3=\{1,1,0,1\}$; $q_4=\{1,1,1,0\}$.

Based on the data of the matrix $[C_{nl}]$ and all possible combinations (10), we obtain the matrix $[Q_{mj}]$, each row of which contains 0 and 1 and displays one of the combinations of i elements from K_0 elements. K_0 is the number of elements in the row of the matrix.

Each row of the matrix $[Q_{mj}]$ is formed from the sequence $G=\{g_j\}$, corresponding to the combination (10) and obtained by the formula (11), as follows:

$$q_{mj} = g_j, if \quad c_{h_1h_2}c_{h_1h_3}...c_{h_{i-1}h_i} > 0, \qquad (12)$$

where: $m=1,2,3,...$ is the number of the current row of the matrix $[Q_{mj}]$;

$j=1,2,...K_0$ – is the column number of the matrix $[Q_{mj}]$;

$c_{h_nh_l}$ - an element of matrix (5), standing at the intersection of the row h_n and column h_l;

h_nh_l – is one of the possible combinations of i elements of $h_1,h_2,...,h_i$ with two elements in each. All possible such combinations we define as the coefficient of the generating function at s^2:

$$F(s) = \sum_{u=0}^{i} \alpha_u s^u = (1+h_1s)(1+h_2s)...(1+h_is), \qquad (13)$$

Obviously, the row of the matrix $[Q_{mj}]$ defines one group of operators that may be directed to the joint execution of the application. Thus, the matrix $[Q_{mj}]$ determines the acceptable options for the formation of groups ("teams") of operators for joint work in the information space.

Based on the above considerations, we can formalize our task as follows:

$$P_r^m = \sum_l \sum_{i=r+1}^{N} \sum_{k\in K_i} P_{ir_i}^{(k)} x_i^{(k)} \to \max \qquad (14)$$

$$\sum_{k\in K} x_j^{(k)} - \sum_{i=r+1}^{N} \sum_{k\in K} P_{ij}^{(k)} x_i^{(k)} = a_j, \; j=r+1,r+2,...,N \qquad (15)$$

$$\sum_{i=r+1}^{N} \sum_j \sum_{k\in K_i} P_{ij}^{(k)} T_{ij}^{(k)} x_i^{(k)} \le T_0, \qquad (16)$$

$$\sum_{k\in K_i} \delta_i^{(k)} q_{mk} = 1 \text{ at all } i, \qquad (17)$$

$$\delta_l^{(k)} = \delta_v^{(k)} = .. . = \delta_n^{(k)}, \text{ at all } k\epsilon K \qquad (18)$$

$$x_i^{(k)} - M\delta_i^{(k)} \le 0, \text{ at all } i \text{ and all } k\epsilon K_i. \qquad (19)$$

$$x_i^{(k)} - w\delta_i^{(k)} \ge 0, \text{ at all } i \text{ and all } k\epsilon K_i \qquad (20)$$

$$\sum_{j=1}^{r} \sum_{i=r+1}^{N} \sum_{k\in K_i} P_{ij}^{(k)} x_i^{(k)} = 1, \qquad (21)$$

$$x_i^{(k)} \ge 0 \quad \text{at all } i \text{ and all } k\epsilon K_i. \qquad (22)$$

Here M and w are a very large and very small numbers.

Constraint (17) defines the possibility of joint work of operators in one group, as well as the fact that only one person performs each operation.

Constraint (18) is necessary in order to ensure the coincidence of the selected alternatives for dependent vertices.

Constraints (19) and (20) together with constraint (22) indicate the need for only one $x^{(k)}_i$ to be different to 0.

Constraint (21) is a normalizing condition that ensures the absorption of the process (with probability 1).

To form the vector of assignments of operators to operations of the activity algorithm, we introduce the matrix $U=[u_{nl}]$, which displays the correspondence of the vertices of the event graph to the operations of the work graph:

- matrix dimension – n_0xL;
- the number of rows of the matrix $[u_{nl}]$ equals n_0 and corresponds to the number of operations of the work graph;
- the number of columns of the matrix L is equal to the largest number of vertices of the event graph corresponding to one of the operations of the work graph;
- nonzero elements of row n of the matrix are the numbers of the vertices of the event graph that model the n-th operation of the work graph.

The coordinates of the vector $X^m=\{x^m_1,x^m_2,...,x^m_{n0}\}$ characterize the variant of assigning the operators of the m-th group to operations of the activity algorithm and are determined through the values $x^{(k)}_i$ and the elements of the correspondence matrix $[u_{nl}]$ as follows:

- The number of elements of the vector X^m is equal to the number of operations of the work graph: n_0
- $x^m{}_n = k, if \quad x_i^{(k)} > 0 \; and \; i = u_{nl}, n = 1,2,...,n_0$ (23)

Index m means that the optimal solution is determined for the m-th group of operators.

The fixing vector $X=\{x_1,x_2,...x_{n0}\}$, which gives the maximum of the objective function among all possible groups of compatible operators, is the result of solving the optimization problem:

$$X = X^{m_0}, if \; P_r^{m_0} = \max_m (P_r^m) \qquad (24)$$

C. Simplified example

Let it be necessary to fulfill the simplest application (Fig. 1). To do the work, it is possible to involve 4 operators with known values of the probabilities of error-free execution and mathematical expectations of the time required to complete individual operations. The transition probability matrices (for the graph in Fig. 1.*b*), characterizing the error-free behavior of the operators, are shown in Fig. 2.

1st operator, matrix $[P_{ij}^{(1)}]$				
1	0	0	0	0
0	1	0	0	0
0	0	0	0,91	0,09
0,92	0	0,08	0	0
0	0,05	0,95	0	0
2nd operator, matrix $[P_{ij}^{(2)}]$				
1	0	0	0	0
0	1	0	0	0
0	0	0	0,9	0,1
0,93	0	0,07	0	0
0	0,03	0,97	0	0
3rd operator, matrix $[P_{ij}^{(3)}]$				
1	0	0	0	0
0	1	0	0	0
0	0	0	0,99	0,01
0,98	0	0,02	0	0
0	0,06	0,94	0	0
4th operator, matrix $[P_{ij}^{(4)}]$				
1	0	0	0	0
0	1	0	0	0
0	0	0	0,93	0,07
0,935	0	0,065	0	0
0	0,05	0,95	0	0

Fig. 2. Transition probability matrices for the event graph

Fig. 3.*a*. shows the restrictions on grouping operators (compatibility matrix). *It is required* to form a group of compatible operators, which provides the maximum probability of error-free execution of the application (the time limit is excluded from this demo).

Solution. We form a matrix regulating the permissible group activity (Fig.3.*b*.)

a
$$[C_{nl}] = \begin{bmatrix} 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 \end{bmatrix}$$

b
$$[Q_{mj}] = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 \end{bmatrix}$$

Fig. 3. Matrices of mapping the possibility of joint work of system operators: *a* - compatibility matrix of work in pairs; *b* - a matrix modeling the permissible group activity

We set the vector of initial probabilities: $a = (a_3, a_4, a_5) = (1,0,0)$.

Figure 4 shows a fragment of the obtained optimal solution to problem: (14), (15), (17) - (22). To fulfill the application, the 3rd group of operators is assigned. (the working operation is performed by the 2nd operator, the control operation is performed by the 3rd operator). Thus, the restriction (17) uses the 3rd row of the matrix $[Q_{mj}]$). Figure 5 shows a comparison of the optimal variant with other possible assignments of operators (the difference even for such a simplified example is significant for critical systems).

24	**Variables**												
25	Variable Name	X_3^1	X_3^2	X_3^3	X_3^4	X_4^1	X_4^2	X_4^3	X_4^4	X_5^1	X_5^2	X_5^3	X_5^4
26	Value	0,0000	0,0000	1,0858	0,0000	0,0000	1,0749	0,0000	0,0000	0,0000	0,0109	0,0000	0,0000
27	Lower limit	0	0	0	0	0	0	0	0	0	0	0	0
28		**Integer variables**											
29	Variable Name	δ_3^1	δ_3^2	δ_3^3	δ_3^4	δ_4^1	δ_4^2	δ_4^3	δ_4^4	δ_5^1	δ_5^2	δ_5^3	δ_5^4
30	Value	0	0	1	0	0	1	0	0	0	1	0	0
31	Upper limit	1	1	1	1	1	1	1	1	1	1	1	1
32	Integer	Integer	Integer	Integer	Integer	Integer	Integer	Integer	Integer	Integer	Integer	Integer	Integer
33													
34		i=3	i=4	i=5								Route	
35	Probabiliti of finding of the system in the initial state in the peak i	1	0	0	The objective function	$X_3^{(1)}*P_{31}^{(1)}+X_3^{(2)}*P_{31}^{(2)}+X_3^{(3)}*P_{31}^{(3)}+X_3^{(4)}*P_{31}^{(4)}+X_4^{(1)}*P_{41}^{(1)}+X_4^{(2)}*P_{41}^{(2)}+X_4^{(3)}*P_{41}^{(3)}+X_4^{(4)}*P_{41}^{(4)}$---->max					0,999674	Maximum	
36		**Limitations on $x_i^{(k)}$ and $P_i^{(k)}$**											
37	The type of limitation										The left part	Sign	The right part
38	To variables	$X_3^{(1)}+X_3^{(2)}+X_3^{(3)}+X_3^{(4)}-(X_4^{(1)}*P_{43}^{(1)}+X_4^{(2)}*P_{43}^{(2)}+X_4^{(3)}*P_{43}^{(3)}+X_4^{(4)}*P_{43}^{(4)}+X_5^{(1)}*P_{53}^{(1)}+X_5^{(2)}*P_{53}^{(2)}+X_5^{(3)}*P_{53}^{(3)}+X_5^{(4)}*P_{53}^{(4)})=1$									1,0000	=	1
39	To variables	$X_4^{(1)}+X_4^{(2)}+X_4^{(3)}+X_4^{(4)}-(X_3^{(1)}*P_{34}^{(1)}+X_3^{(2)}*P_{34}^{(2)}+X_3^{(3)}*P_{34}^{(3)}+X_3^{(4)}*P_{34}^{(4)}+X_5^{(1)}*P_{54}^{(1)}+X_5^{(2)}*P_{54}^{(2)}+X_5^{(3)}*P_{54}^{(3)}+X_5^{(4)}*P_{54}^{(4)})=0$									0,0000	=	0
40	To variables	$X_5^{(1)}+X_5^{(2)}+X_5^{(3)}+X_5^{(4)}-(X_3^{(1)}*P_{35}^{(1)}+X_3^{(2)}*P_{35}^{(2)}+X_3^{(3)}*P_{35}^{(3)}+X_3^{(4)}*P_{35}^{(4)}+X_4^{(1)}*P_{45}^{(1)}+X_4^{(2)}*P_{45}^{(2)}+X_4^{(3)}*P_{45}^{(3)}+X_4^{(4)}*P_{45}^{(4)})=0$									0,0000	=	0
41	To variables	$X_4^{(1)}*P_{41}^{(1)}+X_4^{(2)}*P_{41}^{(2)}+X_4^{(3)}*P_{41}^{(3)}+X_4^{(4)}*P_{41}^{(4)}+X_5^{(1)}*P_{52}^{(1)}+X_5^{(2)}*P_{52}^{(2)}+X_5^{(3)}*P_{52}^{(3)}+X_5^{(4)}*P_{52}^{(4)}=1$									1,0000	=	1

Fig. 4. Fragment of the solution in EXCEL (the 3rd group of operators is selected)

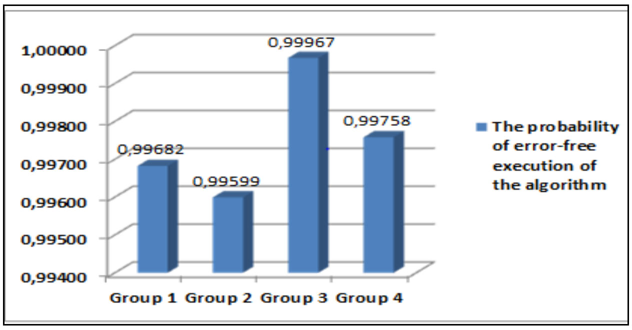

Fig. 5. Comparison of the effectiveness of alternative options

IV. Conclusion

The share of group operator activity is growing sharply in modern management systems. The reliability of control processes substantially depends on the optimality of the distribution of functions between individual operators. The proposed model of organizing group activities takes into account the reliability and time characteristics of the operators, their compatibility with each other and maximizes the probability of error-free execution of tasks, entering the system. The development was tested during the practical design and operation of control systems for various purposes and can be recommended for building decision support systems for operators of complex control systems.

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