Optimization of the Activity of Operators of Critical Systems by Methods of Regulating Operational-Tempo Tension

Evgeniy Lavrov and Nadiia Pasko

October 10, 2020

Optimization of the Activity of Operators of Critical Systems by Methods of Regulating Operational-Tempo Tension

Evgeniy Lavrov

Sumy State University,
Sumy, Ukraine
prof_lavrov@hotmail.com

Nadiia Pasko

Sumy National Agrarian University
Sumy, Ukraine
senabor64@ukr.net

Abstract. The model of the influence of the available time on the tension of operators and the infallibility of their activity is considered. The productions and methods of solving possible optimization problems are developed to search for ergonomic reserves to increase the efficiency of critical systems.

Keywords. Critical system, IT resources, ergonomics, poly-ergative system, incident management, human operator, algorithm of activity, operational-tempo tension, self-control, optimization of activities.

1 Introduction

Modern technological, transport, aerospace and energy systems are inherently critical [1,2] because even minor disruptions to their operation can lead to accidents, being catastrophic in most cases. Decision-making processes in critical infrastructures involve the need to process large amounts of information in real time [1,2]. Maintenance of IT resources of critical systems in the effective state and the ensuring their high reliability and efficiency are becoming an increasingly serious problem [1,2].

The analysis of the real operators' activity made it possible to determine the following failure conditions for most cases [3–5]:

- Operational-tempo tension of the activity is the cause of erroneous reactions;
- There are no real mechanisms in place to ensure ergonomic quality, aimed at providing the standards of operator's activity;
- Management of time constraints on the implementation of activity algorithms can be one of the main reserves of increasing ergonomics.

Scientists working within the framework of the functional structural theory of ergotechnical systems of Prof. A.I. Gubinsky, have traditionally paid much attention to the study of optimization problems for operators [6]. Characteristics of some new problems, specific for polyergatic systems, are given in the paper [7]. Unfortunately, despite the huge scientific reserve of that school, in the field of optimization of the human-machine interaction, tasks, as a rule, are solved with the assumption of invariability of the characteristics of the operator in the process of activity and without taking into account the effect of the time resource on the quality of implementation of the algorithms available.

2 Problem Statement

The task is to identify current problems and develop appropriate models that allow solving the problems of optimizing the discrete activity of operators by varying the values of parameters that characterize time resources, i.e. by means of regulation of operational-tempo intensity.

3 Approach

3.1 Models for Managing the Operational-Tempo Tensity

A Model for Assessing the Impact of the Operational-Tempo Tension on the Quality of Activities. Professor P.P. Chabanenko [8] succeeded to identify and formalize the mechanism of the operator's flexible response to the available time resource (based on the study of real engineering and psychological data).

Tension, as a psychological fee for achieving the goal of activity, includes several components, the main ones being the tempo, determined by the time deficit to solve the problem, and the operational one, determined by the nature of the operations of the activity algorithm. The joint operational-tempo tension is determined by the simultaneous influence of two noted factors: The tension H defines the probability P_0 of switching on the self-monitoring of the current operation by the operator [8]:

$$P_0 = -1.836H^2 + 0.962H + 0.874, \tag{1}$$

where H is a ratio of the time required to complete the operation at the maximum rate to the allowable time actually given to the operator to perform this operation.

Optimal tension of the operator's activity: $H_{opt} = 0.262$. The area $H < H_{opt}$ corresponds to an insufficient load on the operator, and the area $H > H_{opt}$ corresponds to an excessive load on the operator.

When $H = H_{opt}$, there is a probability to start a self-monitoring function $P_0 = 1$, which corresponds to the case of setting error-free operation.

When $H = 1$, the probability $P_0 = 0$, which corresponds to the speed setting. An illustration of settings types in the operator's activity is shown in Fig. 1.

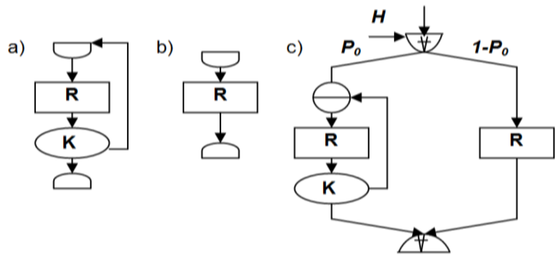

Fig. 1. An illustration of setting types in the operator's activity: a) error-free; b) speed; c) flexible response to the resource of time; R – working operation; K – control operation (notations by [6]).

Models of Activity Optimization by Means of Management of Operational-Tempo Tensity. Time limitations are determined by the characteristics of the flows of incoming signals or orders, or various organizational decisions (including the number of operators in the shift and distribution of functions among them). They may be set instructively by the managing operator or they can be established by software and technical means of activity management.

Depending on the nature of the activity and the level of optimization (function, complex of functions, etc.) we distinguish 2 classes of possible tasks.

Choosing the optimal time constraint for the implementation of activities (1st class of tasks). Task 1.1 (single criterion):

There are given: The structure of the activity algorithm; characteristics of reliability and execution time of operations, permissible time limits for the implementation of the activity algorithm in the form of the lower limit of T_{min} and the upper limit of T_{max} (may not be available); and the maximum permissible activity tensity H_0. It is necessary to choose the limit value T, imposed on the implementation time, which provides the maximum probability of the error-free execution:

$$B(T) \to \max \tag{2}$$

$$H(T) \le H_0 \tag{3}$$

$$T_{\min} \le T \le T_{\max} \tag{4}$$

where T is the allowable time for activity implementation; $B(T)$ is a probability of error-free execution; $H(T)$ is an intensity of the activity; H_0 is a maximum permissible intensity; T_{min}, T_{max} are minimum and maximum times to implement activity.

Task 1.2 (multiple criterion):

The criterion for minimizing the intensity is added to the formulation of the Task 1.1. (2) – (4) instead of, or in addition to the restriction on the intensity (3).

$$H(T) \to \min \tag{5}$$

Task 1.3 (optimization of income from activities):

The statement appears due to the need to solve the problem of the type "what is better: a greater number of implementations of activity algorithm with low infallibility or high infallibility with fewer implementations". The economic consequences of correct (incorrect) implementations of activities can be evaluated in various ways, for example, "income from correct implementation" and "damage from improper implementation".

Consider one of the possible formulations of the problem, taking into account the economic consequences of the activity. The following statements are given in addition to the initial data of tasks 1.1 and 1.2, where C_1 is an income from a single error-free implementation of the activity; C_2 is a damage from a single implementation of the algorithm with an error; $T^{'}$ is a total time during which the activity algorithm should be repeated (taking into account the deduction of time for various breaks: technological, for leisure, etc.). If we consider that the number of applications realized in time is determined by the time allocated for a single implementation $n=T^{'}/T$, the target function will have the form

$$\frac{T'}{T}(C_1 B(T) - C_2(1 - B(T))) \to \max \tag{6}$$

under the constraint (3)-(4).

Task 1.4 (multiple criterion analogue of task 1.3):

The criterion of intensity minimization (5) is added to the statement of task 1.3, instead of, or in addition to the constraint (3).

In the formulations of tasks 1.1-1.4, there is no explicit restriction on the timely implementation of the activity algorithm, since, as follows from the initial assumptions, the activity is pre-configured and the operator provides (at T_{max} not less than the minimum required time for implementation of the activities) timely execution (by enabling or disabling the self-monitoring of operations).

The way to solve the tasks of choosing the optimal time limitations for activity implementation:

Since the analytic dependence for $B(T)$ cannot be defined in principle, and the mathematical model, algorithm and program for calculation of the probability of error-free execution at a given point (for a given T) are developed (see [3–5]), we propose a numerical approach to the solution, based on determining values $T_1, T_2, \ldots, T_s \in [T_{min}, T_{max}]$, the calculation of the criterion function for these values (in case of single criterion optimization) or the "convolution" of the criteria functions (in case of multi criterion optimization) and the values of the indices to which the constraint is imposed (H), and determining the optimal value or search area narrowing (and the repetition of the procedure).

Optimization algorithms based on one-step or multi-step choice are possible. The one-step choice consists of determining the number of points N, calculating values

$$T_i = T_{i-1} + \frac{T_{\max} - T_{\min}}{N}, \tag{7}$$

where $i=1,\ldots,N$, $T_0=T_{min}$, computing $B(T_i)$, $H(T_i)$ (using algorithms and programs [3–5,9,10]) or other criteria functions (depending on the task), and determining the optimal value by a simple search. The disadvantage of the one-step choice is that a large number of points N are needed to ensure high accuracy.

A multi-step search is implemented in a coherent strategy related to the following actions:

1) The use of the selection rule for the first few points $T_1, T_2, \ldots, T_s \in [T_{min}, T_{max}]$, and localization of the minimum point on the segment $[T'_{min}, T'_{max}]$;

2) Choosing points $T_{S+1}, \ldots, T_K$ on the localized segment and determining the next segment;

3) The analysis of the solution that was obtained for an admissible approximation to the optimal one, and the optimal sequential search, carried out by one of the known methods, for example, "Fibonacci search", "Golden section" method, etc.

Distribution of the directive time for realization of activities between their fragments (2nd class of tasks):

Task 2: The statement makes sense in the case when the algorithm of the operator's actions is divided into several parts (fragments): each part is executed in the interval between two events. And the first event (signal) is synchronized with the beginning of the implementation of the algorithm corresponding to the activity fragment, and before the second event (signal) arrives, the algorithm must be completed. Such a situation usually occurs when fragments of system operation algorithms are realized in parallel by a human operator and a machine (with a starter and a functionary of type "AND"[6]).

The fact that it is not always expedient to operate the automation machine with the maximum possible speed is noted in a number of ergonomic studies: For example, in some cases it is recommended to introduce a delay in the "computer response" in order to ensure the comfort of the operator [8].

However, there is no way to determine the optimal reaction time in each particular case. We assume that for technological or economic reasons the maximum permissible time T for the implementation of the algorithm of functioning (AF) of the entire system is set. The task is to determine the directive times for the operator to perform individual fragments performed between the signals of automatic means, ensuring the maximum probability of error-free realization of the entire AF. At the same time, restrictions on the intensity of activity on each of the fragments can be introduced. Here is the definition of vector $(T_1, T_2, \ldots, T_n)$ that provides:

$$F_B(B_1(T_1), B_2(T_2), \ldots, B_n(T_n)) \to \max \tag{8}$$

$$F_T(T_1, T_2, \ldots, T_n) \le T \tag{9}$$

$$H_i(T_i) \le H_i^0, i = 1, \ldots, n \tag{10}$$

where F_B is a dependence of the probability of error-free execution of AF from $B_i(T_i)$, $i=1,\ldots,n$, determined by the structure of AF; T_i is a directive execution time of the i-th fragment of AF; $B_i(T_i)$ is a probability of error-free execution of the i-th fragment of AF; $H_i(T_i)$ is strength of the i-th fragment; H^0_i is maximum permissible tension for the i-th fragment; $F_T(T_1, T_2, \ldots, T_n)$ is a dependence of AF execution time on the execution time of its individual fragments, determined by the structure of AF; n is a number of

AF fragments. F_B and F_T are determined by the models developed for the typical operational structures [3, 10].

In the particular case, when AF fragments are sequentially performed, the statement (7)-(9) takes the form:

$$\prod_{i=1}^{n} B_i(T_i) \to \max \tag{11}$$

$$\sum_{i=1}^{n} T_i \le T \tag{12}$$

$$H_i(T_i) \le H_i^0 \tag{13}$$

The way of solving the task of directive time distribution to realize the activity between their fragments:

Step 1: Generation of a set of directive time values of the fragment implementation for each *i*-th fragment of $i=1,\dots,n$, for example, as follows:

1a. Definition of the range of research $[T^i_{min}, T^i_{max}]$,
where T^i_{min} is the time required to implement the AF fragment without performing functional control for all operations (for example, for a sequential chain of operations,

$$T^i_{\min} = \sum_{j=1}^{n_i} T_{P_{ij}} \ , \tag{14}$$

where n_i is the number of basic work operations in the *i*-th fragment, T_{Pij} is the mathematical expectation of the execution time of the *j*-th operation in the *i*-th fragment);

T^i_{max} is the maximum time value for the AF fragment implementation, provided that all operations are performed with self-monitoring and taking into account the variance of the execution time, for example, for a sequential chain of operations

$$T^i_{\max} = \sum_{j=1}^{n_i} T_{PK_{ij}} + 3\left(\sum_{j=1}^{n_i} D_{PK_{ij}}\right)^{1/2} , \tag{15}$$

where T_{PKij} and D_{PKij} are the mathematical expectation and a variance of the execution time in the *i*-th fragment of AF of the *j*-th self-monitoring operation.

1b. Definition of the number of investigated values of the directive execution time N_i for each *i*-th fragment $i=1,\dots,n$, and generation of the following values: $T_{i,1}, T_{i,2}, \dots, T_{i,Ni} \in [T^i_{min}, T^i_{max}]$, in the simplest case

$$T_{i,k} = T_{i,k-1} + \frac{T^i_{\max} - T^i_{\min}}{N_i} , \tag{16}$$

where $i=1,\dots,n$ and $T_{i,0}=T^i_{min}$.

Step 2. Evaluation of error-free and activity intensity values on each i-th fragment, $i=1,\ldots,n$, with all the generated values of the directive time: $B_i(T_{i,j})$, $H_i(T_{i,j})$, $i=1,\ldots,n$, and $j=1,\ldots,N_i$. The evaluation is carried out by using models and programs developed in [3–5, 9 and 10].

Step 3. An exception for each i-th activity fragment of $Ti,j(i=1,\ldots,n, j=1,\ldots,N_i)$ those values that do not satisfy the constraints on the activity tensity $H_i(T_{i,j})\leq H^0{}_i$.

Step 4. Choosing the best option. With the generated variants of the execution of fragments with available estimates of the quality indicators, the task is reduced to the standard problem of maximizing the probability of error-free execution of AF under the constraint on the mathematical expectation of the execution time [6,7 and 10].

Step 5. Investigation of the vector obtained as a result of the solution of the optimization problem. $(T^*{}_1,T^*{}_2,\ldots,T^*{}_n)$; generation of directive time values for each i-th fragment in the range $[T^*{}_i - \Delta_i, T^*{}_i + \Delta_i]$, ($\Delta_i$ can be determined, for example

$$\Delta_i = \frac{T^i_{\max} - T^i_{\min}}{N_i} \tag{17}$$

(see 1b)), and transition to step 2 (steps 2-5 should be repeated until the solution with required accuracy is obtained).

The convenience of the approach is that one of the steps reduces the task to the known problem of optimizing a human machine system and can be solved by any known method [6,7, 9,10] with any structure of connections between operations.

4 Applications

The models were used in the development of the following systems ensuring ergonomic quality:

- Automated processing plants for various purposes [3];
- Systems of technical support of IT resources in telecommunications [9,10];
- Distributed banking processing systems [4];
- Relevant topics of the training courses on "Ergonomics" and "Information Systems" at the Sumy State University, the Sumy National Agrarian University and the National University of Bio-Resources and Nature Management (Kyiv).

5 Conclusion

Operational-tempo tension is determined by time constraints on the activity of operators of critical systems and significantly affects the indicators of error-free functioning. It is convenient to evaluate the influence of time resources on the efficiency of ergotechnical systems by using models based on formalisms introduced by Prof. P.P. Chabanenko.

Solving the tasks of choosing temporal constraints for the implementation of activities and the distribution of directive time for the execution of work between its fragments makes it possible to ensure the fulfillment of specified requirements for the operation of critical systems while observing the normative indicators of the intensity of the operators' activities. Solving the problems of choosing a temporary restriction on the implementation of activities and the distribution of directive time for the implementation of activities between its fragments can provide specified requirements for the effectiveness of critical systems, while observing the normative values of the activity intensity of operators.

The models should be used as elements of mathematical support of DSS for operators-managers of critical systems.

References

1. Bloomfield, R., Lala, J.: Safety-Critical Systems. The Next Generation / IEEE Security & Privacy 11(4),11–13 (2013). doi: 10.1109/MSP.2013.95.
2. Skatkov, A., Anikevich, K., Shevchenko, V.: Information model of management of IT resources of critical systems. Collection of scientific works of Sevastopol National University of Nuclear Energy and Industry 1(37), 201–206 (2011). (In Russian)
3. Lavrov, E., Pasko, N., Krivodub, A., Barchenko, N., Kontsevich, V.: Ergonomics of IT outsourcing. Development of a mathematical model to distribute functions among operators. Eastern European Journal of Enterprise Technologies 4(80), 32–40 (2016). doi: 10.15587/1729-4061.2016.66021.
4. Lavrov, E., Pasko, N., Tolbatov, A., Tolbatov, V.: Ergonomic Reserves for Improving Reliability of Data Processing in Distributed Banking Systems. In: Proceedings of 2nd International Conference on Advanced Information and Communication Technologies-2017 (AICT-2017), pp. 79–82. Lviv, Ukraine, July 4–7, (2017).
5. Lavrov, E., Barchenko, N., Pasko, N., Borozenec, I.: Development of models for the formalized description of modular e-learning systems for the problems on providing ergonomic quality of human-computer interaction. Eastern-European Journal of Enterprise Technologies. Ser. "Information technology" 2(2/86), 4–13 (2017). doi: 10.15587/1729-4061.2017.97718.
6. Adamenko, A.N., Asherov, A.T., Lavrov, E.A. et al.: Information controlling human-machine systems: research, design, testing, Reference book, Gubinsky, A.I. & Evgrafov, V.G., eds. Mechanical Engineering, Moscow, (1993). (In Russian).
7. Lavrov, E., Pasko,N.: Approach to optimization models bank forming for distributing of functions between the ACS operators. Eastern-European Journal of Enterprise Technologies. Ser. "Mathematics and Cybernetics – Fundamental and Applied Aspects" 1(4/49), 46–50 (2011). (In Russian).
8. Chabanenko, P.: Investigation of the safety of the functioning of the "human-technical" systems by ergonomic nets. Publishing House of the P.S. Nahimov Academy of the Navy, Sevastopol, (2012). (In Russian).
9. Lavrov, E., Pasko, N., Krivodub, A., Tolbatov, A.: Mathematical models for the distribution of functions between the operators of the computer-integrated flexible manufacturing systems. In: Proceedings of the XIII-th international conference TCSET-2016 "Modern problems of radio engineering, telecommunications, and computer science", pp. 72–76. Lviv-Slavsko, Ukraine, february 23 – 26, (2016).
10. Lavrov, E., Pasko, N., Tolbatov, A., Tolbatov, V.: Cybersecurity of Distributed Information Systems. The Minimization of Damage Caused by Errors of Operators During Group Activity. In: Proceedings of 2nd International Conference on Advanced Information and Communication Technologies-2017 (AICT-2017), pp. 83–87. Lviv, Ukraine, July 4 – 7, (2017).