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MATHEMATICAL CORRELATION MODELING FOR THE OPERATOR'S OPERABILITY, FATIGUE AND ERROR-MAKING IN METALLURGICAL INDUSTRY USING ANYLOGIC SYSTEM DYNAMICS TOOLS

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Keywords: prediction of operator's errors, operability, fatigue, error-making, human factor, metallurgical equipment, complex technical system.
Abstract. A mathematical model is presented for predicting the change dynamics in factors affecting the functional characteristics of the operator in metallurgical industry (MI), when operator can make an error causing a failure of the whole system. The factors as operability (*X*), fatigue (*Y*) and operator's error-making (*Z*) during the working day have been chosen as such functional characteristics.

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ВЗАИМОСВЯЗИ РАБОТОСПОСОБНОСТИ, УТОМЛЯЕМОСТИ И ОШИБАЕМОСТИ ОПЕРАТОРА МЕТАЛЛУРГИЧЕСКОЙ ОТРАСЛИ ИНСТРУМЕНТАМИ СИСТЕМНОЙ ДИНАМИКИ ANYLOGIC

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Ключевые слова: прогнозирование ошибок оператора, работоспособность, утомляемость, ошибаемость, человеческий фактор, металлургическое оборудование, сложная техническая система.
Аннотация: Представлена математическая модель прогноза динамики изменения факторов, влияющих на функциональные характеристики оператора металлургической отрасли (МО), в результате чего оператором может быть совершена ошибка, приводящая к выходу из строя всей системы. В качестве таких функциональных характеристик выбраны факторы: работоспособность (*X*), утомляемость (*Y*) и ошибаемость (*Z*) оператора в течение рабочего дня.

This paper presents numerical modeling based on mathematical models of the correlation between operability, fatigue and operator's error. Calculations are performed in two stages: first, a preliminary assessment of the parameters of the model described by the system of recurrent equations (1) is carried out in the Excel spreadsheet processor, and then in the AnyLogic environment according to experimental data for the system of differential equations (2) the model parameters are calibrated and its adequacy is checked [1-3].

Figure 1 shows the interference of indicators-variables X, Y, Z. The scheme is organized in the form of an oriented graph, where the vertices are the indicators X, Y, Z, the direction of the arcs points towards the indicator that is being influenced, and the arc sign shows a direct (+) or inverse (–) relationship.

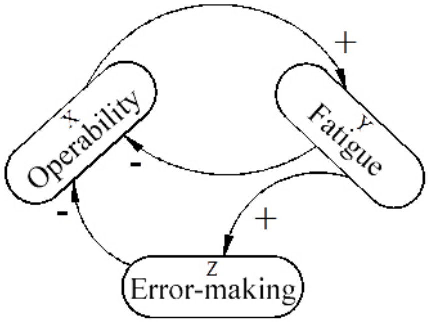

Fig. 1. Graph of connections for functional characteristics of a human operator

$$\begin{cases} \dfrac{dx}{dt} = a_1 \dfrac{x}{d_1 x + c_1}\left(1 - \dfrac{x}{k_1}\right) - b_1 xy - h_1 xz; \\ \dfrac{dy}{dt} = a_2 \dfrac{y}{d_2 y + c_2}\left(1 - \dfrac{y}{k_2}\right) + b_2 xy; \\ \dfrac{dz}{dt} = a_3 \dfrac{z}{d_3 z + c_3}\left(1 - \dfrac{z}{k_3}\right) + b_3 yz. \end{cases} \quad (1)$$

$$\begin{cases} x_{i+1} = x_i + a_1 \dfrac{x_i}{d_1 x_i + c_1}\left(1 - \dfrac{x_i}{k_1}\right) - b_1 x_i y_i - h_1 x_i z_i; \\ y_{i+1} = y_i + a_2 \dfrac{y_i}{d_2 y_i + c_2}\left(1 - \dfrac{y_i}{k_2}\right) + b_2 x_i y_i; \\ z_{i+1} = z_i + a_3 \dfrac{z_i}{d_3 z_i + c_3}\left(1 - \dfrac{z_i}{k_3}\right) + b_3 y_i z_i. \end{cases} \quad (2)$$

A model satisfying the assumptions described above can be presented in continuous form as systems of differential equations (1) or in discrete form of recurrent relations (2). The initial conditions of the system (1) are

$$x_0 = x(0),\ y_0 = y(0),\ z_0 = z(0) \quad (3)$$

To implement the developed model presented by a system (1) (a detailed description of the mathematical model [4]), it is necessary to determine the following operator's parameters: a_1, b_1, k_1, h_1, a_2, b_2, k_2, a_3, b_3, k_3 and the initial conditions of the x_0, y_0, z_0 system. Let's use the following interpretation of the parameters: a_i is the growth rate of the $i^{\text{-th}}$ indicator determined by the logic of the internal process; b_i and h_1 – influence coefficients of the combined action of indicators; k_i – the parameter to regulate the limit value of the $i^{\text{–th}}$ indicator; the parameters c_i and d_i are the parameters of the nonlinearity form of the right part of the system.

At this stage, the parameters are determined based on preliminary tests of the operator according to his reactions to intensity work changes, work duration, fatigue characteristics, etc., and after the Excel implementation of the system (2), they are refined by trial and error method and considering the analysis of the qualitative behavior of studying processes on the examples of real operators. For the first tests, people were selected with high physical, psychophysical, educational and other abilities, characterizing the maximum operators' suitability for the work performed in most comfortable conditions for work and recreation at the enterprise. So, a system with the best characteristics (baseline) is set, which in further models are adapted to real conditions using coefficients as estimations of factors according to Table 1.

Figure 2 shows the behavior of the system solution within a 240-minute period. The maximum working capacity value $x = 0{,}882$ for the studied case is obtained at $t = 82$ min. Then the operator's operability decreases smoothly enough and by the end of the interval reaches a value of 0,795. This behavior corresponds to the observed initial growth of the indicator *x*, according to its final characteristics.

The Y and Z indicators characterize another dynamic: with work time increase, the operator fatigue and error rate increase to 0,295 and 0,075, which is also consistent with experimental observations.

Tab. 1. Value of system (2) parameters

№	Parameter	Value	№	Parameter	Value
1	a_1	0,02	11	x_0	0,3
2	a_2	0,002	12	y_0	0,01
3	a_3	0,002	13	z_0	0,01
4	b_1	0,02	14	c_1	0,13
5	b_2	0,0075	15	c_2	0,15
6	b_3	0,001	16	c_3	0,2
7	k_1	0,9	17	d_1	0,2
8	k_2	0,9	18	d_2	1
9	k_3	0,9	19	d_3	1
10	h_1	0,005	–		

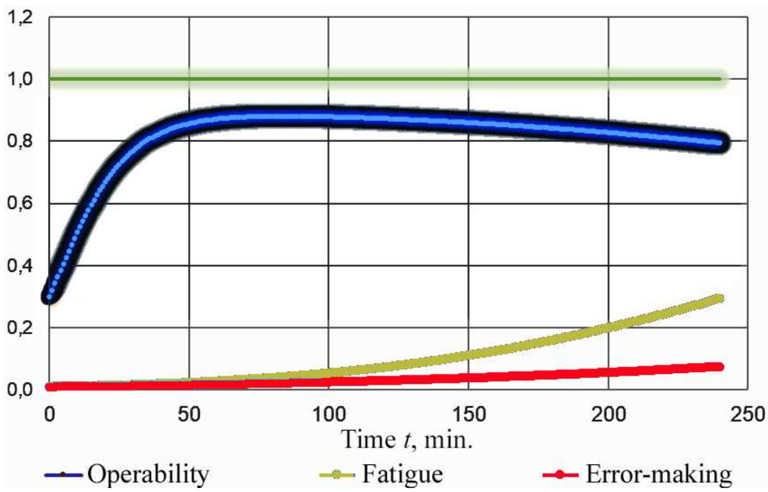

Fig. 2. Behavior of the system solution over a 240-minute period

According to output indicators X, Y and Z classification the operator has high efficiency, low fatigue and a low degree of error within four hours of his work. This corresponds to a high level of functional characteristics of the operator in the "man – machine" system in the production conditions and the external environment, as close as possible to the most favorable working conditions.

Specialized software designed for implementing the simulation tasks, such as AnyLogic, has a developed computing apparatus for solving models of different types. Three modeling approaches are implemented like:

– discrete-event (process) modeling;

– agent modeling;
– system dynamics.

The AnyLogic program was developed in 2003 by the Russian XJ Technologies company [5]. The AnyLogic Model Development Environment is a Java application. The above investigation uses the AnyLogic 8 University 8.7.2 version of the program for open research in the universities.

The working window of the system (2) modeling project with the tools of the AnyLogic program in the «System Dynamics» palette is shown in Figure 3.

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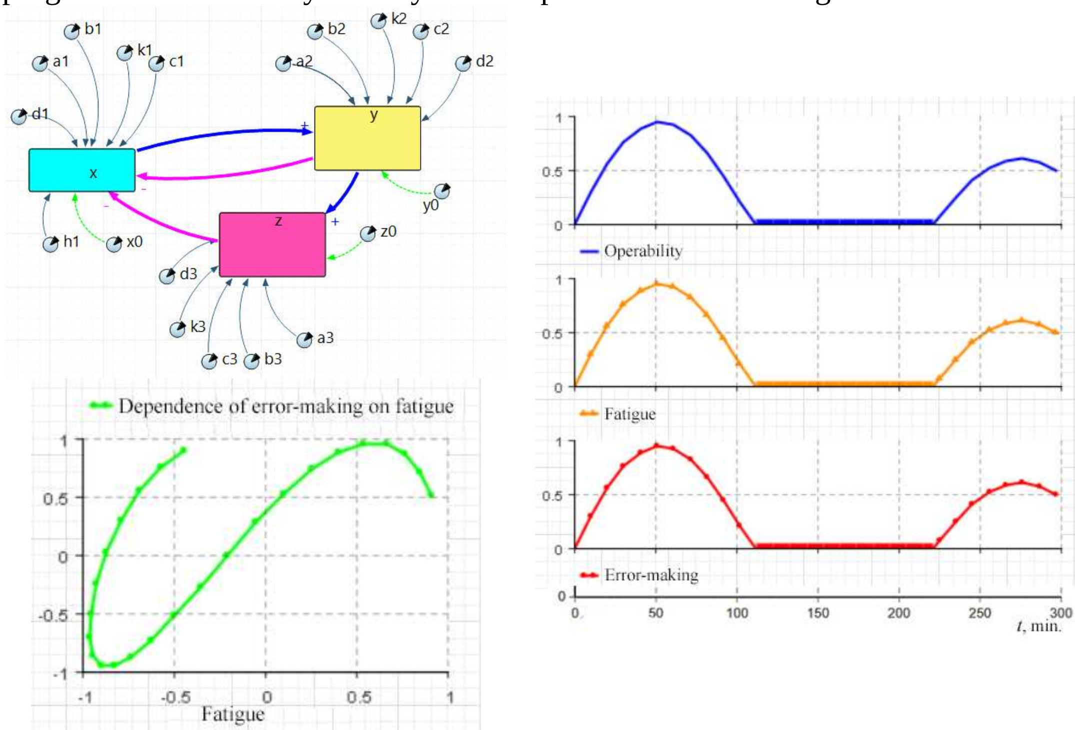

Fig. 3. Working window of the system (1) modeling project

All the necessary parameters of the system (Table 2), differential equations (1) and forms of graphical display of the results of the model run are embedded inside the program, the graphical window reflects a block diagram of the variables X, Y, Z ratio and constant parameters and templates of graphs for visualizing system solutions.

When the program is started (simulated), a compiler is started as well to build the Java program code in accordance with the specified conditions, translates it, creates an executing module and runs it for operation.

The result of running the model with the specified parameters is graphically shown in Figure 4. The model time is 240 minutes, the run time in the model during simulation is 3,83 seconds.

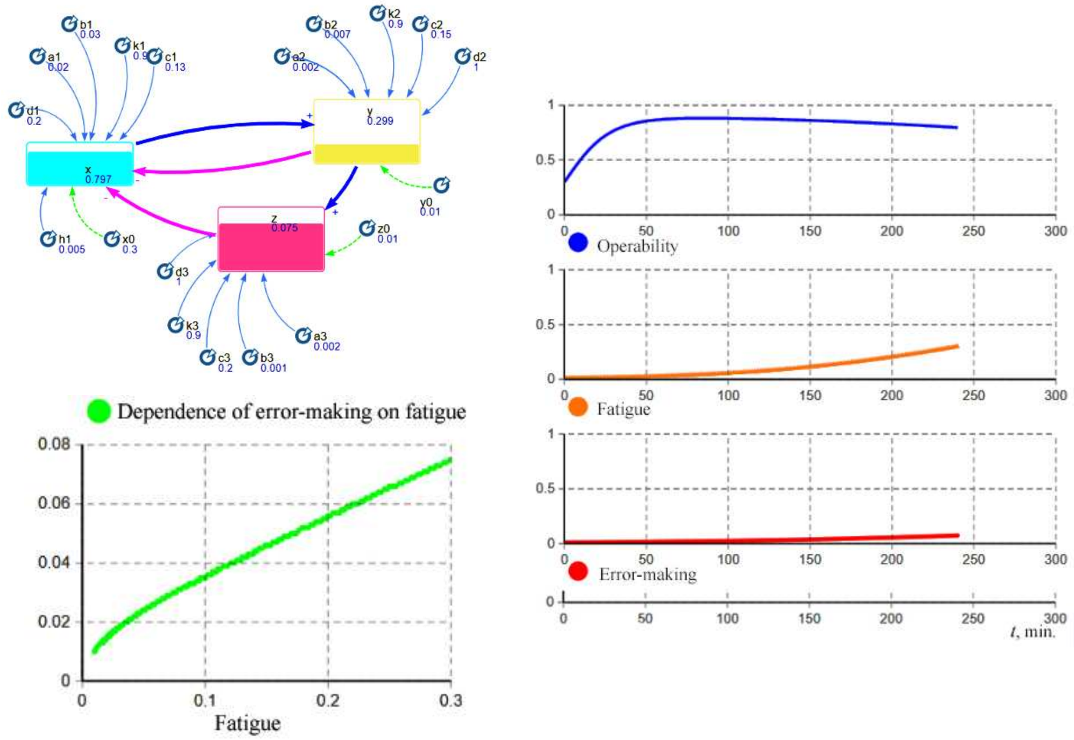

Fig. 4. The result of the model run with the specified parameters in graphical form

Table 2 shows the comparative results of model (2) solution with approximate parameters in Excel and AnyLogic programs for the maximum and values of variables X, Y, Z obtained at the final 240-minute period.

Tab. 2. Comparative results of solving the model

Time *t*, min	X	Y	Z	Software
240	0,795	0,295	0,075	Excel
240	0,797	0,299	0,075	AnyLogic
Discrepancy, %	0,25	1,36	0,00	–
max	0,882	0,295	0,075	Excel
max	0,882	0,299	0,075	AnyLogic
Discrepancy, %	0,00	1,36	0,00	–

As we can see from Table 2, the discrepancy between the runs of the model created in different software environments does not exceed 1,36%. One should consider that solution in the AnyLogic environment is more accurate, since it is based on the original system of differential equations (2).

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