DOI: 10.5604/01.3001.0054.6152
Volume 123 • Issue 2 • April 2024
Journal of Achievements in Materials and Manufacturing Engineering
International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Stochastic models of risk management of worker fatigue emergence

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ABSTRACT

Purpose: The purpose of the paper is to develop stochastic models for managing the risk of fatigue in an organisation, taking into account the intensity of the negative impact of fatigue factors on workers at the workplace and the intensity of their recovery from such an impact.

Design/methodology/approach: It uses the method of analysis of scientific literature to actualise the purpose and define the research tasks; Markov process theory methods are used for mathematical description of random processes of worker fatigue development and their recovery from it during a work shift; methods of probability theory and queuing are used to find the limiting probability distribution of random Markov process' states.

Findings: The proposed stochastic models allow the organisation to carry out the process of managing the risk of fatigue emergence by changing the work-rest schedule's duration, depending on the parameters' characteristics of the negative impact intensity of fatigue factors on workers and the recovery of their corpora from such an impact. By changing the specified parameters' characteristics, it is possible to determine the work schedule during which the period of worker's fatigue will be as long as possible and the rest schedule during which the period of recovery from the fatigue state will be minimal.

Practical implications: The application of the proposed models makes it possible to increase the level of labour productivity in the organisation by determining such durations of work and rest schedules, which provide the opportunity for workers to carry out labour activities during the maximum possible period of time of the work shift, without reaching a fatigued state.

Originality/value: For the first time, an approach for managing the fatigue risk is proposed by establishing dependencies between the duration of work and rest schedule and the parameters' characteristics of the negative impact intensity of the fatigue factors on the worker and their recovery from such an impact, based on the application of the Markov processes theory.

Keywords: Health and safety, State fatigue, Work-rest schedule, Fatigue factor, Professional risk

Reference to this paper should be given in the following way:

A.P. Bochkovskyi, N.Yu. Sapozhnikova, Stochastic models of risk management of worker fatigue emergence, Journal of Achievements in Materials and Manufacturing Engineering 123/2 (2024) 72-85. DOI: https://doi.org/10.5604/01.3001.0054.6152

INDUSTRIAL MANAGEMENT AND ORGANISATION

1. Introduction

One of the main tasks of the operation of occupational health and safety management systems at enterprises, in institutions and organisations (hereinafter organisations) is to ensure the safety and health of workers, as well as to maintain a high level of their work capacity (level of labour productivity) throughout the entire work shift. The solution to these tasks lies in the development of a system of labour protection measures and tools that can effectively minimise both the risk of accidents, occupational diseases, industrial accidents and catastrophes (hereinafter incidents) and fatigue risk, which reduces labour productivity and causes most of the specified incidents [1,2].

For example, according to the data analysis on the causes of accidents and industrial accidents carried out in the research [3], it was established that 67.1% of the incidents' causes are manifestations of the "human factor", which, in turn, arose as a result of the workers' fatigue emergence. In certain spheres of activity (aviation, transport, etc.), the percentage of these incidents' causes (due to fatigue) is even higher and ranges from 70% to 90% [1, 3-6].

Therefore, the analysis results of the fatigue emergence causes, given by the International Labor Organization (ILO), as well as other researchers, indicate that the workers' fatigue state develops and occurs as a result of violation or absence of work and rest schedule (WRS) in the organisation. As follows, as a result of overtime work, increased durations of work schedule during the work shift, insufficient duration and quantity of rest schedule, inconsistency of WRS with human biological rhythms, as well as work under conditions of increased stress [7-9].

A joint global study by the ILO and the World Health Organization (WHO), as well as the results of other research, showed that fatigue development and onset as a result of improperly organised work and rest schedule is also the main cause of a number of occupational diseases that today, by the number of cases, occupy the first places in the world (cardiovascular diseases (stroke, etc.), diseases of the musculoskeletal system, nervous system, etc.) [1,2,9,10].

In addition, the problem of the lack of proper WRS in organisations leads to significant annual economic losses due to a decrease in the level of labour productivity, even in economically developed countries. For example, in Australia, which is one of the most advanced countries in the world in the field of continuous improvement of psychosocial measures for occupational safety and health, the annual average economic losses from a decrease in labour productivity due to the development and onset of fatigue in employees are about 27% [2].

This problem is strengthened by the fact that, according to the ILO data, 39% of workers in the world work overtime and up to 41% in conditions of increased stress, which significantly intensifies the development and onset of fatigue in workers [11,12]. At the same time, according to survey data of both employers and employees, more than 90% of enterprises in the world do not implement any measures to improve the specified working conditions [11,12].

In most cases, the situation is caused not so much by the negligence or irresponsibility of business entities but by the lack of effective approaches to determining the WRS duration, which they could use in organisations to manage the fatigue risk among employees, since the demand for the use of such approaches among employers is, which, in particular, is emphasized in the research [13].

The problem of implementing the management of fatigue risk among employees can be conventionally divided into two interrelated directions. The first of them relates to the development of WRS quantitative characteristics (determination of quantitative characteristics of the WRS duration and periodicity during a work shift). The second is the development of qualitative characteristics of such schedules (characteristics of active or passive rest, nomenclature and norms of consumption of functional food products, etc.) [14,15].

The first direction (i.e., the development of WRS quantitative characteristics) is the most important one, which primarily involves setting certain time limits for the WRS duration for each professional group of employees, compliance with which does not allow an employee to be fatigued at the workplace. However, when determining the durations, the WRS qualitative characteristics must also be considered [13,16]. Taking the characteristics into account is necessary in view of the fact that they can intensify the processes of recovery of the employee's body from the fatigue effects (during the rest period) and, thus, reduce the duration of the rest period, as well as increase the resistance of the employee's body to the accumulation of such effects during the work schedule duration and, as a result, extend its duration [13,17]. The introduction of WRS quantitative and qualitative characteristics in the workplace is aimed mainly at achieving and maintaining a high level of productivity and safety during a work shift (by preventing the occurrence of fatigue in employees), which, in turn, allows to increase the economic efficiency of the organisation, due to the rational organisation of the employee's working time and maintaining their physiological capabilities to perform their professional duties effectively and safely.

Thus, the simultaneous application of measures to implement these areas allows the organization to manage the risk of fatigue (to prevent incidents and maintain a high level of labour productivity during a work shift) by managing the WRS duration at workplaces, namely, by establishing the maximum possible work duration and the minimum possible duration of rest schedules which should exclude the fact that an employee is in a fatigue state during a work shift.

Based on this, it is obvious that in order to be able to manage this risk, the organization must have the practical ability to determine the WRS quantitative characteristics, taking into account the objective (stochastic) characteristics of the processes of fatigue development in an employee and recovery of their body from such a state during a work shift [18]. Both the possibility and effectiveness of managing the process of the fatigue risk and, accordingly, the level of safety and productivity in the organisation depends on the possibility of taking such characteristics into account.

2. Literature review

To determine the WRS quantitative characteristics of the duration, today, approaches are mainly used that are based on experimental studies of the physiological ability of an employee to perform professional duties for a certain period of time (within the work schedule) before the onset of fatigue. As well as determining the ability of the employee's body to recover from such a state within a certain (shorter) period within the framework of the rest schedule (taking into account its qualitative characteristics) [19]. The completion moment of the work schedule is determined according to the results of measuring the physiological indicators of the employee's body (the state of the nervous, respiratory, and cardiovascular system, depending on the method used) or by using methods for assessing subjective well-being (Samn-Perelli Fatigue Scale, Chalder Fatigue Scale, etc.) at the time when the employee has reached the specified fatigue state [20,21]. Accordingly, the completion moment of the rest schedule is determined by the time the employee recovers from fatigue. The state of recovery of the employee's body from fatigue was also determined using the above methods.

It is clear that both the processes of fatigue development and recovery from fatigue in each employee are purely individual and depend on many factors (age, phenotype, genetic, etc.) inherent in each person. In addition, the dynamics of these processes are also affected by negative factors of the labour process or fatigue factors (FF), which are also individual for each workplace. It is obvious that the time characteristics of fatigue onset processes and recovery from such a state are also different for each employee of a joint professional group.

For the possibility of taking into account such factors during the WRS development, the studies are conducted within the framework of sufficiently large control groups of workers of the same profession (1000 people or more), which are formed from workers of different ages, health conditions, etc. [13]. Based on the research results, data are collected on the physiological ability of each employee (from the control group) to work for a certain period before the fatigue onset and the period of time during which each employee recovered from this condition. The data collected for each employee (regarding WRS individual durations) are processed using statistical analysis methods. Based on the results of such processing, recommendations are formed for establishing quantitative characteristics of the WRS duration for employees of a certain professional group, which, in fact are recommendations for the WRS duration for the average employee of a certain profession. The results obtained by processing data on employees of such a large research group can provide a sufficiently objective result for the average employee. Still, it is not always possible to collect such a group and organise its research process [22,23].

In order to eliminate the shortcomings, the vast majority of modern researchers determine the WRS characteristics by studying small control groups of employees (10-20 people) [24-26]. To increase the objectivity of the results obtained during data processing (obtained from small control groups), mathematical methods such as scenario analysis, fuzzy logic methods, Monte Carlo method, hierarchy analysis, etc. are used [24,25,27]. As in the previous approach, the results are used as recommendations for establishing the WRS duration for the average employee of a particular occupational group.

It should be noted that current regulations in most countries (which contain recommendations on the frequency and WRS duration for workers in certain professions) are based on the results of this research. However, due to the fact that the recommendations are developed specifically for the average worker, their effectiveness in preventing the development and onset of fatigue in a real worker (i.e., at the individual level), in most cases, is insufficient [2,28].

This is explained by the specified recommendations. However, they take into account certain objective factors that affect the development and fatigue onset in an employee (age, genetic, phenotypic, etc.) but do not take into account the FF inherent in a certain workplace (primarily psychophysiological (stress) factors) that can significantly intensify the onset of such a condition. Therefore, in most cases, the use of this approach leads to the fact that the worker (in real production conditions) continues to be in the work mode, even after the moment when the fatigue state has already set in, which is a significant drawback [2].

In addition, since the WRS characteristics (within the framework of the above-mentioned approaches) are determined, generally speaking, by the usual timing of the work shift of an average employee, recommendations (or standards, depending on the legislation requirements of a particular state) regarding the periods of their duration are always static in time. That is, during a work shift, an employee of a certain profession (regardless of their individual characteristics and corresponding characteristics of their workplace) must, for example, be on the work schedule for 2 hours and then rest for 15 minutes, then again two hours of work and the indicated duration of rest, and so occurs throughout the work shift.

Such recommendations not only, in certain cases (if we are talking about their normative nature), legally restrict the employer from implementing measures to optimise the WRS at the workplaces where they turned out to be ineffective or insufficient (in particular, due to the inconsistency of the WRS qualitative characteristics, which were taken into account during the development of recommendations for working conditions at such workplaces), but actually make it impossible to implement the process of managing the fatigue risk in the organization, which, accordingly, negatively affects both the safety level and the labour productivity level in the organisation, which is also a significant drawback of the above-mentioned approaches to the WRS development [2,29].

In order to eliminate the mentioned shortcomings and in order to more effectively prevent the occurrence of incidents caused by the fatigue onset among employees at workplaces, as well as to increase the labour productivity level, the researchers proposed to apply in organisations a systematic approach to managing the risks of fatigue occurrence – Fatigue Risk Management System (FRMS) [30,31]. As noted, the FRMS system is more effective in comparison with the above-mentioned approaches to RPV development and with alternative systems for managing relevant risks, for example, with the AMOC (Alternative Method of Compliance) system [32]. The efficiency of the FRMS system, in this case, is achieved due to the fact that within its framework, the quantitative characteristics of the WRS duration are supposed to be determined based on finding the probability characteristics of fatigue onset for each specific employee at the end of the work schedules (taking into account the NFs that make a negative impact on the employee at the workplace). It also finds the appropriate characteristics of the recovery of their body from the consequences of such a condition at the end of rest schedules. This is due to the application of an individual risk-oriented approach to WRS development in the organisation [33].

Therefore, the main advantage of FRMS is the individuality of the approach to determining the WRS characteristics, which, unlike others, allows to exclude with a sufficiently high probability the fact that an employee is in the workplace (during the work shift duration) in a fatigue state. In addition, applying the probabilistic approach allows the modelling of the WRS quantitative characteristics depending on the changes in the WRS qualitative characteristics (which cannot be carried out within the framework of the traditional approaches analyzed above).

Considering the progressivity of the mentioned system, countries such as France, Canada, etc., have already begun to implement it to manage fatigue risks in organisations at the state level [34,35].

However, it should be noted that the FRMS system is currently being implemented in practice only for a few occupations, mainly for occupations in civil aviation. It is due to the fact that for such professions, researchers have developed both approaches to the identification and FF monitoring, which affect the development and fatigue onset in workers, and approaches to determine the WRS quantitative characteristics [36,37]. At the same time, the approaches cannot be considered perfect due to the fact that they do not yet allow us to assess the objective (stochastic) characteristics of the fatigue development process (which is due to the negative impact on the employee of the corresponding FF) when determining the WRS quantitative characteristics, because, in their essence, they are expert, that is, subjective [38].

To manage the fatigue risk in workers of other professions, the use of the FRMS system is still limited, primarily due to the lack of objective probabilistic approaches to determine the WRS quantitative characteristics [8,39].

Realising the need to apply the FRMS system to professions where the incidents' causes, as well as in aviation, are primarily due to the fatigue onset in the employee (medical professionals, emergency services, road operators, etc.), researchers are currently developing appropriate recommendations for its implementation in the relevant areas of activity to manage the fatigue risk. However, so far, such recommendations mainly relate to developing FF identification and monitoring approaches. Instead, research on the development of approaches to determine the WRS quantitative characteristics is still at an early stage [7,40,41].

Thus, as can be seen, there is an urgent scientific and practical problem of developing approaches to determine the quantitative characteristics of the WRS duration, taking into account the random characteristics of fatigue development (accumulation of consequences) during the work schedule and the recovery of the employee from such consequences during rest schedules, which could be used to manage the fatigue risk to ensure the possibility of implementing the FRMS system in organisations (regardless of their activity field).

The urgent problem can be solved by developing stochastic models that will allow determining the probabilistic characteristics of the time points of the beginning and end of the work and rest schedules and, accordingly, determining their duration, taking into account the random characteristics of the impact on the FF employee and their recovery from the consequences of such impact. The models will ensure the achievement of the highest possible level of productivity and safety in the organisation by establishing (for each workplace) the maximum possible work duration and the minimum possible rest duration, which, in turn, with a probability close to 1, will prevent an employee from being in a fatigued state at the workplace during a work shift. The relevance of solving the identified scientific and practical problem in this way is also emphasised in research [8,42,43].

Developing such models based on the mathematical apparatus' using the Markov processes' theory is advisable, as it is a flexible tool for studying random processes [44,45]. Such a mathematical apparatus has gained the widest application in the fields of economics and logistics, namely, for developing approaches to managing the fleet of technological equipment and the goods movement in warehouses in organizations [46]. At the same time, based on the results of the literature analysis, the authors are unaware of the application of this mathematical apparatus in the field of occupational safety and health, namely, in managing fatigue risk in workers. Therefore, given the significant achievements of the scientific and applied use of the Markov processes' theory in the fields of economics and logistics, the approach described in [46] was taken as a basis for solving the identified topical problem.

The need to use stochastic models to determine the quantitative characteristics of work and rest regimes is due to the need to take into account the objective random (stochastic) characteristics of the accumulation of negative effects in the body of an FF worker during the duration of the work regime. Also, there is a need to consider the relevant characteristics of the accumulation consequences of such exposure during the rest of the schedule.

The fact is that the characteristics (intensity) of the negative impact on the employee of these FFs (e.g., the level of working area's illumination, microclimatic indicators, indicators of air purity of the working area, psychophysiological factors, etc.) during the work regime period are not constant in time, but are constantly changing. Therefore, the consequences of the negative impact of the FFs, which are (as noted above) the causes of the development and onset of fatigue, also accumulate in the worker's body with a random intensity in time [44,45,47]. According to, the intensity of elimination of the consequences of the accumulation of the negative effects of FF from the worker's body (due to natural physiological processes occurring in the worker's body) during the rest schedule also has random characteristics in time [44,45,47].

Taking into account the specified random characteristics when determining the WRS duration, in contrast to the above-analysed approaches, in which the characteristics of the intensities of accumulation and removal of the effects of FF are considered constant over time (or are not taken into account), allows not only to objectify the process of managing the fatigue risk in the organisation but also provides an opportunity for economic entities to establish longer periods of work regimes and shorter rest schedule (compared to traditional approaches). It, in turn, allows for increasing indicators of the level of labour productivity due to an increase in the total period of duration of work regimes during both the work shift and the total period of duration of labour activity. At the same time, it is very important that at the end of the work regime, the worker only reaches the state of fatigue but does not pass into the state of over-fatigue. At the end of the rest schedule, the employee has fully recovered from the accumulated effects of fatigue.

For the possibility of determining the probability of the occurrence of both the state of fatigue in an employee at an arbitrary moment during the working regime and the probability of recovery of the employee from the state of fatigue at an arbitrary moment during the rest schedule (taking into account the stochastic characteristics of the processes of accumulation and removal of the consequences of the negative impact of FF in the employee's body), it is advisable to apply the mathematical apparatus of the theory of Markov processes. It is due to the fact that mathematical models built on the basis of the application of the specified mathematical apparatus (Markov models) allow the calculation of the probability of the system being in one or another state at one or another moment, taking into account random characteristics affecting the state of the system. The development of the models is implemented using the construction of matrices and diagrams (in the form of a certain block diagram) or transitions (Markov diagrams), which make it possible to visually display the process of transitions of the system from one state (block) to another in a short period, and the sum of all probabilities of the state of the system is equal to one [48].

The specified properties of Markov models make it possible to determine the probability of finding (or not finding) an employee in a state of fatigue during a work shift, during which the multiple processes of accumulation of the FFs negatively impact the employee's body and removal of such impact are observed. In addition, the use of Markov models allows us to determine quantitative characteristics of the RPV periods and use special software (for example, Matlab) to calculate such characteristics.

Markov processes are widely used in practice for modelling and optimising various transport systems, where the components describe alternating processes of random fluctuations in the lengths of transport queues at cargo transhipment points and cargo in the warehouse. There is also research on the use of such processes for modelling various logistics systems operating under conditions of uncertainty and risks [49]. However, the use of the mathematical apparatus of Markov processes for developing WRS to manage the risk of fatigue in workers is still unknown.

3. Materials and methods

Based on the results of the analysis, as well as on objective considerations, in order to solve this current scientific and practical problem, we will assume that the development (accumulation) of fatigue is a random process in time since it depends both on the negative impact on the FF worker during the duration of the work period and on the person's vegetative biological rhythms, which are constantly changing during the work shift [13]. Similarly, the employee's recovery process from the effects of fatigue also has random characteristics over time.

We also accept that an employee, starting a work shift, performs professional duties for a certain time, which we consider a work schedule. During the work schedule duration, the employee develops (accumulates) a fatigued state due to the FF's negative impact on them. We consider the intensity of fatigue accumulation to be a random variable with the parameter γk $(k = 0,1,2, \dots, K)$. The moment of the current work schedule's end is considered the moment of the fatigue onset (which in practice can be determined, for example, using the Samn-Perelli Fatigue Scale or other existing methods) [20,21,50].

At the end of the work schedule, the employee immediately switches to the rest schedule, which also lasts for a certain period. During the rest schedule, the employee's body recovers from the negative consequences of fatigue accumulation. We also consider the intensity of recovery of the worker's body from the fatigue state as a random variable with the αk $(k = 1,2, \dots, K)$ parameter.

We consider the moment of the end of the current rest schedule to be the moment of the employee's recovery from the fatigue state (the onset of which occurred within the framework of the previous work schedule). The *K*-th time of the work schedule or the *K+1* time of the rest schedule is, respectively, the time of the work shift's end (the time when the fatigue maximum permissible level accumulates in the worker's body). That is, *K+1* rest schedule, it is a long period from the end moment of the current work shift to the moment of the start of a new work shift, during which the employee has time to fully recover from the accumulated (for the current work shift) fatigue state.

We believe that after the current work schedule is completed, the employee's body is likely to $\xi k (0 < \xi k \leq 1)$ immediately begin to recover from the state of accumulated (during the current work schedule) fatigue. The meaning of this condition is the need to take into account the fact that in practice (due to various circumstances, scilicet the conscientiousness level of the employee to comply with the occupational safety requirements and health instructions on compliance with the WRS, cases of production necessity, etc.), the completion moment of the work schedule does not always coincide with the beginning of the rest schedule (the beginning of the body's recovery from fatigue). Based on this, we believe that at при $\xi k = 1$, the completion moment of the work schedule is the beginning of the rest schedule.

It is quite natural to assume that at the end of the *k-th* rest schedule, an employee does not have time to fully recover from the fatigue effects accumulated during the previous *(k - 1)* work schedule. That is, the process of fatigue development (accumulation) from the beginning of the work shift to the moment of its completion will be expressed as:

$$\gamma 0 \leq \gamma 1 \leq \ldots \leq \gamma K, \alpha 1 \geq \alpha 2 \geq \ldots \geq \alpha K.$$

The mathematical apparatus of the Markov processes theory was used to mathematically describe the processes of fatigue development and employee recovery from the consequences of such a state.

Therefore, based on the conditions adopted above, the current state of the employee during the work shift can be described by a random vector

$$(\eta(t), \beta(t)), \tag{1}$$

where $\eta(t)$ is the component that describes the fatigue accumulation process in the employee and takes the value 0 when at $\boldsymbol{t}$ time the employee is in work schedule (fatigue development) and 1 if the employee is in rest schedule (recovery from fatigue); $\beta(t)$ – the number of work schedules completed by the $\boldsymbol{t}$ moment.

For any distribution function, process (1) is not Markovian. Still, if we introduce an additional component $\delta(t)$, which is the time elapsed from the rest period starting till $\boldsymbol{t}$ moment, the process becomes Markovian [45,46,51]. Thus, in the following, we will consider the following random process:

$$\Xi(t) = \begin{cases} (0, \beta(t)), \text{ if } \alpha(t) = 0 \\ (1, \delta(t), \beta(t)), \text{ if } \alpha(t) = 1, \end{cases} \tag{2}$$

where $\alpha k = \int_0^\infty td\,Ak(t) < \infty, k = 1,2,\dots,K$,
Ak – distribution function of a random value αk.

Let us consider the probability of states (fatigue state development (accumulation) during the work schedule duration and employee's recovery from such a state during the rest schedule, respectively) of the Markov process (2) [46,51]:

$$q0k(t) = P\{\eta(t) = 0, \beta(t) = k\},$$
$$k = 0,1,2,\dots,K,$$
$$q1k(y,t)dy = P\{\eta(t) = 1, \beta(t) = k, y < \delta(t) < y + dy\},$$
$$y \geq 0, k = 1,2,\dots,K. \quad (3)$$

Therefore, the task of solving a specific actual problem is the need to find the introduced probabilities (3). Finding the entered probabilities will allow you to determine a number of basic indicators for the possibility of determining the WRS quantitative characteristics durations and implementation of the managing process of fatigue risk. Inparticular, the probability that at the time of the new work shift starting, the employee's body has fully recovered from the fatigue state accumulated at the end of the previous work shift; the probability that at the time of the *k-th* work schedule starting, the worker has recovered from the fatigue state that occurred in the previous $(k-1)$ work schedule; the probability that at the ***t*** moment the worker has reached the fatigue state (switched to rest schedule).

4. Results

Let's draw a diagram of the states and transitions of the Markov process we are analyzing (Fig. 1). This diagram describes the accumulation the processes of fatigue state in the worker's corpus (during the periods of work schedules) and recovery of his/ her body from the consequences of such a state (during the rest schedules) during the current work shift (from the moment of its beginning to the moment of its completion (the moment of completion of the *K-th* work schedule)).

Based on standard probabilistic considerations based on the probability consideration of state transitions of the specified Markov process, namely the probability of transitions of an employee from the fatigue state accumulation $(\gamma k\Delta t + o(\Delta t))$ to recovery state $(\alpha k\Delta t + o(\Delta t))$ and vice versa in a short period,$(t, t+\Delta t)$, using the full probability formula, we obtain for transitional probabilities qik $(i = 0,1)$ the following system of equations [46,51]:

$$q00(t+\Delta t) = (1-\gamma 0\Delta t)q00(t) +$$
$$+\sum_{k=0}^{K-1}(1-\xi k)\,\gamma kq0k(t)\Delta t + o(\Delta t),$$
$$q0k(t+\Delta t) = (1-\gamma k\Delta t)q0k(t) +$$
$$+\int_0^\infty q1k(y,t)\frac{Ak(y+\Delta t)-Ak(y)}{1-Ak(y)}dy + o(\Delta t),$$
$$k = 1,2,\dots,K;$$
$$q1k(y+\Delta t, t+\Delta t) = q1k(y,t)\frac{1-Ak(y+\Delta t)}{1-Ak(y)} +$$
$$+o(\Delta t), k = 1,2,\dots,K;$$
$$q1k(0, t+\Delta t)\Delta t = \gamma k - 1\xi k - 1q0, k-1(t)\Delta t + o(\Delta t),$$
$$k = 1,2,\dots,K. \quad (4)$$

Considering system (4) at the transition to the boundary $\Delta t \to 0$, we obtain a system of differential equations describing the dynamics of the random process (2) [46,51]:

$$\frac{d}{dt}q00(t) = -\gamma 0q00(t) + \sum_{k=0}^{K-1}(1-\xi k)\gamma kq0k(t),$$
$$\frac{d}{dt}q0k(t) = -\gamma kq0k(t) + \int_0^\infty \phi k\,(y,t)dAk(y),$$
$$k = 1,2,\dots,K,$$
$$\left(\frac{d}{dt}+\frac{d}{dy}\right)\phi k(y,t) = 0, k = 1,2,\dots,K,$$
$$\phi k(0,t) = \gamma k - 1\xi k - 1q0, k-1(t), k = 1,2,\dots,K, \quad (5)$$

where function $\phi k(y,t) = q1k(y,t)/(1-Ak(y))$, whereby $\phi k(0,t) = q1k(0,t)$.

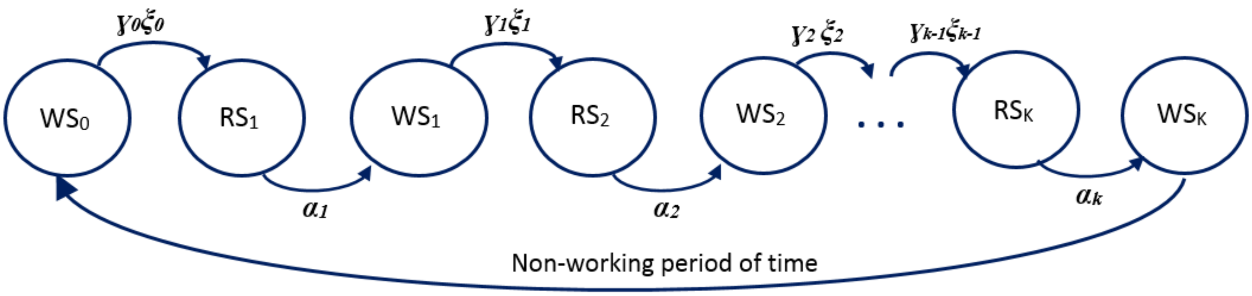

Fig. 1. Diagram of states and transitions of the Markov process of accumulation of fatigue state in the worker's body during the work shift, where WSk is the *k-th* work schedule during the work shift *(k = 0,1,2,..., K),* RSk is the *k-th* rest schedule during the working shift *(k = 1,2,..., K)*

To find the probabilistic characteristics of the moments of onset of fatigue state in a worker and their recovery from such a state, which will allow determining the WRS quantitative characteristics' during a work shift and managing the fatigue risk, it is necessary to solve the resulting system of differential equations (5). Solving the system of Kolmogorov's direct differential equations, which is represented by the system (5), for the probabilities of Markov chains' states (Fig. 1) involves finding the limiting probabilities of these states [45,51,52]. During the work shift, the average number of moments of fatigue state onset in an employee is equal to the average number of recovery moments from such a state or the average number of moments of the employee's recovery from fatigue state (the system is in statistical equilibrium or stationary regome), to find this solution, we will use the stationary probability distribution of introduced Markov process' states, which has the following form $\{q0, \phi k(y)\}$ [46,51,52]. The initial conditions for solving system (5) and the normalisation condition for the system are as follows [46,51,52].

Initial conditions

$$q00(0) = 1, qjk(0) = 0, (j,k) \in \Xi \setminus (0,0). \quad (6)$$

Norming condition for the system (5):

$$\sum_{k=0}^{K} q0k(t) + \int_0^\infty \sum_{k=1}^{K} \phi k(y,t)\,(1 - Ak(y))dy = 1 \quad (7)$$

To find the introduced stationary probability distribution, based on (5) - (7), using the mathematical apparatus of queuing theory and Markov process theory, we obtain the following system of linearly dependent algebraic equations [46,51,53]:

$$-\gamma 0 q00 + \sum_{k=0}^{K-1} (1 - \xi k)\gamma k q0k + \gamma K q0K(t) = 0, \quad (8)$$

$$\gamma k q0k = \int_0^\infty \phi k(y) dAk(y)\,, k = 1,2,\dots,K, \quad (9)$$

$$\frac{d}{dy}\phi k(y) = 0, k = 1,2,\dots,K, \quad (10)$$

$$\sum_{k=0}^{K} q0k + \int_0^\infty \sum_{k=1}^{K} \phi k(y)(1 - Ak(y))\,dy = 1. \quad (11)$$

Since, all of the equations presented are linearly dependent, the solution of the system (8) - (11) implies that equation (8) can be discarded. At the same time, based on (5) and taking into account $\phi k(y) = \phi k(0), \mathrm{y} \geq 0, k = 1,2,\dots,K$ (see 10), we obtain:

$$\gamma k q0k = qk - 1\xi k - 1q0, k - 1, k = 1,2,\dots,K. \quad (12)$$

In turn, solution (12) makes it possible to find the desired probabilities to determine the quantitative characteristics of the RPW duration and to implement the control process of the fatigue risk in organizations [46,51,53]. Namely:

- the probability that at the beginning of a new work shift, the employee's body has fully recovered from the fatigue state accumulated at the previous work shift end:

$$q00 = \left[1 + \gamma 0 \sum_{k=1}^{K} \frac{1}{\gamma k} \prod_{k=0}^{k-1} \xi k + \gamma 0 \sum_{k=1}^{K} \alpha k \prod_{k=0}^{k-1} \xi k\right]^{-1}; \quad (13)$$

- is the probability that at the beginning of the *k-th* work schedule (at time t), the employee has recovered from the fatigue state that occurred in the previous $(k-1)$ work schedule:

$$q0k = \frac{\gamma 0}{\gamma k} \prod_{k=0}^{k-1} \xi k q00, k = 1,2,\dots,K; \quad (14)$$

- is the probability that at time t, the employee has reached a fatigue state (moved to the rest schedule):

$$q1k = \gamma 0 \alpha k \prod_{k=0}^{k-1} \xi k q00, k = 1,2,\dots,K. \quad (15)$$

5. Discussion

The presented models allow an organisation to establish probabilistic characteristics of both the onset of a fatigued state in an employee and the recovery of their body from the consequences of such a state at an arbitrary time t during a work shift, depending on the controlled parameters' characteristics.

As can be seen in models (13) - (15), the controlled parameters are the parameters of the accumulation of fatigue in the employee's body (γk) and the recovery of the body from this state (αk).By changing these parameters' characteristics, it is possible to change the duration of both work and rest schedules, thereby fulfilling the task of managing the fatigue risk in the organization. Namely, the task of establishing such characteristics of the controlled parameters that allow achieving the highest possible level of productivity and safety during a work shift. In other words, the task of establishing such characteristics of the γk parameter, at which the period of development of the employee's fatigue state (from the moment of the beginning of the current work mode to the ***t*** moment)will be as long as possible. Also, such characteristics of the αk parameter, at which the period of recovery of the employee's body from fatigue (from the moment of the beginning of the current rest schedule to the ***t*** moment) will be minimal.

Since fatigue development depends on the negative impact characteristics on the employee of the FF, the γk parameter in the presented models essentially characterizes this impact intensity. Thus, by changing the impact intensity of these FFs on the employee, we essentially change the γk

parameter's characteristics and, accordingly, change the work schedule duration.

Accordingly, the αk parameter characterises the intensity of the worker's recovery from fatigue. Since the intensity of such recovery depends on the rest schedule qualitative characteristics, by changing the specified characteristics, we change the αk parameter characteristics and, accordingly, the characteristics of the rest schedule duration.

Thus, the practical task of the process of managing the fatigue risk in the organisation is reduced to the need to constantly maintain the values of the intensity parameters of the negative impact on the employee of the FF (γk) established (using model (14)) during the work schedules, which ensure the maximum possible duration of this mode. Also, there is a need to constantly maintain the established (using model (15)) values of the intensity parameters of the employee's recovery from fatigue (αk) during the rest schedules, which ensures the minimum duration of this schedule during the work shift. In addition, this control process should also provide for compliance with the characteristics of the non-working period (from the end of the previous *K-th* work shift to the beginning of the current work shift), established (using model (13)), during which the employee has time to fully recover from fatigue (see condition (6)).

It should be noted that in order to ensure the constant maintenance of the parameter values established by the results of applying models (13) - (15) and during the work shift (in particular, as part of the FRMS implementation), the organization must have the practical ability, firstly, to identify the specified FFs at each workplace, and secondly, to monitor and adjust the γk parameter values constantly and αk for each identified FF.

The procedure for FF identifying at workplaces is usually carried out (or can be carried out) during workplace certification by working conditions. Based on the certification results, the FF nomenclature that has a negative impact on the employee and the actual characteristics of such impact are established, which are the input data for models (13) - (15).

For a certain number of FFs, mainly of physical and chemical nature (noise, vibration, microclimate factors, lighting, chemicals and compounds, etc.), determining objective characteristics of such impact is not a problem since they can be measured by instruments (directly). The characteristics of the impact of other FFs (mainly psychophysiological) cannot be objectively established today since they cannot be directly measured (studied). Therefore, the characteristics of such FFs during certification are determined either by expert assessments or indirect research methods [13,54,55].

The next task (after the identification procedure) of the process of managing the fatigue risk in the organisation is to ensure the practical possibility of conducting a procedure for continuous monitoring (during the work shift) of the γk and αk values parameters established by the modelling results and (for each FF identified at the workplace), as well as the procedure for promptly changing the values of such parameters (in case of deviation of actual values from those set by the modelling results).

The negative impact characteristics on the employee of the FF vast majority of physical and chemical hazards (γk parameter values) can be both objectively monitored and corrected, for example, by using certain automation tools (sensors for monitoring parameter values, regulating devices, etc.). Certain automated monitoring tools can also be used to monitor and correct most FFs of a psychophysiological nature. Namely, means of monitoring the psychophysiological state of an employee, for example, means of recognising the state of working capacity by continuously scanning facial expressions, etc., which are now being constantly improved due to the development of information technology [4,56].

At the same time, the implementation of procedures for monitoring and adjusting the αk parameter values characterising the intensity of an employee's recovery from fatigue is more problematic in terms of practical implementation. For certain fatigue symptoms, such as physiological ones, which are inherent mainly in work involving physical (dynamic) loads of the employee, monitoring of the αk parameter values can be carried out continuously by monitoring the state of the cardiovascular system (pulse rate, pressure, etc.), using, for example, individual cardiovascular devices or other appropriate means [13]. Other fatigue symptoms, such as behavioural symptoms (decreased performance, attention, erroneous actions), as well as psychophysical symptoms (deterioration of sensitivity, feeling of tension), are inherent mainly in work involving mental (static) stress, monitoring of the αk parameter values can be carried out only by monitoring the dynamics of changes in the concentration of certain substances in the employee's body (hormones, etc.) [13,57]. Individual means of monitoring such indicators are known but not widespread [56].

It is possible to adjust (maintain) the value of the αk parameter, depending on the indicated fatigue symptoms, only through the use of the work schedule qualitative characteristics (complexes of physical exercises, the use of physiological food, drinks, etc.) The development of such characteristics, depending on the fatigue symptoms, is a separate complex scientific problem, the solution of which is expected to be addressed in the further development of this research.

It should be noted that occupational safety and health management systems in modern organizations, within the framework of which the process of managing the fatigue risk (and the FRMS system is implemented), do not provide for the use of the above means of continuous parameters' monitoring and adjustment of the γk and αk. At the same time, the practical possibility of comprehensive implementation of procedures for continuous monitoring and prompt correction of such parameter values in organizations can still be ensured, for example, by introducing an automated occupational health and safety management system into the existing OHSMS of organizations, which was developed by the authors in the framework of a previous study and has been successfully tested in real production conditions [58].

Such a system, in particular, allows achieving and maintaining the γk and αk parameters' values, which were set according to the modelling results (for the vast majority of FF) in automatic mode, through the use of a system of appropriate control and actuating devices, as well as monitoring the employee's compliance with the WRS established at the workplace, which, in turn, provides a practical opportunity to manage the fatigue risk in the organization. The practical implementation of the developed models in the specified system (for the possibility of evaluating the degree of effectiveness of its application for the process of managing the risks of fatigue among employees in organizations) is a promising direction for the development of the presented research.

6. Conclusions

The models (13) - (15) proposed in the research allow the organization to carry out the process of managing the fatigue risk at the workplace (including the FRMS system implementation) by establishing probabilistic characteristics of the moments of fatigue onset in an employee during the work schedule and the moments of recovery of the employee's body from such a state during the rest schedule, depending on the parameters' characteristics of the intensity of exposure to negative fatigue factors (γk) and intensity of its recovery from such impact (αk) during the work shift, respectively. From a practical point of view, the implementation of this process requires the following two consecutive stages of fatigue risk management.

The first stage of management involves determining, with the help of the proposed models, such characteristics of these parameters that, with a probability close to 1, will enable the organization to establish the maximum possible duration of work and the minimum possible duration of rest, which, with a probability close to 1, will prevent the employee from being in a fatigued state at the workplace and ensure the highest possible level of labour productivity during the work shift. And also to establish such a duration of the non-working period (after the end of the current work shift) during which the employee fully recovers from the accumulated (at the end of the previous work schedule) fatigue consequences.

The second stage involves the need to constantly maintain (at each workplace) the values of the controlled parameters (γk) and (αk) established by the modeling results for each identified negative factor during the work shift by implementing procedures for their continuous monitoring and adjustment. Since the existing occupational health and safety management systems (within which the processes of managing this risk are carried out) do not allow to objectively carry out these necessary procedures, in order to objectively implement the process of managing the fatigue risk in organisations, the authors propose to use the automated occupational health and safety control system developed by them as part of the previous research.

Acknowledgements

The authors are grateful to the administration of the National University "Odesa Polytechnic" for the opportunity to conduct the research.

Research funding

This research did not receive any financial support.

Authors contribution

The idea of the study, its concept, works on the main chapters – Bochkovsky A.P. (75%).

The references, creation and design of the drawing, as well as the general design of this publication – Sapozhnikova N.Yu. (25%).

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