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Elaboration of occupational risks evaluation models considering the dynamics of impact of harmful factors

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ABSTRACT

Purpose: Elaborate and substantiate stochastic models of occupational risk evaluation for application in the occupation health and safety.

Design/methodology/approach: Analysis of scientific and technical literature and regulatory framework for risk evaluation in the occupation health and safety; methods of probability theory, theory of Markov processes; methods of restoration theory.

Findings: A system of differential equations and limit conditions for finding the limit distribution of probabilities of a random process of occupational dangers is derived. Based on the results of solving the limit value task, expressions to determine a number of key indicators by which the level of occupational risk can be evaluated are obtained.

Research limitations/implications: The proposed approach aims to evaluation the risk associated with the impact on the employee of harmful factors, but can also be used to evaluate the injury risk. But in this case the received limit value task will be much more difficult.

Practical implications: The application of the proposed approach allows to increase the level of occupational safety by taking into account the stochastic characteristics of the negative factors impact on the employee during occupational risks evaluating, as well as the possibility of setting such values of controllable parameters that will allow with a certain probability to ensure not to exceed the level of impact accumulation in the employee of the consequences of these factors.

Originality/value: Stochastic models of occupational risk evaluation based on the application of Markov drift processes for the modeling the hybrid nature of the negative factors impact on the employee, which occurs within the real systems "man - technical system - production environment" were elaborated and substantiated for the first time.

Keywords: Safety and health management, Markov drift processes, Stochastic models, Risk evaluation, Occupational risk

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INDUSTRIAL MANAGEMENT AND ORGANISATION

1. Introduction

The issue of creating healthy, comfortable and safe working conditions is traditionally considered in the system "man – technical system – production environment" [1,2]. The key element of this system is the employee, because being an object of risk, needs protection from the negative impact of the other two elements. The negative nature of the impact on the employee of the production environment, as well as the technical system can be manifested in two main types of occupational dangers [3,4]: occupational injuries; occupational diseases. Moreover, in both the first and second cases, occupational dangers can be fatal. The issue of occupational injuries, within the research system, can be considered conditionally in terms of the immediate impact on the employee of dangerous production factors. Generally, such impact is exerted by the technical system (equipment), which is due to the violation of the normal modes of its operation and maintenance. Therefore, it may be considered that the negative impact occurs as a result of the failure of the technical system. The issue of occupational diseases, in turn, should be considered in terms of the cumulative effect in the employee of harmful production factors released into the work area during the operation of the technical system.

However, regardless of the object of danger, the negative impact on the employee is inherently dynamic and hybrid, i.e part of the processes can change continuously over time (but with random intensity), and the other part – discreetly, i.e abruptly.

For example, an accident as a result of an employee's violation of occupational safety instructions might occur at a certain random time, and the period of employee's restoration from the consequences of the accident (treatment, rehabilitation) is also random because it depends on the severity of the consequences.

In the case of an example of negative impact on the employee of harmful production factors, which may result in occupational disease, it is necessary to consider the processes of random intensity of impact on the employee of these factors during the work shift and recovery when such impact is absent.

For the mathematical description of the given hybrid processes it is expedient to use a special subclass of Markov processes – so-called Markov drift processes. This type of Markov processes is a flexible mathematical tool for modeling various real processes.

Its advantage is that it contains, in contrast to the classical Markov chains with countable sets of states and continuous time, both discrete and continuous components, which are interconnected by certain relations [3, 5-7]. Markov drift processes are widely used for modeling and optimization of various transport systems, where discrete components describe random volatilities in the length of traffic queues at transshipment points, and continuous – random volatilities in shipment in the warehouse [8,9]. There are also studies on the application of such processes to model various logistics systems operating in conditions of uncertainty and risks [10-12]. However, to model the dynamic characteristics of the hybrid impact on the employee of dangerous and harmful production factors within the systems "man – technical system – production environment", the application of this subclass of Markov processes is not yet known [13-23].

Thus, a method of occupational risks evaluation for the bus driver based on the Risk Score was developed in the study [13]. The positive side of the study can be considered a try to evaluate the occupational risk taking into account the intensity of the impact on the employee of negative factors. But the random, dynamic nature of this impact was not taken into account by researchers, which significantly reduces the objectivity of the results and methods in general. A simplified method of occupational risks evaluation during the use of toxic nanomaterials was proposed by the authors [14]. The developed risk maps allow only analyzing the risks simplified, but do not allow obtaining objective quantitative evaluation results. In [15], a method of risk evaluation based on the use of the Monte Carlo method was proposed by the authors. The positive side of the study is the ability to take into account the stochastic characteristics of failures of production equipment, which can lead to danger occurrence. However, this method does not allow modeling the stochastic characteristics of impact on an employee of harmful factors of the work area and does not take into account the severity of the consequences of the risk implementation to danger, which does not allow using it for a comprehensive evaluation of occupational dangers. The work [16] is devoted to the description and analysis of known methods of danger evaluation including Markov methods of analysis. However, these methods are presented in an elementary interpretation, when only the numerous set of states of the research system and continuous time are considered. In the study [17] a method of risk evaluation during the release of harmful substances into the environment was developed. The positive side of the study is the ability to take into account the severity of the consequences of danger, but at the same time to take into account the randomness of its occurrence and the dynamic characteristics of impact on employee of harmful substances is impossible. The work [18] is devoted to the analysis of risks of occupational dangers occurrence by using the method of analytical hierarchies. The proposed approach allows determining the most important causes of dangers occurrence, but does not allow determining the probability of their occurrence and severity of consequences, which makes it impossible to use it to predict risks. The works [19,20] are devoted to the application of information-analytical system for risk evaluation, whose the algorithm is based on the setting quantitative characteristics of occupational risk on the basis of the constructed mathematical model. For data processing during risk evaluation, the usual methods of statistical analysis, which should be used only in the presence of a large amount of certain arrays of statistical data, which is not always possible, are used. In addition, this approach allows to evaluate only certain occupational risks without taking into account the dynamic characteristics of the random impact of negative factors on the employee, which are always within real systems "man – machine – environment". The main disadvantage of the study [21] is consideration only the consequences of failures of the technical system, which are associated with erroneous actions of employees during the risk evaluation. In this case, the impact of harmful factors on the employee as risks from the technological equipment is not taken into account by researchers. In addition, the random nature of equipment failures is not taken into account, which significantly reduces the objectivity of the results of the proposed risk evaluation approach. In the study [22] the conceptual vision of the authors concerning the development of risk management principles is presented. However, among the described perspective trends the need to take into account the dynamic characteristics of the random impact on the employee of negative factors, which is always during the functioning of real systems "man – machine – environment", was not identified by the authors. The study [23] a mathematical model for risk evaluation using statistical analysis methods was developed. These methods do not take into account the hybrid nature of the random impact of negative factors on the employee, and therefore can not provide objective results. In addition, the limited sample of input data does not allow us to recommend the proposed model for risk evaluation in enterprises in different industries.

The set of international legal documents on risk management in methods of their analysis only contains a special guiding standard for the application of Markov methods in the relevant field (risk management) (IEC 61165:2006 Application of Markov techniques). The sphere of application of this standard is exclusively in the field of analysis of the reliability of technical systems, which could be considered the first disadvantage of its use for analysis and risks evaluation of occupational dangers origin in systems "man – technical system – production environment". Within the standard, the consideration of only two its states – working or non-working is provided for the analysis of reliability of technical systems. This formulation of the problem is elementary and, accordingly, cannot be applied to an objective analysis of the characteristics of the functioning of the research system elements in the occupational health and safety, which is the second disadvantage.

The next, third disadvantage, is the warning about the constancy in time of failures and restorations of elements of research systems, which does not meet the certain requirements of building a stochastic model of occupational risk evaluation. Therefore, given the hybrid nature of the impact of dangerous and harmful production factors (negative factors) on the employee and the lack of the necessary methodological tools for its objective research, it is necessary to elaborate and analyze the stochastic models to objectively occupational risks evaluation.

2. Materials and methods

Within the presented research the following set of scientific methods was used: analysis of scientific and technical literature and legal framework on risk evaluation in the occupation health and safety – to update and formulate the scientific problem; methods of probability theory, theory of Markov processes – to find the limit probability and derive the basic system of differential equations in partial derivatives and the corresponding limit conditions, as well as elaborate the stochastic models for occupational risks evaluation; methods of restoration theory – to determine the conditions for the existence of a steady state of the research process.

3. Results and discussion

As a prerequisite for the formalization of the procedure of occupational risk evaluation it should be considered that during the work shift the employee is negatively affected by a certain harmful production factor that occurs during the operation of certain production equipment. As a result of negative impact on employee there is an accumulation of negative impact from action of the specified harmful production factor. This factor can be any factor of the environment or production process, whose impact under certain conditions can cause occupational disease, reduced ability and other negative consequences.

Also it should be considered that the duration of working and non-working time is mutually independent random variables with distribution functions $A_0(t)$ and $A_1(t)$, respectively. That is, changes in working and non-working times form an alternating restoration process. Address the real production process, when during working time production equipment releases into the work area certain harmful production factors with an intensity W, which in turn accumulate in the employee.

Production equipment can fail at random times and restore during random period of time, also with different statistical characteristics in working and non-working times. At the same time, two types of equipment failures, namely: the first type, when equipment failure does not affect the health of the employee, and the second type, when any deviations from the normal mode of operation of production equipment lead to injury to the employee would be addressed.

It should be considered that in a short interval of time $(t,t+\Delta t)$, equipment failure could occur with probability $\lambda_0\Delta t+0(\Delta t)$ during working time and with probability $\lambda_1\Delta t+0(\Delta t)$ during non-working time, regardless of previous failures. After failure the equipment begins to be restored (repaired) immediately, and the duration of repairs during working and non-working times is distributed according to the exponential law with parameters μ_0 and, μ_1 accordingly.

During non-working time the negative impact of harmful production factors released by production equipment is removed from the employee - with an intensity $U < W$.

Also another real production situation, when as a result of the failure of the second type, the employee during the work shift might receive an industrial injury of varying severity would be addressed. Moreover, in a short interval of time $(t,t+\Delta t)$, the injury could occur with probability $\alpha\Delta t+0(\Delta t)$, regardless of previous injuries. During an occupational injury, the employee loses ability to work for a certain period of time, which is conditionally equal to the time of his treatment and rehabilitation. This period of time is also distributed according to the exponential law with the parameter β $(1/\beta$ – verage duration of treatment and rehabilitation).

Therefore, the described situations allow for consideration of the failure of production equipment of the following two types:

- failure that did not lead to an accident (injury) of the employee (failure of the first type);
- failure that led to an accident (injury) of the employee (failure of the second type).

During the restoration process of production equipment, after the failure of the first type, the functional systems of the employee's body are restored without consequences of the negative impact of harmful production factors that occurred during the equipment operation. This restoration occurs with a certain intensity U.

And during the treatment and rehabilitation of the employee, in addition to restoration from injury, there is also the restoration of the functional systems of body from the negative impact of harmful production factors that occured during the working time. This restoration occurs with an intensity U_1. Upon completion of the treatment and rehabilitation procedures, the employee gets to work.

For a formalized description of the research process, the following notations were introduced:

- $\alpha(t)$ – variable that describes the employment state of the employee during the work shift ($\alpha(t)=1$) and during non-working time ($\alpha(t)=0$) at time t;
- $\gamma(t)$ – variable that describes the efficiency state of production equipment and the employee. $\gamma(t)=0$, if at time t the production equipment is functional and the employee is not injured, $\gamma(t)=1$, if at time t the production equipment is nonfunctional and the employee is not injured; $\gamma(t)=2$, if equipment failure, which resulted in injury to the employee.
- $\xi(t)$ – the accumulation level of the negative impact of harmful production factors in the employee at time t.

From the above assumptions and notations, the process of accumulation of negative effects of harmful production factors in the employee can be described by the following differential equation (with probability 1):

$$\xi'(t) = WI(\alpha(t)=1,\gamma(t)=0) - UI(\alpha(t)=1,\gamma(t)\neq 2,\xi(t)>0) - \\ -U_1 I(\alpha(t)=0,\gamma(t)=2,\xi(t)>0), \qquad (1)$$

where $I(A)$ –indicator of event A.

That is, the task consists in finding the distribution of a random vector $(\xi(t),\ \alpha(t),\ \gamma(t))$. This process is not Markov one at arbitrary distribution functions $A_i(t)$, i=0,1. However, if an additional continuous component $\eta(t)$ – the remaining time from time t to change the alternating process state (a process that describes the change of working and non-working time of the employee) will be added, the process becomes Markov one. Therefore, in the future the random Markov process will be operated

$$\Xi(t) = (\xi(t),\alpha(t),\gamma(t),\eta(t)). \qquad (2)$$

To find the probability distribution (2), a system of differential equations and limit conditions concerning the probability distribution of process (2) should be derived and solved. Characteristics of the states of this Markov drift process, which describes the dynamics of the system "man – machine – environment" are given in Table 1.

Table 1.
Characteristics of the states of Markov drift process

α(t)	*γ(t)*	The intensity of the accumulation of the negative impact of the harmful production factor in the employee	Intensity of elimination derivation of consequences of negative impact of a harmful production factor from the employee	States of the Markov process at a nonzero parameter value *ξ(t)*
0	0	0	U	1
1	0	W	U	2
0	1	0	U	3
1	1	0	U	4
1	2	0	U_1	5

Note:
State 1 – the employee is outside the workplace at time *t* (work shift is over), the equipment is functional and disconnected. Accumulation of negative impact from the factors does not occur ($W = 0$), but the consequences of negative impact are eliminated from the employee with intensity *U*.
State 2 – the employee is at work at time *t* (work shift), not injured, equipment is functional and working. The accumulation of negative impact occurs with intensity *W*, and the elimination of consequences of impact occurs with intensity *U*.
State 3 – the employee is outside the workplace at time *t* (work shift is over); there was the equipment failure of the first type. The equipment is in restoration state, the accumulation of negative impact in the body does not occur; the consequences of the accumulation of impact are eliminated with intensity *U*.
State 4 – the employee is at work (work shift), there was the equipment failure of the first type. The equipment is in restoration state, the accumulation of negative impact in the body does not occur; the consequences of the accumulation of impact are eliminated with intensity *U*.
State 5 – the employee suffered injuries as a result of equipment failure of the second type at time *t*, equipment is in restoration state. The negative consequences of the accumulation of impact of harmful factors (industrial factors) are eliminated with intensity U_1.

Knowing the stationary distribution of the Markov process (2), a number of important indicators could be quantified, namely:

- the probability of an employee's industrial injury, taking into account its severity, which could be characterized by the duration of treatment and rehabilitation;
- the average level of accumulation of negative impact from the action of harmful production factors in the employee $\mathbf{M}\xi = \lim_{t\to\infty} \mathbf{M}\xi(t)$;
- the probability of not exceeding the level of accumulation of negative impact from the action of harmful production factors in the employee of a given critical value σ (hygienic standard), ie

$$\lim_{t\to\infty} \mathbf{P}\{\xi(t) \le \sigma\}. \quad (3)$$

In the above notation to formalize the process of occupational risks evaluation, the parameters *W* – intensity of accumulation of the negative impact of harmful production factors and *U* – intensity of elimination the consequences of the negative impact of harmful production factors from the employee's body that could be considered controlled were formulated. In fact, *W* and *U* depend on other controlled parameters, which are managed through the implementation of organizational, technical, treatment and prevention and other activities and safety means in the workplace. That is, the task of finding such parameters *W* and *U*, which with a high probability enforce the condition could be formulated (see (3)).

$$\xi(t) \le \sigma. \quad (4)$$

Mathematically this condition is as follows:

$$\lim_{t\to\infty} \mathbf{P}\{\xi(t)) \le \sigma\} > 1-\varepsilon,$$

where *ε* – a given small probability (risk criterion).

A more complex formulation of the task is to find such parameters *W* and *U*, at which the time, when the process *ξ(t)* achieve the level σ will be large enough.

In practical terms, to predict the probability of occupational dangers origin the consideration of two cases is of interest [24,25]. The first one is finding the limit distribution of probabilities of a random process of impact on the employee of harmful production factors. The second one is more general and complex, which consists in finding the limit distribution of probabilities of the random process of impact on the employee of harmful and dangerous (due to the failure of production equipment of the second type) production factors.

For a mathematical description of this random process, the following random variables are introduced:

- $\eta(t)$ – the time that had elapsed since the end of the work shift to the time t;
- $\alpha(t)$ – a variable that takes two values: 1 – if at time t is working time and 0 – otherwise;
- $\gamma(t)$ – a variable that takes two values: 0 – if at time t the equipment is functional and 1 – otherwise;
- $\xi(t)$ – the level of accumulation of harmful factors in the employee at time t.

The probability densities that characterize the dynamics of a random process are also introduced $\Xi(t)=(\xi(t),\alpha(t),\gamma(t),\eta(t))$:

$$\mathbf{P}\{\alpha(t)=i,\gamma(t)=k,\tau<\eta(t)<\tau+d\tau,x<\xi(t)<x+dx\}=$$
$$=q_{ik}(x,\tau,t)(1-A_i(\tau))d\tau dx, i=0,1;k=0,1;x>0,\tau>0,$$

$$\mathbf{P}\{\alpha(t)=0,\gamma(t)=0,\tau<\eta(t)<\tau+d\tau,\xi(t)=0\}=$$
$$=q_{\overline{00}}(\tau,t)(1-A_0(\tau))d\tau,\tau>0,$$

$$\mathbf{P}\{\alpha(t)=i,\gamma(t)=1,\tau<\eta(t)<\tau+d\tau,\xi(t)=0\}=$$
$$=q_{\overline{i1}}(\tau,t)(1-A_i(\tau))d\tau, i=0,1;\tau>0.$$

where τ – the time that had elapsed since the beginning of the work shift (from the beginning of the non-working period) to the time t; x – the amount of harmful substances in the employee at time t; q – the density of the probability of joint distribution of the amount of harmful substances and the time remaining before the change of the alternating process; i та k – are discrete variables describing the values of the variables α and γ, respectively, at time t.

For practical use, it is sufficient to find the limit (when t→∞) distributing the introduced random process, namely:

$$\begin{aligned}
&q_{ik}(x,\tau)=\lim_{t\to\infty} q_{ik}(x,\tau,t), i=0,1;k=0,1,\\
&q_{\overline{00}}(\tau)=\lim_{t\to\infty} q_{\overline{00}}(\tau,t),\\
&q_{\overline{i1}}(\tau)=\lim_{t\to\infty} q_{\overline{i1}}(\tau,t), i=0,1.
\end{aligned} \quad (5)$$

Using standard probabilistic reflections based on considering the transitions of the Markov process from one state to another in a short period of time, as well as applying the total probability formula to find the introduced limit probabilities (5), the following system of differential equations in partial derivatives and corresponding limit conditions is derived [26-28]:

Basic system of differential equations:

$$\begin{aligned}
&(-U\frac{\partial}{\partial x}+\frac{\partial}{\partial\tau})q_{00}(x,\tau)=-\lambda_0 q_{00}(x,\tau)+\mu_0 q_{01}(x,\tau),\\
&(-U\frac{\partial}{\partial x}+\frac{\partial}{\partial\tau})q_{01}(x,\tau)=-\mu_0 q_{01}(x,\tau)+\lambda_0 q_{00}(x,\tau), x>0,\tau>0,
\end{aligned} \quad (6)$$

$$\begin{aligned}
&(V\frac{\partial}{\partial x}+\frac{\partial}{\partial\tau})q_{10}(x,\tau)=-\lambda_1 q_{10}(x,\tau)+\mu_1 q_{11}(x,\tau),\\
&(-U\frac{\partial}{\partial x}+\frac{\partial}{\partial\tau})q_{11}(x,\tau)=-\mu_1 q_{11}(x,\tau)+\lambda_1 q_{10}(x,\tau), x>0,\tau>0,
\end{aligned} \quad (7)$$

where $V= W - U$ – the intensity of the accumulation of negative impact in the employee from the action of harmful factors; λ_0 and λ_1 – intensity of equipment failure flow in non-working and working times of time, respectively; μ_0 and μ_1 – the intensity of the flow of the employee's restoration (during non-working and working times, respectively).

Limit conditions describing the working state (functional or not) of the equipment and the state of the employee during working and non-working times:

$$\begin{aligned}
&\frac{d}{d\tau}q_{\overline{00}}(\tau)-Uq_{00}(0,\tau)=-\lambda_0 q_{\overline{00}}(\tau)+\mu_0 q_{\overline{01}}(\tau),\\
&\frac{d}{d\tau}q_{\overline{01}}(\tau)-Uq_{01}(0,\tau)=\lambda_0 q_{\overline{00}}(\tau)-\mu_0 q_{\overline{01}}(\tau),\\
&\frac{d}{d\tau}q_{\overline{11}}(\tau)-Uq_{11}(0,\tau)=-\mu_1 q_{\overline{11}}(\tau),\tau>0;
\end{aligned} \quad (8)$$

Limit conditions describing the change working and non-working times:

$$\begin{aligned}
&q_{00}(x,0)=\int_0^\infty q_{10}(x,\tau)dA_1(\tau),\\
&q_{01}(x,0)=\int_0^\infty q_{11}(x,\tau)dA_1(\tau),\\
&q_{10}(x,0)=\int_0^\infty q_{00}(x,\tau)dA_0(\tau),\\
&q_{11}(x,0)=\int_0^\infty q_{01}(x,\tau)dA_0(\tau);
\end{aligned} \quad (9)$$

$$q_{01}^{-}(0)=\int_{0}^{\infty} q_{11}^{-}(\tau)dA_1(\tau),$$
$$q_{11}^{-}(0)=\int_{0}^{\infty} q_{01}^{-}(\tau)dA_0(\tau), \quad (10)$$
$$q_{00}^{-}(0)=0;$$

Limit conditions describing the transition of the employee from a state of zero accumulation of negative impact from the action of a harmful production factor to a state, when the accumulation begins again (production state):

$$V\int_{0}^{\infty} q_{10}(0,\tau)(1-A_1(\tau))d\tau=\mu_1\int_{0}^{\infty} q_{11}^{-}(\tau)(1-A_1(\tau))d\tau; \quad (11)$$

Condition of normalization:

$$\int_{0}^{\infty}(q_{00}^{-}(\tau)+q_{01}^{-}(\tau))(1-A_0(\tau))d\tau+\int_{0}^{\infty} q_{11}^{-}(\tau)(1-A_1(\tau))d\tau+$$
$$+\int_{0}^{\infty}\int_{0}^{\infty}[(q_{00}(x,\tau)+q_{01}(x,\tau))(1-A_0(\tau))+ \quad (12)$$
$$+(q_{10}(x,\tau)+q_{11}(x,\tau)(1-A_1(\tau))]d\tau=1.$$

Thus, as a result of solving problems (6)-(12) it is possible to determine a number of important indicators for occupational risk evaluation. Namely:

- the probability of exceeding the level of accumulation of negative impact from the action of harmful factors of the established hygienic standards – σ, ie the expression

$$\int_{\sigma}^{\infty}\int_{0}^{\infty}[(q_{00}(x,\tau)+q_{01}(x,\tau))(1-A_0(\tau))+ \quad (13)$$
$$+(q_{10}(x,\tau)+q_{11}(x,\tau)(1-A_1(\tau))]d\tau dx;$$

- the probability that in a random period of time the consequences of the negative impact of harmful production factors in the employee are absent

$$\int_{0}^{\infty}(q_{00}^{-}(\tau)+q_{01}^{-}(\tau))(1-A_0(\tau))d\tau+\int_{0}^{\infty} q_{11}^{-}(\tau)(1-A_1(\tau))d\tau; \quad (14)$$

- the average level of accumulation in the employee of the negative impact of the harmful production factor

$$\mathbf{M}\xi=\int_{0}^{\infty} x\int_{0}^{\infty}[(q_{00}(x,\tau)+q_{01}(x,\tau))(1-A_0(\tau))+ \quad (15)$$
$$+(q_{10}(x,\tau)+q_{11}(x,\tau)(1-A_1(\tau))]d\tau dx.$$

In this case, the controlled parameters are the intensity of the release of harmful substances into the work area (as well as the intensity of their accumulation in the employee) W, as well as the intensity of their elimination from theemployee U. Using the elaborated models, it is possible to select the levels of controlled parameters so that the accumulation of negative impact from the action of harmful production factors in the employee did not exceed the established hygienic standard with a sufficiently high probability close to (13).

For arbitrary distribution functions $A_i(t), i=0,1$ the solution of the limit value task (6)-(12) is a complex mathematical problem. In some, certain cases, for example, if the equipment can fail only during its operation (i.e. when $\lambda_0=\mu_0=0$), it can be solved analytically, by reduction it to a system of integral equations of the type of convolution on the semi-axis. However, in practice, working and non-working times are fixed. Therefore, in our case, the distribution functions are:

$$A_i(t)=\begin{cases}0, 0\le t\le T_i\\ 1, t>T_i\end{cases}$$

Moreover, $T_0>T_1$ ie the duration of the work shift is less than the non-working time.

An important point for this model is the condition of the existence of a stable (or statistically equilibrium) mode of the experimental process of fluctuations in the level of accumulation of negative impact from the action of harmful production factors in the employee. The general meaning of this condition is that for a long time the level of accumulation will not reach critical values for the life and health of the employee. That is, according to this condition, the average intensity of the negative impact from the action of the harmful production factor on the employee must be less than the average intensity of the elimination of consequences of such impact from the body. Compliance with this condition in practice should be achieved through the elaboration and establishment of rational modes of work and rest for employees' workplaces and other occupational health and safety measures. In mathematical form, the necessary condition of the mode of the research process is:

$$Wp_{10}<U$$

where $$p_{10}=\int_{0}^{\infty}\int_{0}^{\infty} q_{10}(\tau,x)(1-A_1(\tau))d\tau dx.$$

Using the methods of restoration theory, it is possible to calculate the probability p_{10}:

$$p_{10} = \frac{\alpha_1 \mu}{(\alpha_1 + \alpha_2)(\lambda + \mu)},$$

where $\alpha_i = \int_0^\infty (1 - A_i(\tau)) d\tau < \infty, i = 0,1$ – average values of the duration of working and non-working times.

Taking into account the given equation, the above condition for the existence of a stable mode of the experimental process is:

$$\frac{\alpha_1 \mu}{(\alpha_1 + \alpha_2)(\lambda + \mu)} < \frac{U}{W}.$$

So, in the future, this condition is deemed fulfilled.

This approach can also be used to evaluate the risk level of occupational injury with certain consequences. But in this case the received limit value task will be much more difficult. In the general case, the practical implementation of the process of occupational risks evaluation to obtain the necessary quantitative results can be done by numerically solving a system of differential equations and limit conditions in special computer software packages, such as Matlab or analytically. In the latter case, for example, the solution of the limit value task for a system of differential equations can be found in the Laplace transform for the case of the Erlang distribution of working and non-working times.

4. Conclusions

The results of research leads to the following conclusions:

1. It is established that the task of occupational risks evaluation is to find the distribution of a random vector with variables describing the state of employment of the employee over time, the efficiency of the employee and production equipment at a certain time, and the level of accumulation of negative impact in employee from action of the harmful production factors over time. It is noted that when a component that characterizes the time remaining from the moment *t* until the change of state of the alternating process is introduced, the process becomes Markov.
2. The characteristics of four possible states of the Markov process for systems "man - technical system - production environment" are determined and given. The main controlled parameters that impact on the level of safety of the employee, namely, the intensity of harmful substances release into the work area *W*, as well as the intensity of their elimination from the employee *U* are set. These parameters can be selected in such a way that to minimize the probability of exceeding the level of accumulation in the employee negative impact from action of a harmful production factor of the established normalized values.
3. In order to find the limit distribution of probabilities of a random process of negative impact on the employee of harmful production factors, the system of basic differential equations and the corresponding limiting conditions are derived. Based on the results of solving the limit value task, expressions to determine a number of key indicators, in which the level of occupational risk can be evaluated are obtained:
   - the probability of exceeding the level of accumulation of negative impact from the action of harmful factors of the established hygienic standards;
   - the probability that in a random period of time the consequences of the negative impact of harmful production factors in the employee are absent;
   - the average level of accumulation in the employee of the negative impact of the harmful production factor.

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