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Original article

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Methodology for Determining the Parameters of a Mathematical Model of the Dynamics of the Psychophysiological State of a Metallurgical Equipment Operator

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Abstract
Introduction. Mathematical modelling is effective in the analysis of industrial safety at metallurgical plants, in particular for tracking problems of the man — machine system. To introduce the time factor, recurrence relations (in a discrete model) and differential relations (in a continuous model) are used. However, it is also necessary to solve the problem of linking the model parameters to the real conditions of the production environment and to the human factor. The aim of this study is to create a method for determining the parameters of simulation mathematical models of the dynamics of the operator's psychophysiological indicators affecting the work.
Materials and Methods. The operator's psychophysiological state (PPS) was assessed by performance, fatigue levels, and error rate. The data were collected by the Digital Correction Task (DCT) test. Based on the obtained results, the experimental values of the operator's PPS indicators, which were reduced to the normalized scale [0, 1], were calculated. These indicators for a particular respondent, the mathematical model and the developed algorithm were used to determine the numerical values of the model parameters. In order to interpret the indicators of performance, fatigue and error rate, we introduced scales with five gradations.
Results. The use of the authors' modified version of the mathematical model showed a significant improvement in its prognostic properties. Out of 10 participants the best result was shown by respondent no. 7, the worst result was shown by respondent no. 8. During the first working hour (from 9.00 to 10.00) their performance increased almost equally, from 0.5–0.55 to almost 0.6. Then the score of respondent no. 7 increased and remained well above the "good" level until the end of the day. The score of respondent no. 8 dropped and was below average from 14.00 to 15.00. The difference was largely determined by the operators' chronotypes. Their chronophysiological characteristics also affected fatigue and error rate. The model's quality varied for different participants in the experiments. In one case it was excellent (mean relative error ≤5%), in three cases it was good (≤10%) and in four it was satisfactory (≤15%).
Discussion and Conclusion. The proposed approach allows us to obtain the dynamic profiles of psychophysiological characteristics for every individual, to assess their interrelationships and to perform a prediction on the basis of a modified mathematical model. However, in order to extend the functionality of the models to the real working conditions of the metallurgical plant operator, it is necessary to increase the sample size, reduce the discrete time step and conduct studies for different working conditions, considering technological, climatic, environmental, psychological and other factors.

Keywords: safety at metallurgical enterprises, man — machine system, psychophysiological state of the operator, operator chronotype, operator performance

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Научная статья

Методика определения параметров математической модели динамики психофизиологического состояния оператора металлургического оборудования

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Аннотация
Введение. Математическое моделирование эффективно при анализе промышленной безопасности на металлургических предприятиях, в частности для отслеживания проблем системы «человек — машина». Чтобы ввести в рассмотрение фактор времени, задействуют рекуррентные соотношения (в дискретной модели) и дифференциальные (в непрерывной). Однако необходимо также решить проблему привязки параметров модели к реальным условиям производственной среды и к человеческому фактору. Цель данного исследования — создание метода определения параметров имитационных математических моделей динамики психофизиологических показателей оператора, влияющих на его работу.
Материалы и методы. Психофизиологическое состояние (ПФС) оператора оценивали по работоспособности, утомляемости и ошибаемости. Данные собрали по тесту цифровой корректурной пробы (ЦКП). На основании полученных результатов вычислили экспериментальные значения показателей ПФС оператора, которые привели к нормированной шкале [0, 1]. Эти показатели для конкретного респондента, математическую модель и разработанный алгоритм задействовали при определении числовых значений параметров модели. Для интерпретации показателей работоспособности, утомляемости и ошибаемости ввели шкалы с пятью градациями.
Результаты исследования. Использование модифицированного авторами варианта математической модели показало значительное улучшение ее прогностических свойств. Из 10 участников наилучший результат оказался у респондента № 7, худший — у респондента № 8. В течение 1-го часа работы (с 9.00 до 10.00) их работоспособность выросла примерно одинаково, с 0,5–0,55 почти до 0,6. Затем показатель респондента № 7 активно увеличивался и до конца рабочего дня оставался существенно выше уровня «хороший». Показатель респондента № 8 падал и с 14.00 до 15.00 оказался ниже среднего. Разницу во многом определили хронотипы операторов. Их хронофизиологические особенности сказались также на утомляемости и ошибаемости. Для разных участников экспериментов варьировалось качество модели. В одном случае оно оказалось отличным (средняя относительная ошибка ≤5 %), в трех случаях — хорошим (≤10 %), в четырех — удовлетворительным (≤15 %).
Обсуждение и заключение. Предлагаемый подход дает возможность получить для каждого индивидуума динамические профили его психофизиологических характеристик, оценить их взаимосвязи и выполнить прогноз на основе модифицированной математической модели. Однако для расширения функциональных возможностей моделей в реальных условиях работы оператора металлургического оборудования требуется увеличить объем выборки, уменьшить шаг дискретного времени и выполнить исследования для различных условий работы с учетом технологических, климатических, экологических, психологических и прочих факторов.

Ключевые слова: безопасность на металлургических предприятиях, система «человек — машина», психофизиологическое состояние оператора, хронотип оператора, работоспособность оператора

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Introduction. According to the Federal Service for Environmental, Technological and Nuclear Supervision of the Russian Federation, by the beginning of 2022, 1,280 hazardous production facilities were registered at metallurgical and coke-chemical plants, 19 of which belonged to the first hazard class, 325 belonged to the second class, and 922 belonged to the third class[1]. According to the "Industrial Pages" journal[2], in 2022, fires and explosions were the most frequent incidents at Russian metallurgical enterprises. These incidents were caused by technical reasons and by violations of industrial safety rules. For example, in January 2022, three employees of the Novolipetsk Metallurgical Plant conducted a routine check of the interdepartment gas main without mandatory gas protection equipment. The workers died as a result of poisoning by toxic fumes and gas.

In [1], technical, sanitary-hygienic, organizational and psychophysiological groups of accident and injury factors at metallurgical and coke-chemical plants are identified. The latter two groups are closely related to the person involved in the production process. From an industrial safety perspective, operators of high-technology units at metallurgical plants are assigned special responsibility. In engineering psychology, they are commonly referred to as "human operators". In the context of this work, the term "operator" will be used to refer to these individuals. On occasion, they prevent the potential for a danger turning into an incident or accident at work.

GOST 12.0.003–2015[3] identifies dangerous and hazardous production factors of psychophysiological effects on humans in an independent block. The operator experiences neuropsychiatric overloads associated with the intensity of the work process[3]. These include:

– mental overstrain;

– overstrain of analyzers;

– monotony of work;

– lack of confidence in actions due to the lack of education and experience.

Emotional overloads lead to overwork, poor health, stress, etc. [1].

The reliability of a person as an element of a complex technical system depends on internal and external conditions that change over time. Another variable is the person themselves. Work is performed by people with different personal qualities, health, experience, etc.

In [2], data on accidents (AC) in the forging and pressing production (FPP) for 1985, 1987 and 1989 were analyzed. Some patterns in the distribution of hours from start of work to incident were noted. These trends can be attributed to the human element, more specifically, the daily work schedule (Fig. 1).

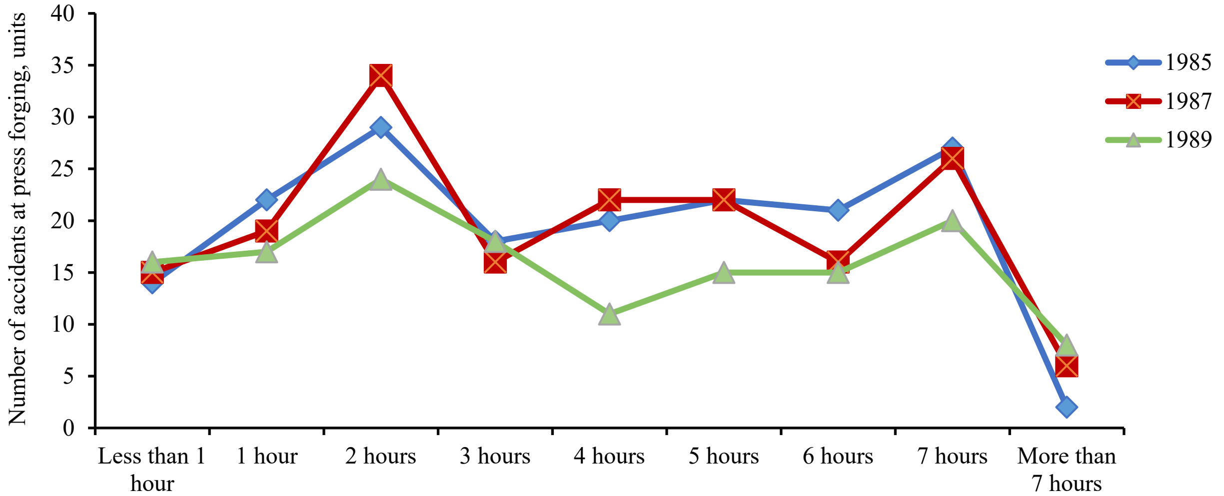

Fig. 1. Distribution of AC in forging and pressing production according to the number of hours since start of work to AC [2]

[1] Annual report on the activities of the Federal Service for Environmental, Technological and Nuclear Supervision in 2021. Moscow: 2022. P. 407. URL:https://www.gosnadzor.ru/public/annual_reports/Годовой%20отчет%20за%202021%20г.pdf (accessed: 22.11.2023). (In Russ.).

[2] Opasnaya tendentsiya: avarii i ChS na metallurgicheskikh proizvodstvakh v 2022–2023 godakh. *Promyshlennye stranitsy.* URL: https://indpages.ru/safe/avareeee-na-myetallurgeechyeskeeh-proeezvodstvah/?ysclid=lnshtjh0z2208396380 (accessed: 22.11.2023). (In Russ.).

[3] GOST 12.0.03–2015. Occupational safety standards system. Dangerous and harmful working factors. Classification. *Elektronnyi fond pravovykh i normativno-tekhnicheskikh dokumentov.* URL: https://docs.cntd.ru/document/1200136071 (accessed: 21.11.2023). (In Russ.).

The graphs in Figure 1 show a fairly pronounced synchronicity of peaks, as well a minimal number of accidents during the last hours of operation. This suggests that the operator's working time is a significant factor in the occurrence of industrial accidents.

In [3], the need to take into account the operator's chronotype when determining professionally important qualities was established experimentally.

For metallurgical industry enterprises, mathematical modeling methods are effective in analyzing situations that:

– are related to industrial safety;

– may occur in a complex technical man — machine system;

– are formed and develop in various conditions of the internal and external environment.

Mathematical models describing the operator's psychophysiological state have been developed in various mathematical formulations. Tools for measuring primary indicators have also been used. V.G. Abashin has found out how the use of biometric technologies is associated with the psychophysiological state of the operator of automatic workplaces, its efficiency, a decrease in the number of defects and accidents of the technological process caused by human error [4]. The operator's performance is modeled by keyboard handwriting. For this purpose, fuzzy sets are used as the basis of adaptive models, both biometric and multibiometric [5].

The authors [6] use biometric features in a mathematical model (voice, keyboard handwriting and the manner in which they work with a computer mouse). This allows them to judge the operator's psychophysiological state: norm, fatigue, intoxication, excitement, relaxation (falling asleep). The models are based on the Bayes strategy, as well as the neural network approach, and allow you to assess the level of the operator's psychophysiological state and predict their ability to perform their current tasks.

In [7], simulation mathematical models of the interrelation of factors of the operator's psychophysiological state were developed. The authors used recurrent relations in a discrete model and systems of differential equations in a continuous model, which allowed them to introduce the time factor into consideration. In this case, the parameters of the model were determined by:

– the results of testing a particular employee;

– their ability to a certain type of activity;

– the results of experimental studies on the workplace and the operator's functional actions.

This part of the simulation is less formalized than others and has the greatest impact on the possibility of using the model to correct the real actions of the operator. The problem has not been solved at the moment. Thus, the issues of determining the parameters of mathematical models that can correctly describe the interrelationships of various factors of the operator's psychophysiological state remain relevant. The aim of this article is to develop a methodology for determining the parameters of such models. Scientific research in this area will help to determine indicators of the condition of the metallurgical equipment operator, which affect their functional performance and can cause serious errors with negative consequences.

Materials and Methods. To assess the operator's psychophysiological state, the following indicators were selected:

– efficiency (the ability to purposefully perform work of a specific quantity and quality for a specified time);

– fatigue (decreased performance with impaired coordination of movements, decreased concentration and accuracy of decisions [8]);

– error rate (estimated by the number of erroneous actions).

Fatigue can be determined by subjective and objective measures [9]. Subjective levels of fatigue were determined using the fatigue assessment scale[4] (FAS) [10]. It was developed by a group of Dutch scientists led by H.J. Michielsen. This scale consists of 10 questions related to the respondent's overall well-being on a daily basis.

Digital correction test (DCT)[5] was used as a source of objective parameters in this work. According to its results, the experimental values of the indicators of the operator's psychophysiological state were calculated. Numerical values for model parameters were determined for a specific respondent by a combination of the named indicators and the model used.

The task of determining the parameters of a mathematical model that described the interrelationship between various psychophysiological factors of an operator was divided into two stages.

The first stage was the experiment. Participants were tested and data was collected on the working conditions of the operator and their personal qualities, which may affect the studied parameters of work activity.

The second stage was calculation. The database collected at the first stage was used. Taking into account the chosen mathematical model, its parameters were estimated for each individual employee. With a sufficient amount of statistical

[4] Fatigue Assessment Scale (FAS). URL: https://wasog.org/dynamic/media/78/documents/Questionairres/fas_rus_anon.html (accessed: 21.11.2023). (In Russ.).

[5] Tsifrovaya korrekturnaya proba.URL: https://metodorf.ru/tests/korrekt/korrektchis.php (accessed: 18.08.2023). (In Russ.).

data in a wide range of variable parameters, averaged models were built that could be used to predict changes in the operator's psychophysiological performance in various conditions and taking into account the time factor.

In this study, a program presented by the online resource "Interactive Portal — book of self-development and success techniques"[6] was used for electronic testing.

When performing the DCT, the participant looked through the numerical array generated by the program line by line and then crossed out the numbers specified in the task. They were given three minutes to complete the test. The program then generated the results described below.

1. The main primary indicators:
– test execution time t;
– total number of digits viewed up to the last selected digit N;
– total number of viewed up lines C;
– total number of digits to be crossed out n;
– total number of crossed-out digits M;
– number of correct answers S;
– number of missed digits P;
– number of wrongly selected digits O.
2. Calculated indicators that characterize:
– speed (productivity) of attention A;
– accuracy of work T (in three variants);
– mental productivity E;
– mental performance A_u;
– concentration of attention K;
– stability of concentration of attention K_u;
– volume of visual information V;
– speed of information processing Q.

To solve this problem, the indicators were selected, on the basis of which efficiency X, fatigue Y and error rate Z of the operator were evaluated according to formulas (1–4).

1. Mental efficiency A_u (according to the digital correction test[7], the unit of measurement is signs per second):

$$A_u = (N/t) \times ((M - (O + P))/n). \quad (1)$$

To bring the indicator to a normalized scale [0, 1] in dimensionless units, the authors proposed formula (2). The result will be the *i-th* value of the efficiency indicator X (corresponds to discrete conditional time i):

$$x_i = A_{ui} / \max\{A_u\}, \quad (2)$$

where $max\{A_u\}$ — maximum possible value of mental efficiency for this type of test, regardless of the employee being tested.

Let us consider a standard DCT test with 1600 digits. We suppose the respondent completed the test correctly in 180 seconds. In this case, value $max\{A_u\}$ would be 8.889 characters per second. If the respondent completed the test in less than 180 seconds, value X in the calculation using formula (2) would be greater than 1. Then value 1 was taken for X.

2. Fatigue Y was estimated by indicator K (concentration of attention):

$$Y = (1 - K/100), \quad (3)$$

where $K = (M–0)\ n\ 100$ — coefficient characterizing concentration of attention, %.

This indicator Y took dimensionless values in the range [0, 1].

3. Error rate Z was proposed to be estimated by the formula:

$$Z = (O + P)/(M + P). \quad (4)$$

This indicator also took values in the range [0, 1].

In the future, we will characterize X, Y and Z as unified quantitative indicators of the operator's psychophysiological state associated with their main production activity. To interpret indicators X, Y and Z, a scale has been developed, presented in Table 1.

[6] Interaktivnyi portal — kniga metodik samorazvitiya i dostizheniya uspekha. URL: https://metodorf.ru/ (accessed: 18.10.2023). (In Russ.).
[7] Tsifrovaya korrekturnaya proba. URL: https://metodorf.ru/tests/korrekt/korrektchis.php (accessed: 18.10.2023). (In Russ.).

Table 1

Interpretation of the values of indicators in a qualitative form

Indicator	Ranges of indicator values / qualitative characteristics				
Efficiency X	[0–0.20] low	[0.20–0.40] below average	[0.40–0.60] average	[0.60–0.80] good	[0.80–1.00] high
Fatigue Y	[0–0.20] low	[0.20–0.40] below average	[0.40–0.60] average	[0.60–0.80] above average	[0.80–1.00] high
Error rate Z	[0–0.01] insignificant	[0.01–0.05] noticeable	[0.05–0.10] significant	[0.10–0.20] significant	[0.20–1.00] high

Indicators X, Y and Z are dimensionless, unified with values in the range [0, 1].

At the second stage, there were two ways to select the parameters of a mathematical model.

1. Using the Excel Solution Search module, a system solution scenario was created for some initial parameters. It was based on a system of recurrent equations of a mathematical model in a discrete form. Then, the Solution Search output the optimal values of model parameters for the objective function, equal to the sum of the squares of the deviations of the calculated values of indicators X, Y and Z from the experimental ones.

2. In the Anylogic program[8], that allows you to automatically select the parameters of the considered mathematical models in the discrete form of recurrent relations and in the form of a system of differential equations. It is advisable to use Anylogic after analyzing the results of a preliminary assessment of the model parameters using the Excel Solution Search module.

To test the proposed methodology, ten people were selected — students and employees of the Donbass State Technical University. They worked as operators on training simulators with automatic and semi-automatic control. At the beginning and at the end of the working day, the subjective level of fatigue was assessed on the FAS scale. At the beginning of each hour, from 9.00 to 16.00, DCT tests were performed. The data were processed according to formulas (1–4) for each respondent. The test results and their unification (X, Y and Z) were used at the second stage to determine the parameters of the mathematical model.

In this paper, we applied a model in recurrent form [7], which was described by a system of equations:

$$\begin{cases} x_{i+1} = x_i + a_1 \dfrac{x_i}{d_1 x_i + c_1} \cdot (1 - \dfrac{x_i}{k_1}) - b_1 x_i y_i - h x_i z_i, \\ y_{i+1} = y_i + a_2 \dfrac{y_i}{d_2 y_i + c_2} \cdot (1 - \dfrac{y_i}{k_2}) + b_2 x_i y_i, \\ z_{i+1} = z_i + a_3 \dfrac{z_i}{d_3 z_i + c_3} \cdot (1 - \dfrac{z_i}{k_3}) + b_3 y_i z_i. \end{cases} \quad (5)$$

The solution of system (5) is three conjugate time series of length m indicators $X = \{x_i, i=0, 1, 2, ..., m\}$, $Y = \{y_i, i=0, 1, 2, ..., m\}$, $Z = \{z_i, i=0, 1, 2, ..., m\}$. Index i — variable that characterizes the discrete time in the system. Parameters a_j, b_j, k_j, h, d_j, c_j (j = 1, 2, 3) are determined as a result of solving the optimization problem based on the initial test data.

The mathematical model of the optimization problem is described by system of constraints (6) and objective function (7).

$$\begin{cases} \delta_{xi}(a_j, b_j, k_j, h, d_j, c_j) = (x_i^{\phi} - x_i^{p})^2 \le \Delta, \\ \delta_{yi}(a_j, b_j, k_j, h, d_j, c_j) = (y_i^{\phi} - y_i^{p})^2 \le \Delta, \\ \delta_{zi}(a_j, b_j, k_j, h, d_j, c_j) = (z_i^{\phi} - z_i^{p})^2 \le \Delta, \\ a_j, b_j, k_j, h, d_j, c_j \ge 0, \\ x_i^p \ge 0, y_i^p \ge 0, z_i^p \ge 0, \\ x_i^p \le 1, y_i^p \le 1, z_i^p \le 1, \\ i = 1, ..., m, \\ j = 1, 2, 3. \end{cases} \quad (6)$$

[8] AnyLogic: imitatsionnoe modelirovanie dlya biznesa. URL: https://www.anylogic.ru/ (accessed: 12.11.2023). (In Russ.).

$$\Psi(a_j, b_j, k_j, h, d_j, c_j) = \sum_{i=1}^{m} \delta_{xi} + \sum_{i=1}^{m} \delta_{yi} + \sum_{i=1}^{m} \delta_{zi} \rightarrow min\,. \tag{7}$$

Here, index *ф* marks the actual values of indicators *X, Y* and *Z* found as a result of processing operator testing data, *p* — calculated values of *X, Y* and *Z* determined from the solution of system (5) and depending on variables a_j, b_j, k_j, h, d_j, c_j (j = 1, 2, 3) sought in this optimization problem. For variable variables a_j, b_j, k_j, h, d_j, c_j restrictions are set by the maximum allowable value of Δ squared deviations (δ_{xi}, δ_{yi}, δ_{zi}) calculated values of *X, Y* and *Z* from the actual values for all m values of the considered time series. Objective function $\Psi(a_j, b_j, k_j, h, d_j, c_j)$ is equal to the sum of the squared deviations (δ_{xi}, δ_{yi}, δ_{zi}).

The generalized reduced gradient (GRG) method was used to solve the optimization problem.

Results. The first stage was experimental. Test results of the participants in the experiment (respondents no. 1–no. 10), converted to unified indicators *X, Y* and *Z*, are shown in box plots (Fig. 2–4). The center of the distribution (median) is a dot, a rectangle indicates the boundaries of variation (quartiles 25%–75%), "whiskers" — the lower and upper limits of the indicator values (min — max). The diagrams were made using the "Statistica" software package.

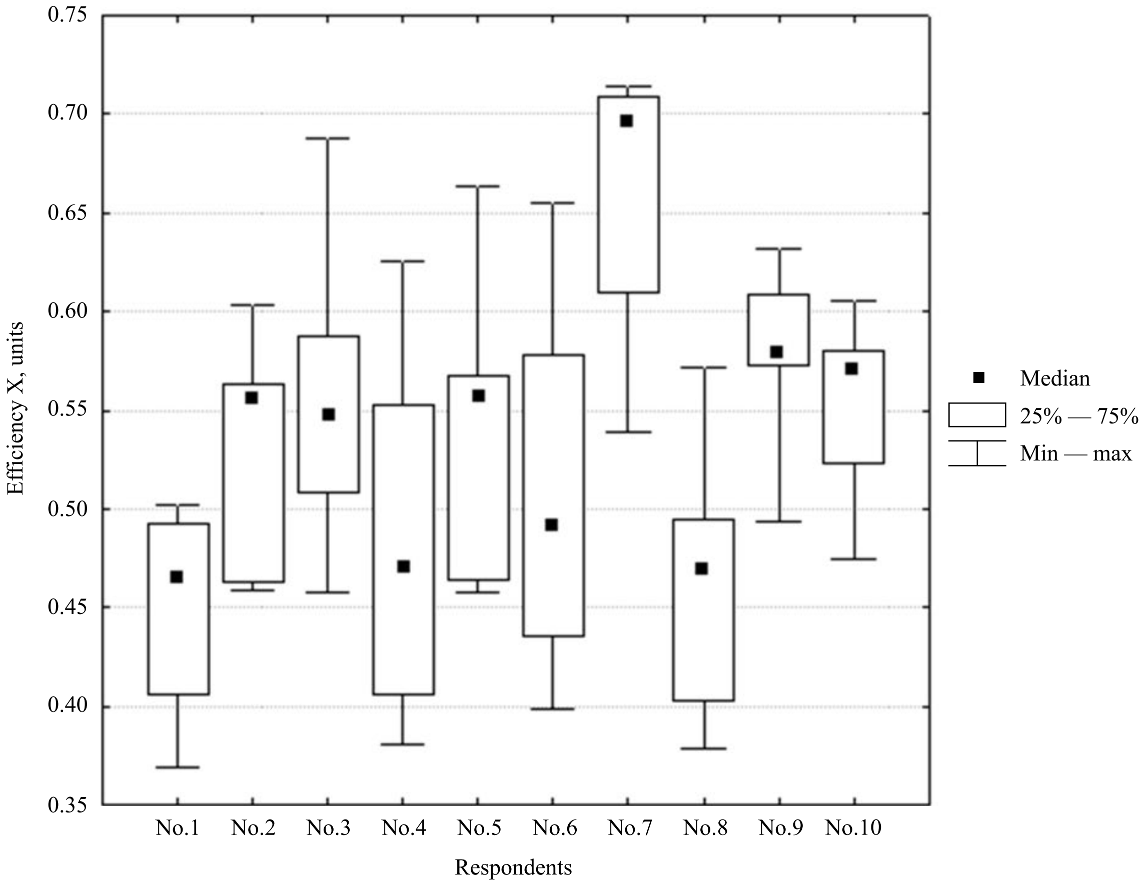

Fig. 2. Indicators of an operator's efficiency

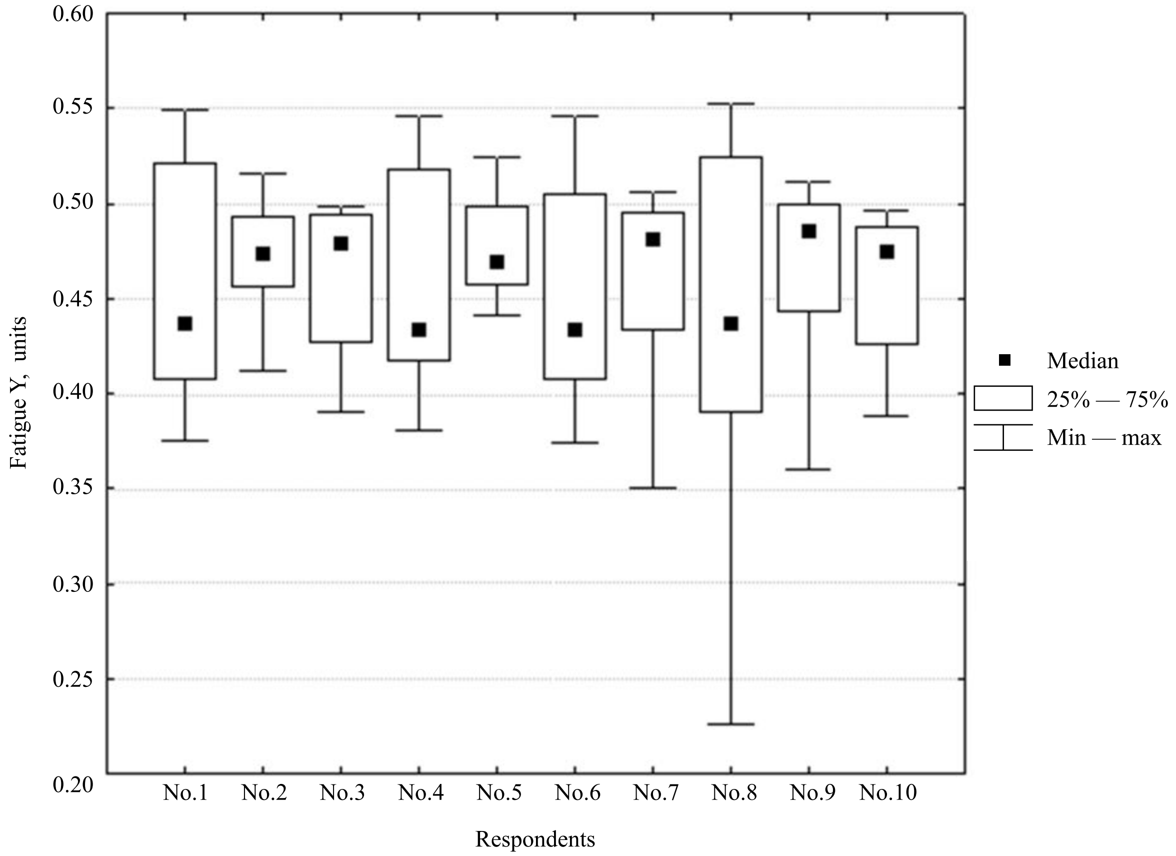

Fig. 3. Indicators of an operator's fatigue

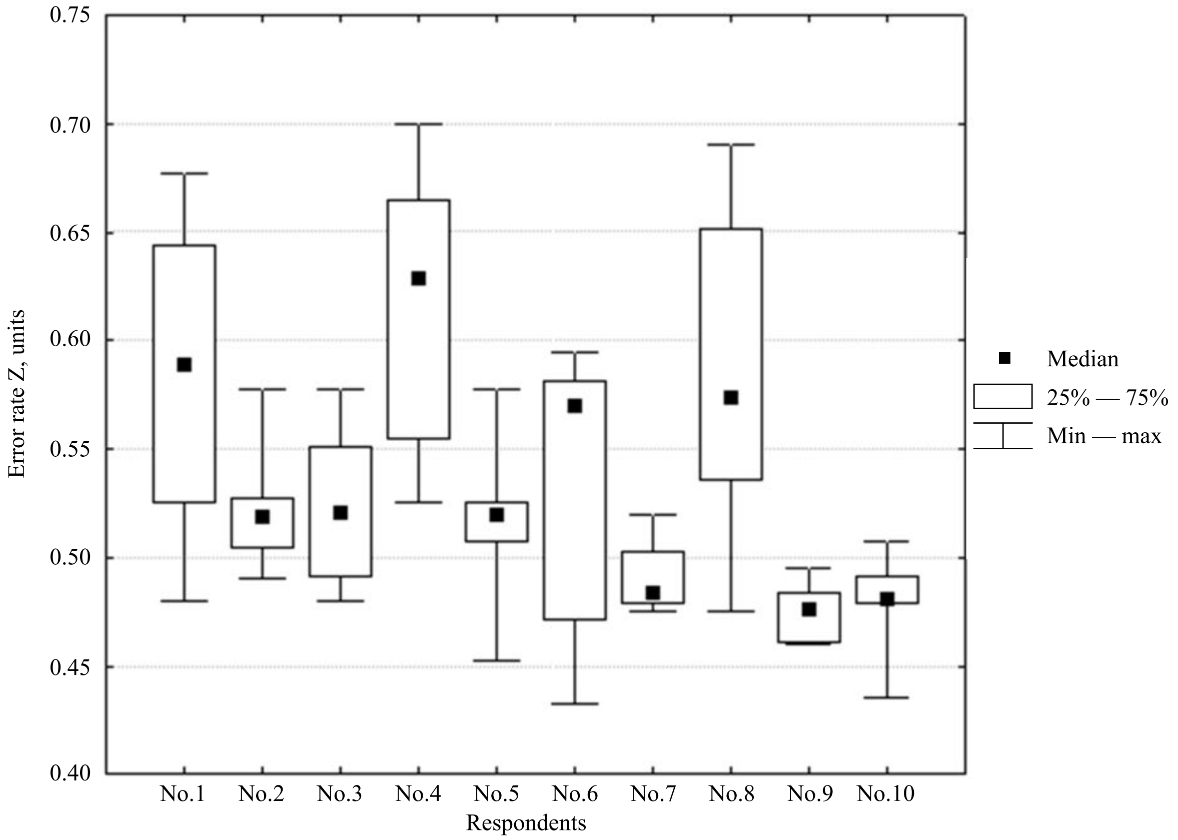

Fig. 4. Indicators of an operator's error rate

The analysis of Figures 2–4 allowed us to identify respondents with the best and the worst estimates of their performance (Table 2). The levels of indicators *X, Y* and *Z*, correlated with the gradations of Table 1, as well as quartiles and intervals of variation of indicators, were taken into account.

Table 2

Ranking of respondents based on test results

Evaluation criteria	Options (respondent's number)	
	the worst	the best
Efficiency *X* (the more, the better)	8, 1, 4, 6	7, 9, 3
Fatigue *Y* (the more, the worse)	8, 1, 4, 6	7, 10
Error rate *Z* (the more, the worse)	4, 8, 1	9, 10, 7
Integrally (taking into account *X*, *Y*, *Z*)	8, 4, 1	7, 10, 9

The graphs in Figure 5 reflect the performance dynamics for respondents no. 7 (dotted line, best result) and no. 8 (solid line, worst result).

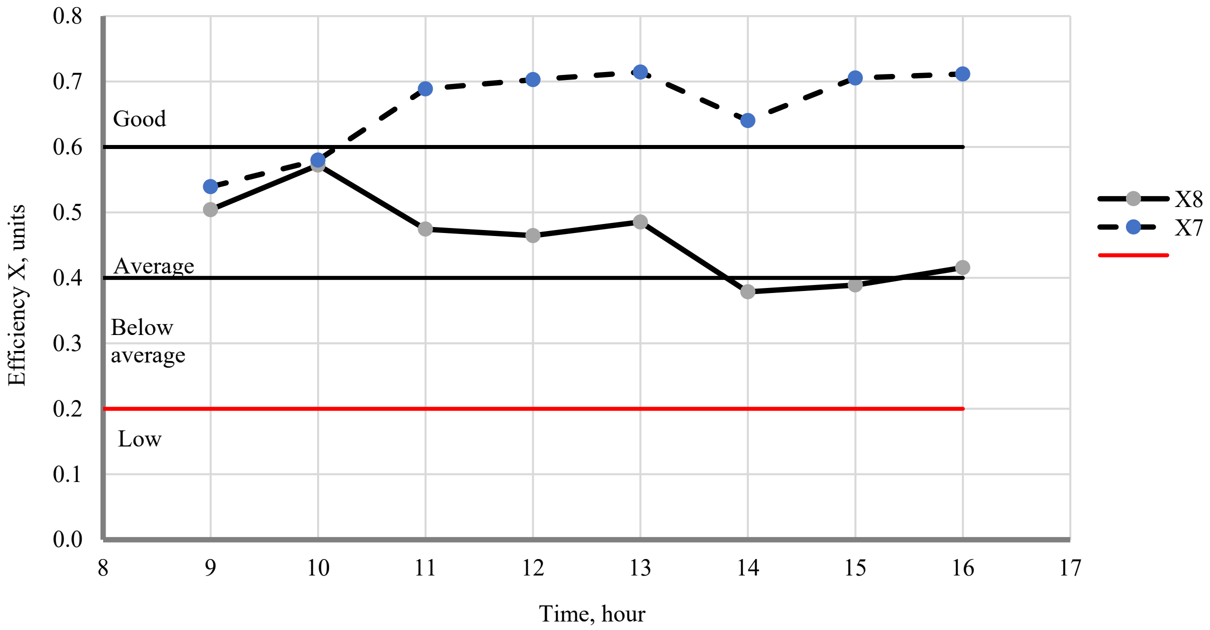

Fig. 5. Dynamics of an operator’s efficiency

To explain a rather large difference in the data of respondents no. 7 and 8, we took into account their age, gender, occupation, well-being, etc. The chronotype factor turned out to be the most significant. The classification, adopted in 1970, implies three categories of people with distinctive behavioral characteristics and a genetic difference in biorhythms. These are the so-called "larks", "owls" and "pigeons" [11]. Respondent no. 8 according to the chronotype was "lark", no. 7 was "owl". As a result, the efficiency of no. 8 decreased by the day’s end, and for no. 7 it increased (Fig. 5). The chronophysiological features of operators were also manifested in the dynamics of their fatigue and error rates.

The second stage was calculation. The parameters of model (5) calculated for each participant of the experiment were obtained. To this end, we solved the optimization problem (6)–(7). Table 3 provides the ranges of parameter changes.

Table 3

Ranges of parameters of mathematical model (5) for a group of experiment participants

Indicator	Parameter ranges	Indicator	Parameter ranges
a_1	0.0004–0.0300	b_3	0.0001–10.1400
b_1	0–0.9700	k_3	0.0020–0.0700
k_1	0.5900–1.0000	c_1	0.0010–0.2000
h	0–1.8100	c_2	0.0001–0.0010
a_2	0–0.0010	c_3	0.0100–0.3300
b_2	0.0070–0.2600	d_1	≈ 0
k_2	0,4200–1.0000	d_2	≈ 0
a_3	0.0005–0.0600	d_3	0.0400–0.9800

Table 4 presents the results of evaluating the quality of mathematical models of the dynamics of changes in indicators *X, Y* and *Z*, estimated by the standard error of the model and the average relative error for all respondents.

Table 4

Evaluation of the quality of mathematical models

Respondent's no.	1	2	3	4	5	6	7	8	9	10
Average relative error ε, %	14.27	4.54	20.93	12.80	7.28	12.00	9.66	15.03	12.23	9.70
Standard error, units	0.182	0.107	0.253	0.267	0.158	0.247	0.271	0.256	0.192	0.166

For different respondents, the quality indicators of the model varied in a wide range. Excellent quality ($\varepsilon \leq 5\%$) was obtained in one case, good ($\varepsilon \leq 10\%$) — in three cases, satisfactory ($\varepsilon \leq 15\%$) — in four cases. For two cases (no. 3 and no. 8), it was not possible to satisfactorily solve the problem of optimal selection of parameters of the mathematical model. This suggests that not all influencing factors were taken into account, or model (5) did not work in some cases.

According to the results of the analysis of the algorithm for solving the problem, a number of simplifications will improve the convergence of the results. For example, you can:

– reduce the number of system parameters (5) by three units, reducing the numerators and denominators of the second terms of the right parts of the system by c_1, c_2, c_3 respectively;

– remove the first, second and third restrictions from system (6), transferring them to the status of observed restrictions.

As a result, the algorithm of the GRG method will work better.

Figures 6 and 7 show comparative diagrams for evaluating the quality of the constructed mathematical models in two versions:

– 1 — the original model (5);

– 2 — modified model.

As it can be seen from the diagrams, the solution to the problem of selecting the parameters of the mathematical model of the dynamics of the operator's PPS indicators was significantly improved when using model 2 for all cases except no. 8.

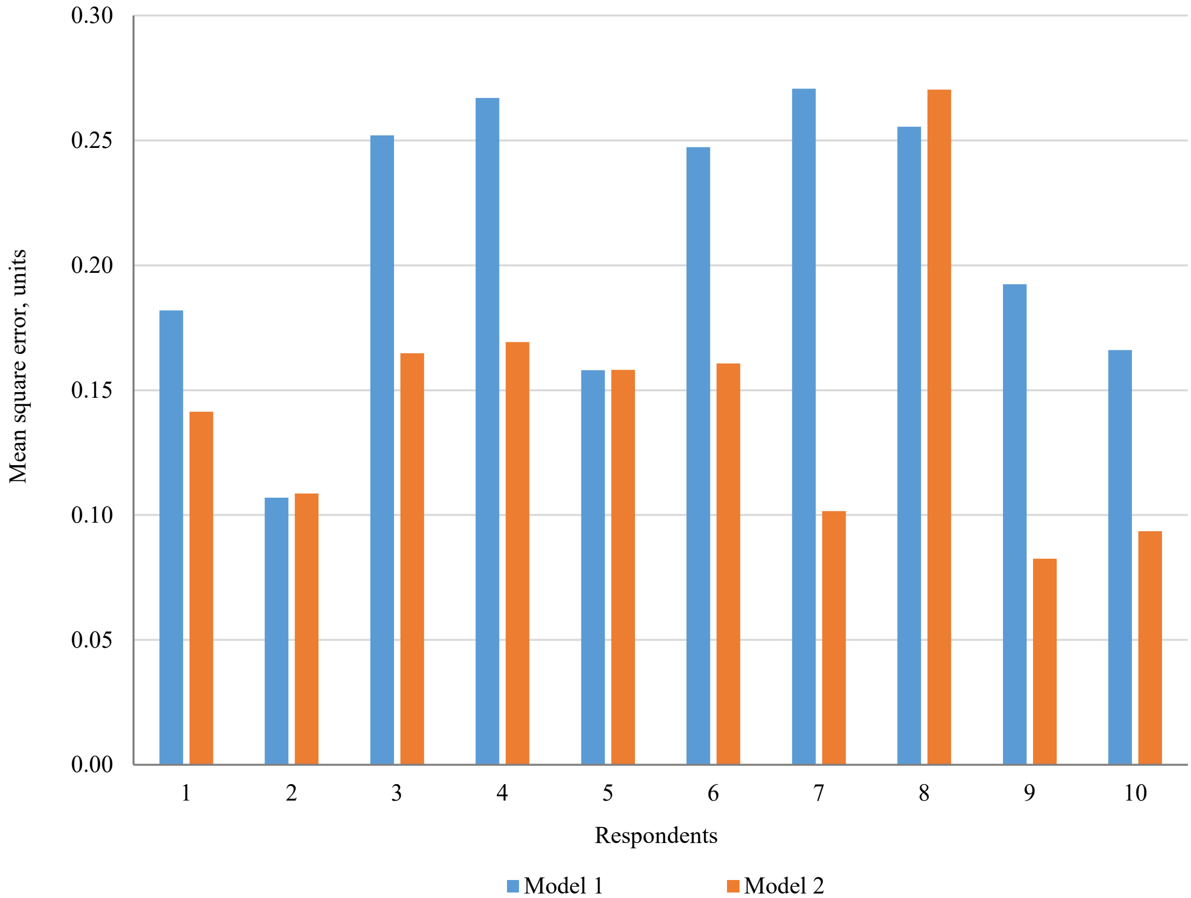

Fig. 6. Comparison of mathematical models based on the mean square error

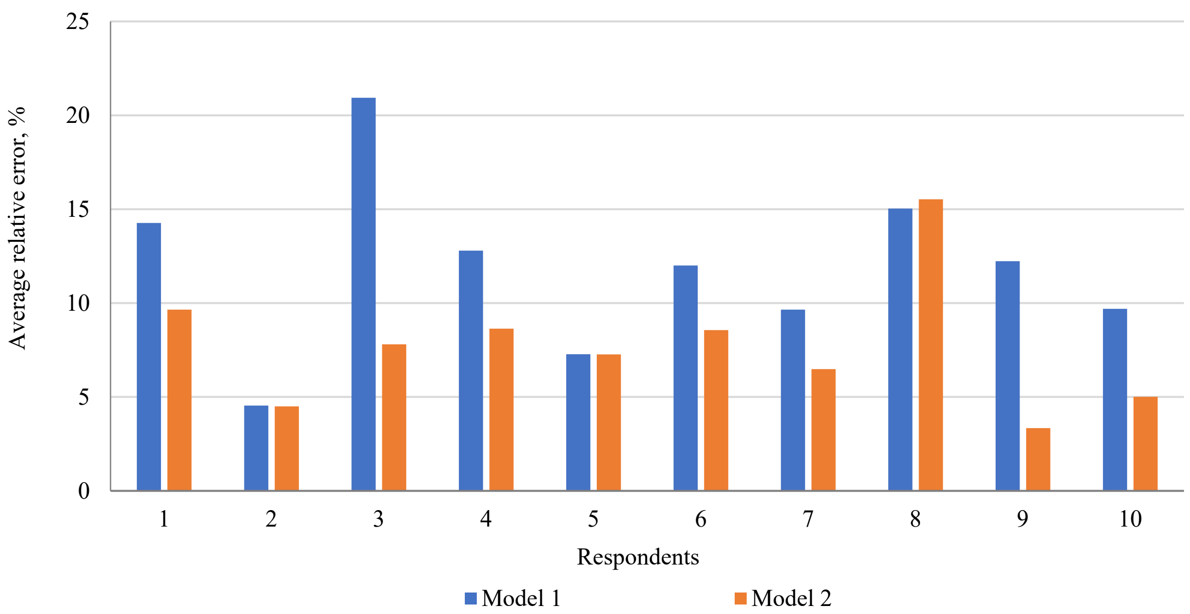

Fig. 7. Comparison of mathematical models by average relative error

Discussion and Conclusion. The proposed approach makes it possible to obtain and predict dynamic profiles of psychophysiological characteristics for each individual, and to create mathematical models of relationships. It is advisable to increase the sample size, reduce the step of discrete time and perform research for various working conditions, including technological, climatic, environmental, psychological and other factors that may affect an employee's efficiency. This should be done to expand the functionality of the models and their application in real-world conditions of operation of the operator of metallurgical equipment.

The discovered effect of the human chronotype on the PPS requires more thorough research. In article [12] devoted to the search for components of the circadian clock in humans, it was shown on large statistical samples that the chronotype depended on many factors (gender, age, work schedule, etc.). All this must be diagnosed and taken into account in mathematical models for evaluating the operators' PPS.

It is also interesting to supplement the model with components of industrial safety culture [13], which can be reduced to a quantitative form and used as correction factors.

In the future, it is planned to improve the model with additional variables. To do this, we will need to record psychophysiological indicators and determine the operator's location in real time.

The methodology presented in this paper can be used as a basis for solving the tasks described below.

– Compilation and analysis of the dynamic profile of an employee when applying for a job as an operator of a machine, unit or device, where such PPS characteristics as efficiency, fatigue and error rate are important. This task is solved for a specific person in certain production conditions, which allows you to choose the operator's optimal mode of work and rest, helps to preserve the health of a specialist and increase the level of industrial safety of the enterprise.

– Formation and maintenance of specialized databases of statistical data, including characteristics of workplaces and employees, and their psychophysiological state. Based on the collected statistical material and real-time monitoring systems of the operator's PPS, predictive models can be built to prevent abnormal and emergency situations at metallurgical enterprises.

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