

Сучасні моделі управління безпекою праці на підприємстві мають ряд недоліків. Головним недоліком подібних моделей є їх спрямованість на аналіз інцидентів чи нещасливих випадків на підприємстві, які вже відбулися. Крім того, існуючі моделі погано враховують вплив кількох виробничих факторів один на інший під час їх сукупного впливу на організм співробітника.

Для усунення цих недоліків поставлено задачу вдосконалення математичної моделі зміни стану організму співробітника підприємства. Як вихідна модель зміни стану організму співробітника підприємства розглянута модель Гаммерштейна. В процесі її вдосконалення для ситуацій неможливості чи сильного обмеження використання технологій відстежування стану співробітника виділено окремі компоненти моделі, який описує стан співробітника безпосередньо перед початком робочої зміни. Для оцінювання взаємного впливу різних виробничих факторів замість векторної функції, яка описує загальний вплив факторів на організм співробітника, в модель введено набір рівнянь множинної регресії, які описують сукупний вплив факторів на окремі параметри стану організму співробітника.

Апробація вдосконаленої моделі проводилася на промисловому підприємстві на прикладі бригади зварювальників (5 осіб). Для оцінювання їх стану використовувались сістолічний артеріальний тиск, діастолічний артеріальний тиск, частота серцевих скорочень та час реакції на світловий подразник. Наведені в статті результати дозволяють зробити висновок про адекватність запропонованої моделі результатам впливу виробничих факторів на організми робітників, які спостерігалися. Відзначено, що результати моделювання в більшості випадків незначно перевищують результати прямих вимірів

Ключові слова: безпека праці, виробничий фактор, стан організму співробітника, модель Гаммерштейна, функціональний модуль

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IMPROVING THE MATHEMATICAL MODEL OF CHANGE IN THE BODY STATE OF AN EMPLOYEE

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1. Introduction

Currently, the need for increasing the efficiency of using the labor of highly qualified employees in enterprise business activities has sharply increased. The results of the analysis published in [1] suggest that this problem arose as a result of

a series of factors. Among these factors, existing violations of labor rights of employees, as well as drawbacks in the system of labor safety and labor protection, are highlighted in [1].

To solve the problem of the shortage of qualified labor resources, it was proposed [1] to realize a series of comprehensive measures. Among these measures, studies on

implementation of international standards regarding working conditions and labor protection in workplaces were especially highlighted. International standard 18001:2007 Occupational Health and Safety Management Systems (OHSAS) [2] is an example of such a standard. This standard specifies requirements to occupational health and safety (OH&S) management system to eliminate or at least minimize risks of enterprise personnel.

According to the standard [2], the employee himself, that is, the person with specific physical, physiological and mental features is the starting point for creating such a system. This approach to building an OH&S management system implies dependence of enterprise functioning, and especially its effectiveness, on the level of motivation of employees, the degree of accounting their interests, labor safety, realization of personal aspirations, etc. Therefore, preventive activities to ensure professional safety and health of staff as well as introduction of a systems approach to managing such activities should be considered the main purpose of such a system. In particular, the OH&S management system built according to requirements of the standard [2] contributes to solution of the following main problems:

- a) identification of control of the risks for health and safety of personnel and other persons;
- b) reduction of likelihood of injuries, health degradation and other bad cases;
- c) ensuring compliance of working conditions of personnel and other persons with regulatory requirements;
- d) rise of overall staff labor efficiency.

To implement the OH&S management system, the use of existing solutions in the field of development and application of a human resource management system (HRMS) is most often proposed. This approach has become one of the reasons why the HRMS segment is one of the fastest-growing business applications in the current global market. However, the difficulty of developing separate supporting systems for HRMS was the negative consequence of this approach. Existing HRMS are complex systems that include interconnected and interdependent subsystems of creation, use, and development of enterprise personnel [3]. Recruiting and retaining qualified employees who are most valuable to the enterprise business processes is the main purpose of applying the HRMS to solve the problem of shortage of qualified labor resources. Therefore, decisions on creation and further development of HRMS depend to a large extent on the specific personnel policy of an enterprise [3]. Such a policy is characterized by many poorly formalizable or completely unformalizable parameters some of which are directly related to psychology. It should also be noted that the development of personnel policy and its implementation as an OH&S management system is extremely difficult in many enterprises. The lack of approaches, models, and methods of organizing the management of human resources including labor safety management suitable for such enterprises is the main cause of this situation. Therefore, studies in this area are one of the most urgent problems.

2. Literature review and problem statement

One of the prerequisites for improving the efficiency of OH&S management systems is the automation of management processes. However, such conditions are very often not fulfilled in the corresponding segment of the current IT mar-

ket. Information systems (IS) of preparation and circulation of documents of the enterprise departments responsible for labor protection, occupational safety and hygiene is the basis of this segment. For example, Labor Expert Management IS [4] should be considered an example of successful OH&S management IS. However, the functions of documentary support for labor protection activities at the enterprise are the main functions in this IS. A similar situation is observed in the Labor Protection module of the Automated Industrial Safety and Labor Protection Management System [5].

Automated Labor Protection [6] IS is an example of the most common ISs in this segment of the IT market. It includes the following functions:

- a) planning the measures aimed at ensuring healthy and safe working conditions for employees;
- b) automated certification of workplaces and personnel;
- c) accounting for personal protective means;
- d) recording the results of medical examinations;
- e) preparation of reporting forms.

It should be noted that the use of typical OH&S management ISs in different regions of the world is limited. For example, specialized OH&S management ICs are almost completely absent in the Ukrainian IT market. However, proposals in this segment of IS [4–6] or the like are extremely hardly realized. Legal restrictions on the use of such systems play an important role. These restrictions may be caused by the following factors:

- a) inconsistency of the legislative base of the measures aimed at management of labor safety in the developer region and the region of consumers of OH&S management ISs;
- b) legal protectionist policy directed at protection of the domestic market against foreign IT products;
- c) restrictions on the supply of IS and other IT products to certain regions (for example, restrictions on the supply of Microsoft and Oracle IT products to Russian enterprises, restrictions on the supply of IT products from the 1S Company to Ukrainian enterprises, etc.) and other factors.

This situation is characteristic not only for the Ukrainian segment of the IT market of OH&S management ISs. Despite the rapid growth of the number of proposals of such ISs in industrialized countries, most of them automate the implementation of far from all functions of the standard [2]. The difference between two main points of view on human resource management, that is, the view of institutional theory and a resource-based view discussed in [7] should be considered as one of the important causes of this discrepancy. Functions of the HRM ISs are formed mainly on the basis of the institutional theory. However, it was shown in [7] that achievement of high enterprise productivity is only possible if the following models and methods are combined:

- a) general models and methods of human resource management based on the institutional theory;
- b) models and methods of managing small groups and individual employees of the enterprise which are the products of the view based on resources.

Dependence of productivity on effective personnel management at an enterprise was confirmed in [8] for enterprises of processing industry. It is also argued in [8] that representation of the model of enterprise productivity by one structural equation or a system of such equations will subsequently become a basis for development of a managerial tool of productivity growth.

As applied to OH&S management information systems, these findings indicate the need for studies in the field of

development and improvement of models and methods that would make it possible to describe an individual employee of the enterprise as an important resource. Several study lines can be distinguished. Development of general models for managing safety of personnel at enterprises of various types is one of these lines. This study line exists mainly due to the insufficient number of IS proposals for various types of enterprises. For example, a general model of labor protection management at small and medium enterprises in Italy was proposed in [9]. An example of constructing an IS for managing productivity of an employee of a construction company based on the productivity model that makes it possible to reduce number of accidents and disease cases is considered in [10].

Other basic lines of these studies are largely determined by the results of the development and improvement of real-time detection and tracking technologies. Such technologies and the tools based on them are widely used to automatically monitor location and state of employees, equipment, and other resources to prevent exposure to harmful production factors and potential accidents. The review conducted in [11] has made it possible to single out the following main areas of application of these technologies for automation of the labor safety management processes:

- monitoring of labor safety;
- prevention of accidents;
- development of safe behavior scenarios;
- highlighting situational alarms and warnings about a security breach;
- ergonomic analysis and monitoring of the physiological state;
- communications-based safety management;
- assessment of effectiveness of these technologies and the technologies created on their basis;
- safety training at workplaces.

The first of the basic lines of these studies was determined by the impossibility or weak opportunities for application of the above technologies in one or more considered areas of labor safety management. First of all, this situation arises because of the lack of necessary knowledge about the subject area. Therefore, this direction is mainly devoted to the development of models, meta-models, and methods of managing labor safety at enterprises of various types based on knowledge. For example, application of mental models for analysis of existing risks and methods for expanding safe behavior of workers of road construction companies was considered in [12]. Studies were described in [13] on the use of meta-synthesis and interpretative structural modeling to identify individual cognitive factors that affect the dangerous behavior of Iranian industrial workers. Issues of application of some current technologies for collecting and processing knowledge about the behavior of workers in dynamically changing environments are considered in [14] on an example of a construction company. The problems of using systematic data maps to fill in the gaps in objective data on the state of a person and solving other problems of managing health risks associated with exposure to chemicals were considered in [15].

The second of the basic directions of these studies was determined by a positive decision on the possibility of using special technologies for detecting and monitoring the state of enterprise employees. In this direction, the main attention is paid to the development and improvement of models

and methods for quantitative assessment and analysis of the state and behavior of a particular employee from the point of view of his work safety. For example, the solution of the problem of determining the optimal working time of an operator of a mechanical olive harvesting machine as a compromise between the efficiency of the harvesting process and safety of the operator's health is considered in [16]. An approach to automatic data acquisition, processing and subsequent biomechanical analysis of workers' behavior to prevent ergonomic risks in construction enterprises is considered in [17]. It should be noted that these problems were solved in [17] using a minimum number of technologies for detecting and tracking the employee status. The solution to the problem of recognizing and analyzing the behavior of workers using the methods of recognizing deep actions and the Bayesian nonparametric hidden semi-Markov model is considered in [18]. Problems of constructing an IS for automation of solution of a problem of assigning production tasks to a specific employee with additional minimization of costs, providing the possibility of further employee training and ensuring the safety of his work are considered in [19]. In this IS, tasks are automated using a neural network and a genetic algorithm for non-dominant sorting and decision-making methods.

However, the issues related to the prediction and prevention of accidents during enterprise processes remain practically unresolved at present. Perhaps this situation has arisen because most of the models and methods discussed above can be considered the elements of an a posteriori analysis of labor safety. A posteriori analysis is performed after events caused by exposure to harmful factors in the work environment leading to injury or health degradation. The result of applying such an analysis consists of an increase in costs of both the employee (to restore his working capacity) and the enterprise (within the framework of legal obligations and their own policies in the field of health and safety).

In this regard, there is a need to develop new and improve existing models and methods to solve the problems of preventing accidents or productivity loss caused by the deterioration of employee state. To solve this problem, it is also proposed to take into account the desire of the enterprise owners and management to reduce unproductive costs for acquisition and operation of special detection and tracking means that work in real time. Therefore, studies in the field of developing new and improving existing mathematical models of analyzing changes in employee state should be recognized as the most promising in this area. Such models should quantitatively assess the body state and then forecast the dynamics of its change for a specific employee of the enterprise before starting his daily professional activity.

3. The aim and objectives of the study

The study objective is to improve models of quantitative control and analysis of the employee's state as an indicator of occupational safety and health at a managed facility (an enterprise). The use of improved models should make it possible to determine the state of an employee and the change in this state under the influence of production factors during the industrial enterprise activities.

To achieve the objective, the following tasks were set:

- to change parameters of the existing mathematical model that describe the reaction of the enterprise employee body to the action of production factors;
- to test the obtained solutions during the development and validation of a functional module of the enterprise OH&S management information system.

4. The results of the change in parameters of the existing mathematical model that describe the reaction of the enterprise’s employee body to the action of production factors

To solve problems of quantitative control and analysis of employee’s state as an indicator of occupational safety and health at the managed facility, the following definitions must be introduced.

It is proposed to designate the set of human body states by *SOST*. The state of the *k*-th employee is defined as $sost_j^k \in SOST, j=1, n$ [20]. Any state from the *SOST* set is determined by a set of parameters of functioning of the *k*-th employee body:

$$sost_j^k = \begin{bmatrix} par_{j1}^k \\ \dots \\ par_{jh}^k \\ \dots \\ par_{jp}^k \end{bmatrix}, \tag{1}$$

where par_{jh}^k is value of the *h*-th measured parameter of the *k*-th employee body, $h=1, \dots, p$.

Then

$$SOST = \left[\begin{bmatrix} par_{11} \\ \dots \\ par_{1p} \end{bmatrix}, \dots, \begin{bmatrix} par_{n1} \\ \dots \\ par_{np} \end{bmatrix} \right]. \tag{2}$$

Let us describe the change in the human body state under the influence of a complex of factors of the production environment which depends only on the effect of these factors. To this end, it is necessary to take into account the initial state of a person and the complex of factors of the working environment acting on this person’s body, $\varphi^1, \dots, \varphi^m, \phi^i, i=1, m$ is the *i*-th factor acting on the body.

$$sost_j^k \in SOST = \bar{w}(t_0) + \Delta \bar{w}(t), \tag{3}$$

where $\bar{w}(t_0)$ is the employee’s body state at the initial time; $\Delta \bar{w}(t)$ is a change in the employee’s body state under influence of a complex of production factors over time *t*, $t \in [0, \dots, t_j, \dots, T]$.

Let us use the Hammerstein model [21] to determine the change in the employee’s body state during the labor process under a joint nonlinear effect of a complex of factors of the working environment on the body. This model was constructed for a system (a human body) with *n* internal parameters (the system state vector) and $\bar{\phi}(t)$ – *m* external time depended on effects:

$$\begin{aligned} \Delta \bar{w}(t) &= \Gamma(\bar{\phi}(t), t_1, t_2) = \\ &= \int_0^{t_2-t_1} \bar{w}(t) \cdot \bar{f}(\bar{\phi}(t_2 - \tau)) d\tau, \end{aligned} \tag{4}$$

where $\bar{f}(\bar{\phi}(t_2 - \tau)) d\tau$ is the vector function of transforming the input effect of factors on the human body in the description of the given body reaction.

This model represents serially connected non-linear static parts and linear dynamic parts. The equation kernel is the Fredholm kernel. It is linear, symmetric and positive, that is, all its eigenvalues are positive. Without limitation of generality, assume that the system is homogeneous, that is, it can withstand time shift, and that $t_1=0; t_2=T$ is the observation time.

This expression can be considered the model of change in the employee’s state under a combined effect of factors during the observation period. The classical Hammerstein model represented by expression (4) is based on assumption of the possibility of measuring the parameters that determine state of the observed biological system at any time from $[t_1, t_2]$. Such an assumption in conditions of impossibility or strict limitation of applying special technologies of detecting and monitoring the employee’s state in real time is usually not fulfilled. Therefore, it is proposed to modify expression (4) proceeding from the assumption that the internal state of the employee’s body remains unchanged at the initial time of the labor process. Then model (4) will take the form:

$$\begin{aligned} \Delta \bar{w}(t) &= \Gamma(\bar{\phi}(t), 0, T) = \\ &= \bar{w}(\tau_0) \cdot \int_0^T \sum_{i=1}^m \left[\int_0^\infty \omega(\tau) (\phi^{ik}(t - \tau)) d\tau \right], \end{aligned} \tag{5}$$

where $\bar{w}(\tau_0)$ is the vector function determining internal state of the human body at the initial point of time τ_0 while any state is determined by a set of parameters from expression (1); $\omega(\tau)$ is an impulse transient matrix-function having size $m \times n$ which reflects a specific, unchanging relationship between the production factors varying in time and a set of parameters characterizing physiological and psychophysiological state of a person at time τ [20]; ϕ^{ik} is the *i*-th production factor that affects the *k*-th employee of the enterprise.

The mathematical model of the relationship between the results of measuring the effect of factors and reaction of the body of the observed employee to this effect can be represented as follows

$$f(\mu_{\phi^{ik}(t)}}) = \int_0^\infty \omega(\tau) \mu_{\phi^{ik}(t)}(t - \tau) d\tau, \tag{6}$$

where $\mu_{\phi^{ik}(t)}$ is the indicator of hazard of the process for the employee for *m* values of the *i*-th factor acting on the *k*-th employee at the time point [20].

Relationship of $f(t)$ and $\mu_{\phi^{ik}(t)}(t)$ is expressed as a relationship of their deterministic components through a differential equation $f(t) + bf(t) = a\mu_{\phi^{ik}(t)}(t)$, provided that $f(t_1)=0$. This model is used in the study of the effect of harmful factors on biological systems [21, 22]. Upon transition to discrete measurement time, a multiple regression equation is obtained with time lagging variables:

$$\bar{f}(\bar{\phi}(T-\tau)) = \sum_{i=1}^m \left[\int_0^{\infty} \omega(\tau) (\phi^{ik}((t-\tau))) d\tau \right], \tag{7}$$

The main method of solving the problem of finding the transition function $\omega(\tau)$ which establishes a specific form of dependence between the results of measuring the impact of production factors and the reaction of the observed employee body to this effect consists of compiling the Wiener-Hopf equation. There are a series of methods for solving the Wiener-Hopf equation which are based on a further parameterization of the problem by expanding $\omega(\tau)$ in a given system of functions or by switching to discrete time. This function allows one to establish the dependence of reaction of any organism on the combined effect of production factors.

Determining the employee state from a set of parameters in accordance with expression (1) and taking into account all improvements proposed above, model (5) can be represented as follows:

$$\begin{aligned} \Delta \bar{w}(t) = \Gamma_2(\mu_{\phi^{ik}(t)}, t_1, t_2) = \\ = \int_0^{t_2-t_1} \begin{bmatrix} par_1(0) \\ \dots \\ par_h(0) \\ \dots \\ par_n(0) \end{bmatrix} \times \begin{bmatrix} \sum_{i=1}^m \int_0^{\infty} \omega_1(\tau) \mu_{\phi^{ik}(t)}(t-\tau) d\tau \\ \dots \\ \sum_{i=1}^m \int_0^{\infty} \omega_h(\tau) \mu_{\phi^{ik}(t)}(t-\tau) d\tau \\ \dots \\ \sum_{i=1}^m \int_0^{\infty} \omega_n(\tau) \mu_{\phi^{ik}(t)}(t-\tau) d\tau \end{bmatrix} dt, \tag{8} \end{aligned}$$

where $par_1(0), \dots, par_h(0), \dots, par_n(0)$ are the employee's body parameters for determining his state at the initial point of time; $\omega_1(\tau), \dots, \omega_h(\tau), \dots, \omega_n(\tau)$ is pulse transition matrix-function of description the body's response to the impact of existing production factors; $\mu_{\phi^{ik}(t)}$ is an indicator of the process hazard for the employee for m values of the i -th factor acting on the k -th employee at a time point.

Thus, it becomes possible to determine the employee's state according to the measured body parameters immediately before the start of his labor activity using expressions (1)–(3). The improved model (8) allows one to determine the change in the employee's body state under the effect of production factors during the execution of production tasks by this employee.

5. Testing the obtained solutions in the process of validation of the functional module of the enterprise OH&S management information system

The improved model (8) was experimentally verified in the process of validating the functional module of labor safety. The list of functional requirements for this module was considered in [23]. The results of the analysis of these requirements are given in [24]. The results of the synthesis of a description of this functional module architecture are given in [25].

The functional module of labor safety was validated at an industrial enterprise in a team of welders (5 persons)

during the development of the functional module of the enterprise OH&S management information system. This team performed electro-gas welding of particularly complex and critical structures and pipelines made of high-carbon steel to be operated under dynamic and vibration loads at high pressure. Any welding process is always accompanied by a number of factors that pose a danger to the health of both the welder and the people present nearby during welding. The most dangerous element in the process of human exposure should be considered the electric arc since the intensity of its radiation is very high. In addition, the following harmful factors varying in their degrees are present with any type of welding:

- ultraviolet radiation;
- blinding brightness of visible light;
- infrared radiation;
- sparks and splashes of molten metal;
- harmful substances such as aerosols and gases released during the welding process (depending on the type of welding, type of electrode, type of work performed and the welded materials).

The impact of the complex of these harmful factors can be critical for the cardiovascular and nervous systems of the human body. Obvious indicators of the state of these systems include systolic, $par_1(t)$, and diastolic, $par_2(t)$, blood pressure, heart rate (HR), $par_3(t)$, and reaction time to the light stimulus, $par_4(t)$. The choice of these parameters was determined by the following considerations:

- a) shifts in the parasympathetic nervous system are among the most characteristic body reactions to electromagnetic fields and are expressed in arterial hypotension and a tendency to bradycardia with frequency and severity depending on the radiation intensity;
- b) under the effect of radio waves on the cardiovascular system, the human body exhibits functional disorders: unstable pulse and blood pressure, asymmetric blood pressure indicators are often found and there may also be a tendency to hypertension;
- c) in persons exposed to optical radiation, disorders of the cardiovascular system develop against the background of functional disorders of the central nervous system.

When testing the improved model (8), the body state parameters were measured in the performers of these works, namely:

- $par_1(t)$: the level of systolic blood pressure;
- $par_2(t)$: the level of diastolic blood pressure;
- $par_3(t)$: heart rate (HR);
- $par_4(t)$: reaction time to a light stimulus.

The following equipment was used to perform these measurements:

- a) a Beurer BC16 electronic automatic blood pressure monitor designed to measure blood pressure and heart rate;
- b) a stopwatch to measure the sensorimotor reaction time.

As appropriate, mobile applications for smartphones or laptops can be used as a means of individual measurement of the sensorimotor reaction time.

An example of the results obtained in measuring the parameters of the body state of one of the welders is given in Table 1.

Graphs illustrating the change in values of the set of parameters of body state of the observed employee during the work shift on different weekdays are presented in Fig. 1–4.

Table 1

The results of measurements of the body state parameters of one of the welders

No.	Measurement time	Weekday	Systolic blood pressure, mm Hg column	Diastolic blood pressure, mm Hg column	HR, bpm	Reaction time, s
1	8.00	Monday	130	85	76	0.4
2	10.00	Monday	132	85	77	0.4
3	12.00	Monday	134	87	78	0.5
4	14.00	Monday	137	89	80	0.6
5	16.00	Monday	137	90	81	0.6
6	8.00	Tuesday	135	90	80	0.5
7	10.00	Tuesday	137	92	82	0.5
8	12.00	Tuesday	139	94	85	0.6
9	14.00	Tuesday	141	95	87	0.7
10	16.00	Tuesday	142	96	88	0.7
11	8.00	Wednesday	135	90	82	0.5
12	10.00	Wednesday	138	91	84	0.5
13	12.00	Wednesday	140	94	87	0.6
14	14.00	Wednesday	143	94	87	0.7
15	16.00	Wednesday	145	95	89	0.7
16	8.00	Thursday	125	84	78	0.4
17	10.00	Thursday	127	85	78	0.4
18	12.00	Thursday	129	87	82	0.5
19	14.00	Thursday	130	87	84	0.7
20	16.00	Thursday	132	88	86	0.7
21	8.00	Friday	140	90	82	0.6
22	10.00	Friday	143	92	85	0.6
23	12.00	Friday	145	95	90	0.7
24	14.00	Friday	147	96	90	0.8
25	16.00	Friday	148	97	92	0.8

The results given in Table 1 allow us to determine the values of the $par_h(0)$ elements of model (8) and actual values of the body state parameters of the observed employee during and after the work shift during the week.

Application of the proposed model (8) to calculate the magnitude of change in values of the body state parameters of the observed employee also requires measuring the effects of the above production factors. During the experiment, the level of EMR in the optical range and air temperature were identified as the main (dominant) production factors acting at the welder's workplace. Current production factors were measured using the following measuring instruments. To measure energy characteristics, we used the RAT-2P thermal radiation meter (manufacturer: Tensor LLC, Chernivtsi, Ukraine), which is designed for measuring integral characteristics of radiation in the entire spectral range. This meter is used to conduct sanitary and hygienic studies in certification of workplaces (recommended by the Ministry of Health of Ukraine). Temperature of the production environment was measured using the Meteoscope-M universal microclimate parameter meter (manufacturer: Tensor LLC, Chernivtsi, Ukraine) designed to monitor environment in residential and industrial premises, in open areas. The Meteoscope-M is used to control microclimate parameters, in certification of enterprise workplaces, offices and

public institutions. The measurement results are given in Table 2.

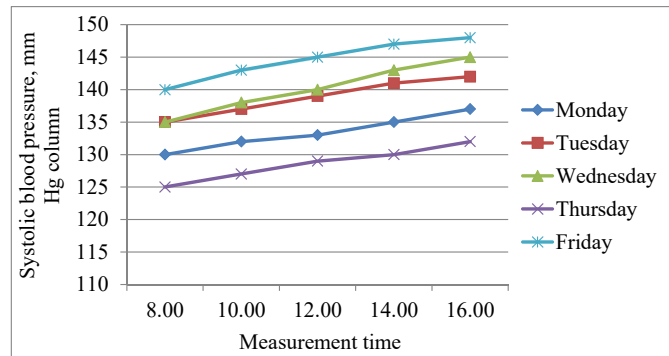


Fig. 1. Chart illustrating a change in the systolic blood pressure in the week and measurement time

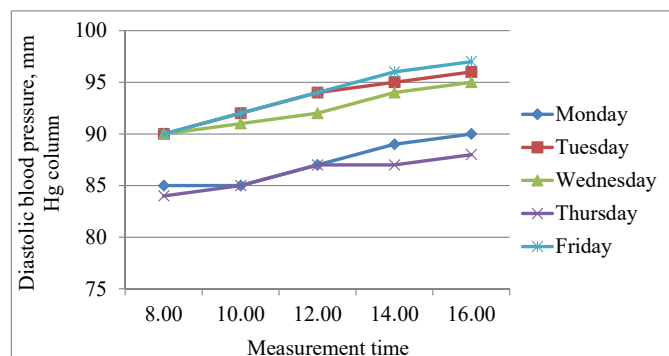


Fig. 2. Chart illustrating a change in diastolic blood pressure in the week and measurement time

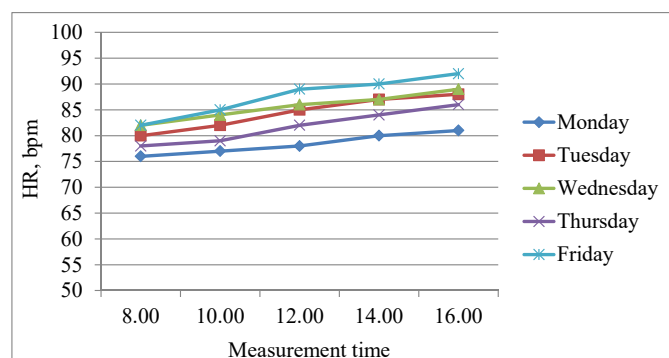


Fig. 3. Chart illustrating a change in heart rate in the week and measurement time

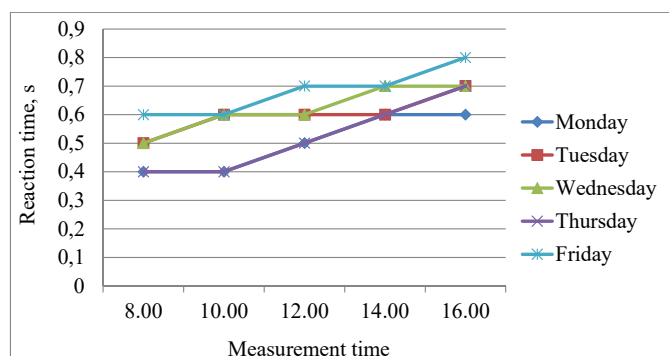


Fig. 4. Chart illustrating a change in reaction time in a week and the measurement time

The results of measuring the action of dominant production factors given in Table 2 determine the values of $\mu_{\phi^{*k}(t)}$ elements in model (8) [20].

Data on external factors were interpolated between shifts with an EMR level equal to zero and an air temperature of 20 °C. Data on the measured parameters of the employee state were interpolated by the Aitken-Lagrange method. The time series obtained for the studied parameters were centered. The Wiener-Hopf equation was solved by discretizing it and reducing to four systems of linear equations. The environmental factors were numbered as follows: 1 for the level of electromagnetic radiation; 2 for air temperature. The measured parameters of the employee's body state were numbered as follows: 1 for the level of systolic blood pressure; 2 for the level of diastolic blood pressure; 3 for the heart rate; 4 for sensorimotor reaction time. The systems of linear equations were solved by the Gauss method with a choice of the main element. In order to regularize the solution, smoothing of the results was applied. Using graphical analysis of the results, the following formula was chosen for $\omega_{11}(\tau)$, $\omega_{21}(\tau)$, $\omega_{31}(\tau)$, $\omega_{41}(\tau)$ functions:

$$\omega(\tau) = Ce^{-a\tau}. \tag{9}$$

The following formula was chosen for $\omega_{22}(\tau)$, $\omega_{31}(\tau)$, $\omega_{42}(\tau)$ functions:

$$\omega(\tau) = C\tau^b e^{-a\tau}. \tag{10}$$

Formula $\omega_i(\tau) = C = \text{const}$ was chosen for $\omega_{12}(\tau)$ and $\omega_{31}(\tau)$ functions.

Relations (9), (10) were linearized by taking logarithms and the coefficients were determined by the least-squares method resulting in the following relationships:

$$\begin{aligned} \omega_{11}(\tau) &= 0.083e^{-0.1613\tau}; \\ \omega_{21}(\tau) &= 5.6 \cdot 10^{-3} e^{-0.3402\tau}; \\ \omega_{31}(\tau) &= 0.00406; \\ \omega_{41}(\tau) &= 9.14 \cdot 10^{-5} e^{-0.0355\tau}; \\ \omega_{12}(\tau) &= -0.00324; \\ \omega_{22}(\tau) &= 0.277 \cdot \tau^{1.409} e^{-0.5498\tau}; \\ \omega_{32}(\tau) &= 0.332e^{-0.3279\tau}; \\ \omega_{42}(\tau) &= 1.134 \cdot 10^{-3} \cdot \tau^{1.748} e^{-1.023\tau}. \end{aligned}$$

In the general case, the phenomena of delay, accumulation of the effect and exponential recovery were observed [22].

Let us consider in a more detail application of model (8) using the example of calculation made on the basis of data measured on Thursday at the start of the shift (Tables 1, 2). First, consider an example of calculating assessment of change in the employee's state in the process of professional activity under the effect of production factors, 2 hours after the shift start. The human body reaction to the effects of production factors was calculated using (7):

$$\begin{aligned} f(\mu_{\phi^{*k}(t)}) &= \sum_{i=1}^N \omega(\tau_i) \mu_{\phi^{*k}(t)}(t - \tau_i) \Delta\tau_i = \\ &= \sum_{i=1}^N \begin{bmatrix} (R_{\mu\mu})_{11} & (R_{\mu\mu})_{12} \\ (R_{\mu\mu})_{21} & (R_{\mu\mu})_{22} \end{bmatrix} \cdot \begin{bmatrix} \omega_{i1} \\ \omega_{i2} \end{bmatrix}, \end{aligned} \tag{11}$$

where $\omega(\tau)$ is the impulse transition matrix-function of description of the body's response to the effect of factors of size $m \times n$; $\mu_{\phi^{*k}(t)}$ is the indicator of the process hazard for the employee for m values of the magnitude of the i -th factor acting on the k -th employee at a time point; $R_{\mu\mu}$ is an element of the matrix for calculating the indicator of total hazard; N is the number of factor measurements.

Then,

$$\begin{aligned} \Delta \bar{w}(\tau) &= \begin{bmatrix} par_1(0) \\ \dots \\ par_h(0) \\ \dots \\ par_n(0) \end{bmatrix} \times \\ &\times \int_0^T \int_0^{\tau} \begin{bmatrix} (R_{\mu\mu})_{11} & (R_{\mu\mu})_{12} \\ (R_{\mu\mu})_{21} & (R_{\mu\mu})_{22} \end{bmatrix} \cdot \begin{bmatrix} \sum_{i=1}^N \omega_{11}(\tau_i) + \omega_{12}(\tau_i) \\ \sum_{i=1}^N \omega_{21}(\tau_i) + \omega_{22}(\tau_i) \\ \sum_{i=1}^N \omega_{31}(\tau_i) + \omega_{32}(\tau_i) \\ \sum_{i=1}^N \omega_{41}(\tau_i) + \omega_{42}(\tau_i) \end{bmatrix} d\tau dt = \\ &= \begin{bmatrix} 125 \\ 84 \\ 78 \\ 0,4 \end{bmatrix} \cdot \begin{bmatrix} 0 & 13 \\ 13 & 26 \end{bmatrix} \cdot \begin{bmatrix} \sum_{i=1}^2 0.083e^{-0.1613\tau_i} - 0.00324 \\ \sum_{i=1}^2 5.6 \cdot 10^{-3} e^{-0.3402\tau_i} + \\ + 0.277 \cdot \tau_i^{1.409} e^{-0.5498\tau_i} \\ \sum_{i=1}^2 0.00406 + \\ + 0.322e^{-0.327\tau_i} \\ \sum_{i=1}^2 9.14 \cdot 10^{-5} e^{-0.355\tau_i} + \\ + 1.134 \cdot 10^{-3} \cdot \tau_i^{1.748} e^{-1.023\tau_i} \end{bmatrix} + \\ &+ \begin{bmatrix} 83 & 112 \\ 112 & 29 \end{bmatrix} \cdot \begin{bmatrix} \sum_{i=1}^2 0.083e^{-0.1613\tau_i} - 0.00324 \\ \sum_{i=1}^2 5.6 \cdot 10^{-3} e^{-0.3402\tau_i} + \\ + 0.277 \cdot \tau_i^{1.409} e^{-0.5498\tau_i} \\ \sum_{i=1}^2 0.00406 + 0.322e^{-0.327\tau_i} \\ \sum_{i=1}^2 9.14 \cdot 10^{-5} e^{-0.355\tau_i} + \\ + 1.134 \cdot 10^{-3} \cdot \tau_i^{1.748} e^{-1.023\tau_i} \end{bmatrix} = \begin{bmatrix} 3 \\ 0.3 \\ 0.2 \\ 0.06 \end{bmatrix}. \end{aligned}$$

The results of the calculation of the change in the values of the employee's state parameters when exposed to production factors 2 hours after the shift starts are given in Table 3.

According to the results given in Table 3, the following conclusion can be drawn. As a result of professional

activity, within 2 hours after the start of the shift, parameters of the employee's body state have changed. An increase in parameters of the body state also indicates an increase in the value of $sost_j^k \in SOST, j=1, n$ from expression (1). Based on the assumption that an increase in this value corresponds to the state worsening, we can conclude that there is some deterioration in the employee's state after 2 hours from the shift start.

Table 2

Measurement results			
Weekday of measurements	Measurement time	EMR level, W/m ²	Temperature, °C
Monday	8.00	0	22
Monday	10.00	60	24
Monday	12.00	82	26
Monday	14.00	110	28
Monday	16.00	100	30
Tuesday	8.00	0	24
Tuesday	10.00	20	25
Tuesday	12.00	34	29
Tuesday	14.00	100	32
Tuesday	16.00	104	34
Wednesday	8.00	0	26
Wednesday	10.00	141	30
Wednesday	12.00	140	33
Wednesday	14.00	119	33
Wednesday	16.00	139	34
Thursday	8.00	0	26
Thursday	10.00	83	29
Thursday	12.00	86	31
Thursday	14.00	95	32
Thursday	16.00	131	32
Friday	8.00	0	24
Friday	10.00	123	25
Friday	12.00	137	27
Friday	14.00	106	26
Friday	16.00	134	26

Table 3

Result of calculations for predicting changes in the employee state parameters 2 hours after the shift start

Parameters used	Parameter values at the time point of the shift start	Calculated magnitude of the parameter change	Predicted parameter value
$par_1(t)$	125	+3	128
$par_2(t)$	84	+0.3	84.3
$par_3(t)$	78	+0.2	78.02
$par_4(t)$	0.4	+0.06	0.406

In the same way, an assessment of change in the employee's state in the course of his professional activity was made using a mathematical model for assessing changes in the employee's state under the effect of production factors, 4 and 6 hours after the shift start. The results of these calculations are given in Table 4.

Table 4

The calculation results

Parameters used	Parameter values at the shift start time point	Calculated magnitude of the parameter changes after 2 hrs.	Calculated magnitude of the parameter changes after 4 hrs.	Calculated magnitude of the parameter changes after 6 hrs.	Predicted parameter value at the shift end time point
$par_1(t)$	125	+3	+1.02	+1.78	132.6
$par_2(t)$	84	+0.3	+1.9	+2	88.2
$par_3(t)$	78	+0.2	+4.03	+4.11	86.16
$par_4(t)$	0.4	+0.06	+0.112	+0.18	0.698

Let us compare the calculated employee's state parameters according to the improved model (8) with the measured values for time points of 2, 4, and 6 hours after the work start and for the time point of the work shift end. Graphs of comparisons of calculated and measured parameters of the observed employee's body state are shown in Fig. 5–8.

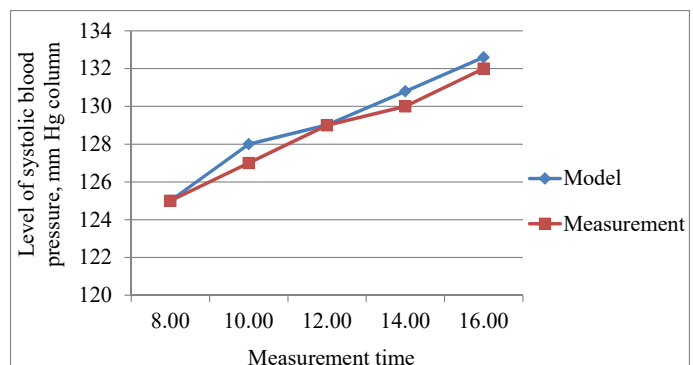


Fig. 5. Comparison of the calculated and measured values of the parameter "level of systolic blood pressure"

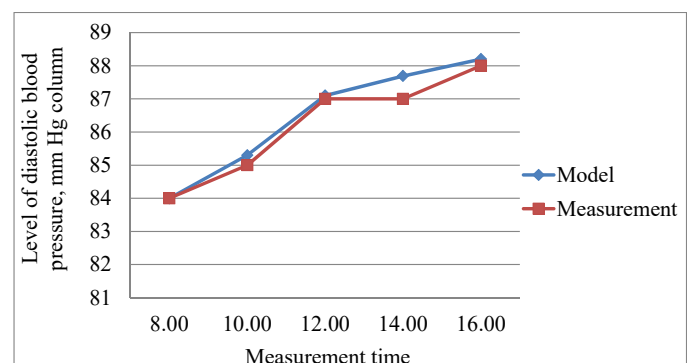


Fig. 6. Comparison of the calculated and measured values of the parameter "level of diastolic blood pressure"

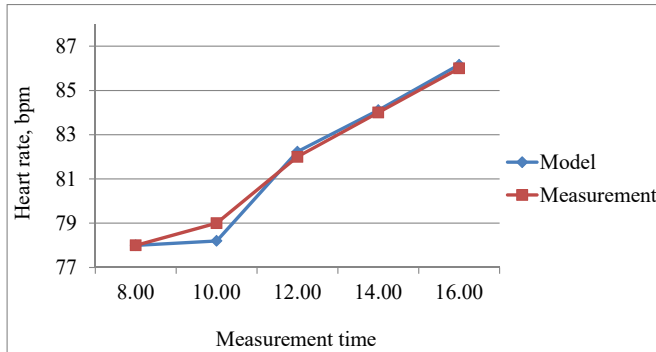


Fig. 7. Comparison of the calculated and measured values of the parameter “heart rate”

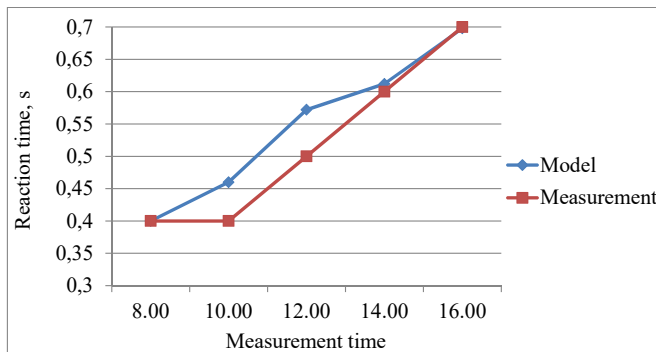


Fig. 8. Comparison of the calculated and measured values of the parameter “time to the stimulus reaction”

Comparison of the obtained results is given in Table 5.

Comparison of the results obtained in direct measurements and calculated using the proposed model for the body state parameters of the observed employee

Values of the employeeworker’s body state parameters		Measurement time				
		8.00	10.00	12.00	14.00	16.00
Systolic blood pressure $par_1(t)$	calculated	125	128	129.02	130.8	132.6
	measured	125	127	129	130	132
	discrepancy	–	+1	+0.02	+0.8	+0.6
	root-mean-square deviation					0.707
	Confidence interval, upper	0	126.09	128.09	129.09	131.1
	Confidence interval, lower	0	127.91	129.91	130.91	132.9
Diastolic blood pressure $par_2(t)$	calculated	84	85.3	87.1	87.69	88.2
	measured	84	85	87	87	88
	discrepancy	–	+0.3	+0.1	+0.69	+0.2
	root-mean-square deviation					0.392
	Confidence interval, upper	0	84.494	86.494	86.494	87.49
	Confidence interval, lower	0	85.506	87.506	87.506	88.51
Heart rate $par_3(t)$	calculated	78	78.2	82.23	84.11	86.16
	measured	78	79	82	84	86
	discrepancy	–	-0.8	+0.23	+0.11	+0.16
	root-mean-square deviation					0.427
	Confidence interval, upper	0	78.449	81.449	83.449	85.45
	Confidence interval, lower	0	79.551	82.551	84.551	86.55
Time to the stimulus reaction $par_4(t)$	calculated	0.4	0.46	0.572	0.612	0.698
	measured	0.4	0.4	0.5	0.6	0.7
	discrepancy	–	+0.06	+0.072	+0.012	-0.002
	root-mean-square deviation					0.047
	Confidence interval, upper	0	0.339	0.439	0.539	0.639
	Confidence interval, lower	0	0.461	0.561	0.661	0.761

The confidence interval in Table 5 was calculated for a confidence level of 0.99.

As follows from Table 5, the results of modeling the changes in values of each parameter fit into the confidence interval in most cases. Therefore, it becomes possible to assume that in general model (8) adequately describes the processes of change of the observed employee parameters. However, application of this model gives the least accurate results of calculation of changes in values of the body state parameters of the observed employee in the first half of the work shift. At the end of the shift, application of the model allows one to obtain somewhat higher than actual values of the body state parameters of the observed employee.

Thus, the problem of assessing changes in the body state according to the results of observing exposure of the human body to environmental factors was solved with the help of an improved mathematical model (8). This problem was solved based on the assumption that it is impossible to determine changes in the employee’s body state based on direct measurements.

6. Discussion of results obtained while improving the mathematical model of employee’s state change and testing of the improved model

Application of the classic Hammerstein model for assessing the employee’s body state was complicated because of difficulties of purchasing and introducing a large number of specialized equipment items enabling acquisition, transfer and processing real-time data on the current state of employees of industrial enterprises. Therefore, modification of model (4) was undertaken by reducing to the minimum the number of measurements of the observed employee’s state parameters, that is, immediately before the shift start, expression (5). In addition, for the case of the action of many production factors in the enterprise processes, it was proposed to take into account the effect of not only each individual factor but also the complex effect of all factors, expression (7). As a result of the improvement of the Hammerstein model (4), a mathematical model (8) was obtained. This model allows one to quantify the change in the values of individual parameters of the employee’s body state during the working shift and at the end time point.

The improved model (8) was tested at an industrial enterprise. A team of welders (5 persons) was taken as an example. The test results have shown that the results of applying model (8) were slightly better than the results of direct measurements of the body state parameters considered above. This can be explained by the following:

- a) integral character of model (8) which leads to accumulation of calculation errors;
- b) incomplete information on the results of the complex effect of all factors on

the employee's body; when constructing the model (8), an assumption was made about cumulative nature of such an impact;

c) incomplete information on the nature of recovery of the observed employee's body from effects of production factors (in the calculation of specific types of relations (9) and (10), an assumption was made about the exponential nature of such recovery).

Values of mean absolute deviations for each of the parameters were acceptable.

The use of improved Hammerstein model (8) makes it possible to formalize the work on making managerial decisions concerning advisability of continuing work of a particular employee until any undesirable event appear. For this purpose, it was suggested that the scalar quantity characterizing the person's state shall be determined on the basis of expression (1) and an increase in the value of this quantity will mean worsening of the body state. Based on this assumption, the authors have developed a method of determining an employee's body state based on the results of observations of individual parameters of this body [26]. According to the observation of the parameters considered above, this method makes it possible to attribute the employee's state to one of the following classes: "suitable", "practically suitable", "border state", "not suitable". Application of the improved model (8) makes it possible to abandon use of direct measurement of parameters of the observed employee's state in this method and switch to the use of calculated values of these parameters. As a result, it became possible to automate the decision-making process to ensure professional safety for the company's employees. Therefore, recommendation to withdraw an employee from the production process is accepted in the following cases:

a) if the results of applying the method described in [26] show that the employee's state belongs to the "border state" class for at least two hours during the work shift;

b) if the results of applying the method described in [26] show that the employee's state has passed from the "border state" class to the "not suitable" class.

According to the results given in Table 4, it can be concluded that the employee's body state worsens at the end of the shift. Moreover, the previously made assumption of the possibility of worsening of an employee's health both as a result of the impact of individual production factors on his body and after their joint impact has turned out to be true. However, the quantitative analysis makes it possible to conclude only about improvement or worsening of the employee's state parameters and not about a qualitative change in the employee's body state. In this regard, there is a need to study the dynamics of changes in both the body state parameters of the observed employee and his general body state. At the same time, a quantitative assessment of the general state of the employee's body should be considered the main indicator of occupational safety and health protection at an industrial enterprise as a whole or in its individual processes.

In addition, it is necessary to study models and methods for classifying and interpreting the body state depending on the following factors:

a) the employee age;

b) the employee qualifications;

c) the list of works that are carried out by the employee, and, consequently, the list of production factors affecting the employee's health at a particular workplace.

The main drawback that impedes application of the proposed improved Hammerstein model (8) is the need for preliminary studies to establish a set of acting production factors and then determine specific type of $\omega_1(\tau), \dots, \omega_h(\tau), \dots, \omega_n(\tau)$ functions. To eliminate this drawback, it is proposed to conduct further studies aimed at development of models and methods of determining type of $\omega_1(\tau), \dots, \omega_h(\tau), \dots, \omega_n(\tau)$ functions including use of artificial intelligence.

7. Conclusions

1. The Hammerstein model has been improved which enables the formal description of the change in the body state with n internal parameters as a result of the effect of m external factors varying in time. The essence of this improvement consists of the reduction of the number of measurements of the employee's state parameters and take into account the impact of not only individual production factors but also their joint impact on the employee's body. The improved Hammerstein model makes it possible to predict changes in the body state parameters based on the results of a single measurement of their values immediately before the start of the shift and data on the effect of production factors during the shift.

2. The improved Hammerstein model was tested in the validation of the functional module of labor safety at an enterprise. The use of this model has made it possible to calculate values of the employee's body state parameters during production activities of the enterprise by the end of the shift, namely:

a) an increase in systolic blood pressure from 125 to 132.6 mm of Hg column (the result of direct measurement at the time point of the shift end is 132 mm of Hg column);

b) an increase in the level of diastolic blood pressure from 84 to 88.2 mm Hg column (the result of direct measurement at the time point of the shift end is 88 mm Hg column);

c) an increase in heart rate from 78 to 86.16 bpm (the result of direct measurement at the shift end is 86 bpm);

d) an increase in time to reaction stimulus from 0.4 to 0.698 s (the result of direct measurement at the time point of the shift end is 0.7 s).

Thus, the implementation and application of the improved Hammerstein model enable avoiding or minimizing the enterprise costs associated with employee's disability because of incidents, preserving the professional health of employees and improving the corporate image.

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