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THE MODEL OF THE PROCESS OF EMERGENCY EVACUATION FROM THE BUILDING WHILE USING THE SELF-RESCUE EQUIPMENT IN CASE OF THE FIRE

Matveev Alexander V.
Saint Petersburg University of State Fire Service of EMERCOM of Russia, Moskovsky Avenue, Saint Petersburg, Russia
E-Mail: fcvega_10@mail.ru

ABSTRACT

The article proposes a stochastic model of the process of emergency evacuation from the height in case of fire while using self-rescue equipment. The technical characteristics of escape equipment and psychophysiological factors of people's behavior in case of fire are simultaneously factored into the united model. An evaluation criterion of the effectiveness of the use of escape equipment in case of fire in the buildings is proposed. The set up model allows estimating the effectiveness of the use of escape equipment from the height, to predict the results of the emergency evacuation system control. The use of the model can help in defending control decisions on the number and types of escape and evacuation equipment from the height that buildings should be equipped with to maintain the required individual fire risk index.

Keywords: emergency evacuation, self-rescue equipment from the height, stochastic model, fire safety, individual fire risk.

INTRODUCTION

A characteristic feature of modern house building is the increase of the number of buildings with a mass gathering of people. These include indoor cultural and sports complexes, cinemas, clubs, shops, industrial buildings, etc. Fires in such premisses are often come amid infractions and death of people. First of all, this refers to fast-evolving fires, which pose hazard to human's lifes in a few minutes after their occurrence and differ in the intensive impact on people of dangerous fire factors. The most safe way of people's safety precautions in such conditions is a well-timed evacuation from the building where the fire occurred.

For example, in Russia the relative number of fires in high-rise buildings is small, but the share of dead per fire in buildings over 25 floors is 3-4 times higher than this figure in buildings up to 16 floors [1].

A lot of people become victims of smoke, which prevented them from finding the main escape route, and then they die from poisoning with combustion products or suffocate due to a lack of oxygen before the arrival of rescuers (Figure-1). Sometimes there are flocks when people move along evacuation routes that do not allow them to escape into the safe area during the time that is taken before the exposure of dangerous fire factors (temperature, smoke, carbon dioxide, etc.) has not yet begun. Under these conditions, self-rescue equipment from the height are not only the last, but often the only opportunity to evacuate people safely from the premisses in which the effects of dangerous fire factors occur [2].

Figure-1. Fire in high-rise building.

Herewith it’s worth to remark that the generally accepted characteristic of the fire safety level of communal buildings is the magnitude of individual fire risk. And it is proposed to take into account the impact of the use of self-rescue equipment from the height on the magnitude of individual fire risk for people in the building under investigation [3, 4].

An analysis of the evacuation of people in case of the fire in buildings shows that this process is nondeterministic. Thus, for example, the analysis of publications [5, 6, 7] allows to draw a conclusion about the in homogeneity and nonstationarity of people's movement along evacuation routes.

Therefore, it is proposed to consider the approach to developing a mathematical stochastic model of the evacuation from the height process that allows to take into account not only the technical characteristics of the escape equipment from the height, but also the psychophysiological factors of the behavior of people during a fire.

MATERIALS AND METHODS

a) The main components of the model of the process of emergency evacuation of people from a building during the fire

The process of emergency evacuation of people from the height in case of the fire in the building, which is carried out due to the functioning of the emergency evacuation controlling system (EECS), is considered.

The study of the effectiveness of any system should be carried out on the basis of the methodology of system analysis [8, 9, 10], which reveals the concepts of "structure" and "system functioning". The structure of the EECS includes a set of self-rescue equipment from the height set in the emergency exits from the building. The process of evacuation of people to the area of fire safety will be understood under the functioning.

The importance of EECS in the fire safety system is come down to determining the influence of the EECS on the individual fire risk in the building and further substantiation of its structure. The goal is such EECS structuring, that would provide the required values of index of its functioning effectiveness, i.e. the required indexes of probability of evacuation of people from the building.

The application of decomposition and aggregation methods [3, 4] (Figure-2) made it possible to present the process of evacuation from a height in the form of three basic components:

$\lambda(t)$ - an intensity of the flow of people's arrival to the emergency exit, from which evacuation is carried out with the help of escape equipment;

$\overline{t_p}$ - an average time spent for preparing the next person to descend into a secure area;

$\overline{t_e}$ - an average time of descending a person into a fire safety area where he will not be affected by fire hazards.

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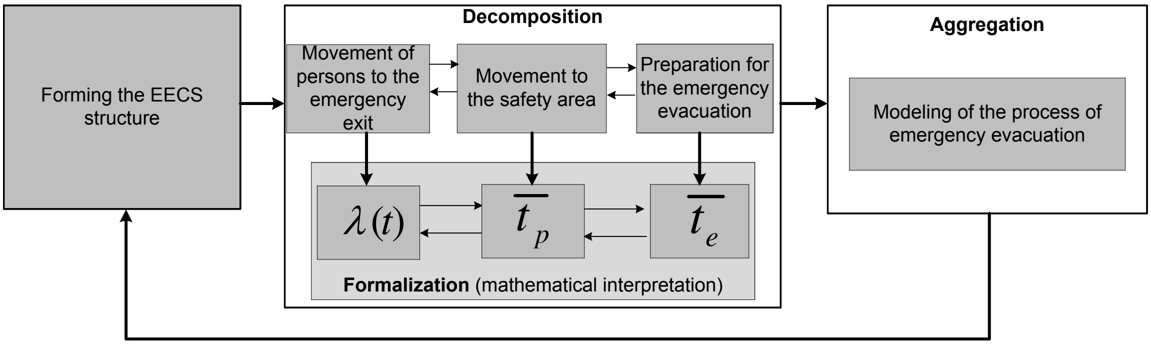

Figure-2. Structural scheme of the process of assessing the effectiveness of the EECS.

This approach makes it possible, by forming the appropriate structure of the EECS and specifying the functions of three basic components, to determine the probability value of emergency evacuation of people, as well as its impact on the individual fire risk in the building. To develop a mathematical model of the emergency evacuation process, the proposed components are presented in the form of the following functions:

- an intensity of training people for emergency evacuation with the help of self-rescue equipment $\mu_1 = \frac{1}{\overline{t}_p}$, where $\overline{t}_p = \overline{t}_i + \overline{t}_d$, $\overline{t}_i$ – an average time, spent on identifying the next evacuee (due primarily to the psychophysiological aspects of people's behavior in the evacuation process, when there may be panic or fear and fear of heights), $\overline{t}_d$ – average time, which is needed for preparing escape equipment for being used (if needed);
- an intensity of descending a person into a fire safety area on (in) the escape equipment $\mu_2 = \frac{1}{\overline{t}_e}$.

b) Mathematical model of the process of emergency evacuation under unsteady flow of people

The use as initial data of the distribution of the probabilities of time for preparation for evacuation and the time of descent under stochastic modeling allows us to reflect the heterogeneity of the introduced functions both in terms of the mobile capabilities of different people in the flow and in the level of their emotional responses to the circumstances of the situation in which they found themselves. This allows you to fully appreciate the possibility of evacuation of people regardless of their age and physical condition.

It is assumed that the time for preparation of each next person for evacuation is distributed according to the Erlang law of the k-th order with the parameter $\mu_1'(t)$, and the time of descenting a person into the fire safety area is distributed according to the Erlang law [11, 12] of the l-th order with the parameter $\mu_2'(t)$:

$$f_p(t) = \frac{\mu_1'(\mu_1' t)^{k-1}}{(k-1)!} e^{-\mu_1'(t)t} (t > 0),$$

$$f_e(t) = \frac{\mu_2'(\mu_2' t)^{l-1}}{(l-1)!} e^{-\mu_2'(t)t} (t > 0). \quad (1)$$

It is suggested to consider a vectorial random function $X(t)$ consisting of 2 random stochastically dependent components $X_1(t)$, $X_2(t)$. The $X_1(t)$ random process is the change in the number of people at the emergency exit waiting for the availability of the escape equipment. This random process depends on the arrival flow of evacuating people $\lambda(t)$ to the emergency exit and the intensity of evacuation $\mu_e(t)$ with the help of a escape equipment.

The random process $X_2(t)$ is the process of using the escape equipment during evacuation, which can be in one of two conditions: D_0 - the condition of waiting of arrival of evacuees, or identification and preparation of a person for descent (escape equipment are available), D_1 - the descent of a person into a fire safety area (the escape equipment are occupied).

Each of two components $X_1(t)$, $X_2(t)$ is a random process. Thus, for each fixed moment of time t, we will consider a random vector in the 2-dimensional space $X(t) = \{X_1(t), X_2(t)\}$.

In order to formulate further arguments and conclusions, we consider the diagram (Figure-3) of the random function $X(t)$~$(G(X(t))$, whose vertices are the components of a given random function. The verges of a given figure determine those connections that exist between separate components of the random function $X(t)$.

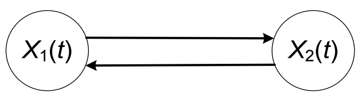

Figure-3. Diagram of a random function $X(t)$

Both processes $X_1(t)$, $X_2(t)$ are transitive [13]; are interconnected, which is reflected in the presence of verges $R[X_1(t);X_2(t)]$=1, $R[X_2(t);X_1(t)]$=1, by virtue of the following.

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The presence of the $R[X_1(t);X_2(t)]$ verge is due to the fact that the number of people at the emergency exit waiting for evacuation influences the intensity of their preparation for evacuation, which is one of the characteristics of the process $X_2(t)$. So, for example, it is obvious that in the absence of evacuating people, i.e. at $X_1(t) = 0$, the escape equipment will remain in the waiting mode all the time, and only at $X_1(t) \neq 0$ the process $X_2(t)$ will change its conditions.

The $R[X_2(t);X_1(t)]$ verge reflects the change in the $X_1(t)$ process as a function of the state $X_2(t)$, namely, the decrease in the number of people waiting for evacuation can occur only in the case when the process $X_2(t)$ is in the condition D_1, i.e. at the time of use of the escape equipment.

The process $X_1(t)$ is a typical "death and reproduction" scheme [13] with $(n+1)$ of the condition S_i (i=0, 1, 2,…,n) and the parameters $\lambda(t)$, $\mu_e(t)$, where S_i is the number of people at the emergency exit, n is the number of people in the building who could not be evacuated along the main routes and should be evacuated using self-rescue equipment. Taking into account the fact that the evacuation occurs exclusively at the moments of the process $X_2(t)$ in the condition D_1, the conditional intensity of the descent of people into the fire safety area is determined as follows:

$$\mu_e(t) = \mu_2(t) q_1(t), \tag{2}$$

where

$q_1(t)$ - is the possibility of the presence of process $X_2(t)$ in the condition D_1,

$\mu_2(t)$ - an intensity of descending people on (in) escape equipment.

The one-dimensional law $X_1(t)$ can be determined by using a system of differential equations:

$$\begin{cases} dp_0 / dt = \mu_e(t) p_1(t) - \lambda(t) p_0(t), \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ dp_i / dt = \lambda(t) p_{i-1}(t) + \mu_e(t) p_{i+1}(t) - (\lambda(t) + \mu_e(t)) p_i(t), \\ (i = 1, 2, \ldots, n-1), \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ dp_n / dt = \lambda(t) p_{n-1}(t) - \mu_e(t) p_n(t), \end{cases} \tag{3}$$

where $p_i(0)=P(S_i(t))$.

The system of equations (3) must be solved under the initial conditions $p_0(0)=1$, $p_i(0)=0$ (i=1,2,…,n).

Multiplying the left-hand and right-hand members of the i-th (i=0,1,2,…,n) equation of the system (3) by the amount i, and carrying out a series of simple transformations of the right-hand member of the equation, and taking into account the formula (2), we obtained formula for the mathematical expectation of the process $X_1(t)$:

$$\frac{dm_{x_1}(t)}{dt} = \dot{m}_{x_1} = \lambda(t)(1 - p_n(t)) - \mu_2(t) q_1(t)(1 - p_0(t)), \tag{4}$$

Thus, a differential equation is obtained for the mathematical expectation of the number of people $m_{x_1}(t)$ in the emergency exit waiting for evacuation when using escape equipment. This equation must be solved under the initial condition $m_{x_1}(0) = 0$. The values of the functions $p_0(t)$, $p_n(t)$ are determined from the system (3).

For the random process $X_2(t)$, when the time of staying in D_0, D_1 conditions is distributed according to the laws (1), it is suggested to use the method of "including supplementary variables" [13, 14, 15], in order to artificially trace the described process to the Markov's process. The diagram of the process conditions for this case is shown in Figure-4.

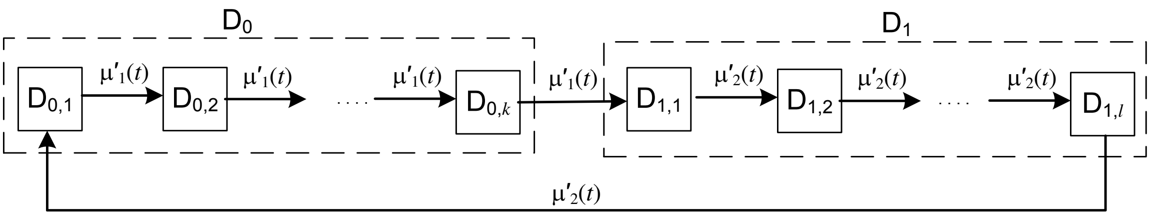

Figure-4. Diagram of the $X_2(t)$ conditions.

According to theorem of the summation of mathematical expectations we obtain:

$$\mu_1'(t) = k\mu_1(t) m_{x_1}(t), \;\; \mu_2'(t) = l\mu_2(t). \tag{5}$$

In the case where $m_{x_1}(t)$ persons are at the emergency exit, the intensity of preparation for evacuation will be determined as follows:

$$m_{x_1}(t)\mu_1 = \frac{1}{\dfrac{\Delta t_u}{m_{x_1}(t)} + \Delta t_m} = \frac{m_{x_1}(t)}{\Delta t_u + m_{x_1}(t)\cdot\Delta t_m}. \quad (6)$$

Using a marked diagram (Figure. 3) and expressions for the characteristics of the process $X_2(t)$ (5,6), a system of differential equations for the conditions probabilities is obtained, where $q_{0,i}(0)=P(D_{0,i}(t))$, $q_{1,j}(0)=P(D_{1,j}(t))$ (the intensities $\mu_1(t)$ and $\mu_2(t)$ are generally assumed to be constant):

$$\begin{cases} \dfrac{dq_{0,1}}{dt} = -k\mu_1 m_{x_1}(t)\cdot q_{0,1}(t) + l\mu_1\cdot q_{1,l}(t), \\ \dfrac{dq_{0,i}}{dt} = k\mu_1 m_{x_1}(t)\cdot q_{0,i-1}(t) - k\mu_1 m_{x_1}(t)\cdot q_{0,i}(t), \quad i=2,\ldots,k \\ \dfrac{dq_{1,1}}{dt} = k\mu_1 m_{x_1}(t)\cdot q_{0,k}(t) - l\mu_2\cdot q_{1,1}(t), \\ \dfrac{dq_{1,j}}{dt} = l\mu_2\cdot q_{1,j-1}(t) - l\mu_2\cdot q_{1,j}(t), \quad j=2,\ldots,l \end{cases} \quad (7)$$

The system of equations (7) must be solved under the initial conditions: $q_{0,1}(0)=1$, $q_{0,2}(0) = \ldots = q_{0,k}(0) = q_{1,1}(0) = q_{1,2}(0) = \ldots = q_{1,l}(0) = 0$.

Thus, analytical dependencies formalizing the general model of the emergency evacuation process in case of fire in the case of a non-stationary flow of people are obtained:

$$\frac{dm_{x_1}(t)}{dt} = \dot{m}_{x_1} = \lambda(t)(1-p_n(t)) - \mu_2(t)q_1(t)(1-p_0(t)),$$

$$q_1(t) = q_{1,1}(t) + q_{1,2}(t) + \ldots + q_{1,l}(t), \quad (8)$$

where $p_0(t)$, $p_n(t)$ are determined from the system (3), $q_{1,j}$ ($j=1,2,\ldots,l$) are determined from system (7).

The developed model allows to determine the value of the probability of emergency evacuation of people (using self-rescue equipment) from a building in case of fire with the help of the formula:

$$P_{evac} = \frac{\int_0^{t_{bl.out.}} \lambda(\tau)d\tau - m_{x_1}(t_{bl.out.})}{n}, \quad (9)$$

where $t_{bl.out}$ - the time of blocking the emergency exit (i.e the time through which the exposure of the hazardous fire factors will begin at the location of the self-rescue equipment).

RESULTS AND DISCUSSIONS

An assessment of the effectiveness of the use of self-rescue equipment from height was made on the example of the evacuation of people from one of the hostels of St. Petersburg. Previous studies have shown that under one of the fire scenarios in the hostel, about 30 people could not have time to get out of the building along the main evacuation routes. People were located at an height of 15 meters.

All self-rescue equipment from height are divided into:

- abseil fire escape system with an automatic regulation of the descent speed;
- abseil fire escape system with manual regulation of the descent speed;
- jumping rescue equipment (pneumatic mattress);
- rescue fixed ladders;
- escape equipment on the basis of an elastic sleeve;
- escape equipment based on a spiral arm, traps (troughs).

To assess the effectiveness of their use during evacuation, one escape mean was considered from the first 4 species, namely:

- Set of individual self-rescue equipment, model "Samospasatel-7" (Device 1, Figure-5);
- Self-rescuer "Bars" (Device 2, Figure-6);
- Rescue fixed ladder "LNS-9" (Device 3, Figure-7);
- Jumping rescue device "Kub Zhizni" (Device 4, Figure-8).

Figure-5. Set of individual self-rescue equipment, model "Samospasatel-7".

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Figure-6. Self-rescuer "Bars".

Figure-7. Rescue fixed ladder "LNS-9".

Figure-8. Jumping rescue device "Kub Zhizni.

In article [16], using the statistical methods, the distributions of the time characteristics $f_p(t)$, $f_e(t)$ for each of the considered equipment were calculated.

A diagram of the probability of evacuation of people using each of the types of escape equipment, depending on the time of blocking the emergency evacuation exit, is shown in Figure-9.

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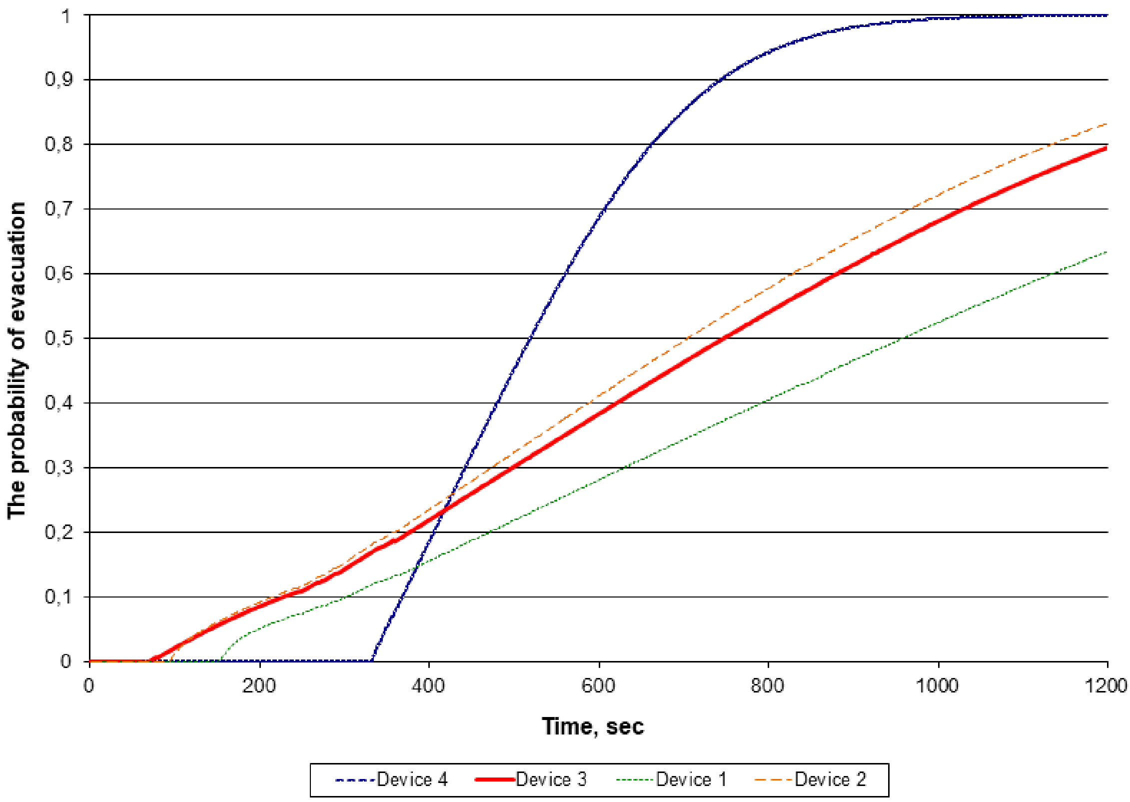

Figure-9. The probability of the evacuation in case of using escape equipment.

The obtained results show that at the initial stage (the first 7 minutes) it is preferable to use a abseil fire escape automatic device "Bars" or a rescue fixed ladder. This is due to the shortest time of preparation of these escape equipment for their use at the initial stage of evacuation. Further, jumping rescue device "Kub Zhizni" is more effective.

CONCLUSIONS

The mathematical model is developed in the article, allowing estimating the influence of psychophysiological factors of people's behavior in case of fires and the use of self-rescue equipment from height to the value of individual fire risk.

The approach proposed in the article allowed a new rational for the process of ensuring the safety of people in buildings in case of fires.

The developed model allows estimating the effectiveness of the use of escape equipment from the height, to predict the results of the emergency evacuation control system. The use of the model can help in substantiation of control decisions on the number and types of rescue and evacuation equipment from the height that buildings should be equipped with to maintain the required individual fire risk index.

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