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Time Factor in the Theory of Anthropogenic Risk Prediction in Complex Dynamic Systems

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Abstract. The article overviews the anthropogenic risk models that take into consideration the development of different factors in time that influence the complex system. Three classes of mathematical models have been analyzed for the use in assessing the anthropogenic risk of complex dynamic systems. These models take into consideration time factor in determining the prospect of safety change of critical systems. The originality of the study is in the analysis of five time postulates in the theory of anthropogenic risk and the safety of highly important objects. It has to be stressed that the given postulates are still rarely used in practical assessment of equipment service life of critically important systems. That is why, the results of study presented in the article can be used in safety engineering and analysis of critically important complex technical systems.

1. Introduction

According to studies [1,2] the anthropogenic risk will be used in this article in the sense of damage (negative consequences) as a result of a possible initial event (failure, disaster, catastrophe) in a stochastic situation of applying a complex dynamic system. Anthropogenic risk, being a random value, is assigned on a probability space (Ω, F, P) which includes:

Ω – non-empty *set of possible outcomes;*

F – σ-*algebra* of events, its elements are sub-sets of set Ω and are called *events,* $\Omega \in F$;

Q – σ-additive set function Q on F and restricted by the condition $Q(\Omega) = 1$ is a probability measure or probability.

For the event $A \in F$ the value of $Q(A)$ is called the probability of possible initial event A.

Triple (Ω, F, Q) is called *probability space* or *probabilistic model.*

As the risk is connected with actual indeterminate situations, then to describe it in mathematical terms of probability theory, it is necessary to satisfy certain parameters and conditions:

- “unpredictability: the outcome of a stochastic situation is impossible to predict with absolute precision. This quality is apparent, because if the outcome of the situation can be predicted exactly, then there is no need to resort to the methods of the probability theory;
- reproducibility: this parameter is a key one in the assuredness of the success of applying the methods of the probability theory to the description of stochastic processes. Probability theory and mathematical statistics are aimed at studying mass phenomena. Considering weak reproducibility of rare events, many attempts at applying the probability theory to the analysis of unique complex systems can yield controversial results, distant from actual events;

- stability of event frequency: the frequency of the event, linked with the situation under study, with multiple repetition of the situation is fluctuating near some number, being closer to it only with more frequent occurrences of the situations" [1].

Risk is always connected with the occurrence of an event, a random event A, which is called a risk event (initial event in case of disaster, emergency) from the multiple of possible F events, that describe the given risk situation. These events are also usually distributed in time in some way and are accompanied with certain material or other damages, also random ones. In this way, risk is characterized by two variables - time T of the occurrence of risk even and value C of damages caused by it. From this point of view, risk is understood as a probabilistic model (probabilistic space)

$$R = \{\Omega, F, Q\} \tag{1}$$

where the two-component random value (T, C) is determined. The first component T is the time of risk event A occurrence, calculated from a fixed moment, and the second component C shows damage brought about by this risk event:

$$R\,(p, c, t) = R\,\{P < p_i, C < c_i, T < t\} \tag{2}$$

where $i = \overline{1, N}$ is the number of possible risk events.

Figure 1 shows the generalized dynamic model of anthropogenic risk of system operation Let us analyze the sets: $Q = \{q_1, q_2, \ldots, q_n\}$, $q_i \in Q$, $i = \overline{1, n}$ is the set of possible initial events (failures, emergencies, disasters), $C = \{c_1, c_2, \ldots, c_n\}$, $c_i \in C$, $i = \overline{1, n}$ – is the set of consequences (damage) of i-th initial events happening, $t_i \in T$ is the set of times, $r_i \in R$ – is the set of possible risks $R = \sum_{i=1}^{n} R_i$.

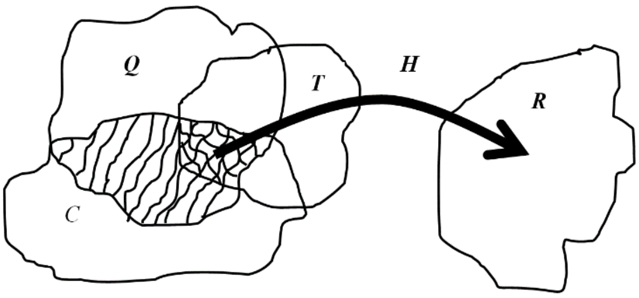

Figure 1. Graphic visualization of the relations between the set of risks R, probabilities of initial events Q, damages C during operating time T of a complex dynamic system.

It is evident, that

$$R = H\,\{\,Q \times C \times T\,\} \tag{3}$$

or in scalar form

$$R\,(q, c, t) = \sum_{i=1}^{n} q_i(t) c_i(t), \tag{4}$$

where H is the operator that implements the relations

$$Q \times C \times T \rightarrow R. \tag{5}$$

Or

$$R\,(q, c, t) = H\,\{t, t_0, R_0(q_0, c_0, t_0), R(q, c)^{t}_{t_0}\}, \tag{6}$$

where t is the time during which the risk is determined;

t_0 – the starting moment of observing the state of the system, $t \geq t_0$;

q_0, c_0, R_0 –probability of initial events of the dynamic system, damage and risk at the starting moment of observing the state of the system, correspondingly.

2. Problem statement

In studies [2,3,7–9] the authors developed the classification of models of anthropogenic risks in complex dynamic systems, giving detailed theoretical basis to the analysis of characteristics of sets R, Q and C when performing the mathematical modelling of the anthropogenic risk.

From a statistical point of view, the components $R(t)$, $Q(t)$ are considered as random time functions, vector ones in the general case. If we regard risk as a possible damage, then the time model $R = f(T)$ should have the following properties:

1) the process of change in time $R = f(T)$ is considered in general as an unsteady stochastic process;
2) the time of observing the system during T is finite;
3) energy spectrum of the random process $R(T)$ is continuous and other than zero on the whole frequency axis $-\infty < \varepsilon < +\infty$;
4) the correlation interval τ_0 of the random function $R = f(T)$ is limited. The correlation interval is understood as a time interval during which the correlation links between separate components $R(t)$, $Q(t)$ disappear completely. With non-stationary character of random function change $R = f(T)$, the correlation interval in general case depends on the examined time period., i.e. $\tau_0 = f(t)$.

Non-stationary stochastic processes of change $R = f(T)$ should be presented as a sum of several processes $R = f(T)$:

$$R(t) = A(t) + B(t) + \varepsilon(t) \tag{7}$$

where $A(t)$ is a non-stationary stochastic process that characterizes irreversible changes in the system due to aging, deterioration and adjustment; $B(t)$ is a stationary stochastic process that characterizes reversible changes $R(t)$ caused by fluctuations of external operating conditions of the system; $\varepsilon(t)$ is a stationary stochastic process of measurement errors $Q(t)$.

Earlier work [4] describes the methods of evaluating the time factor when planning multi-parameter reliability tests of complex systems (parameter Q):

1. Method employing time factor when modelling risk in the conditions of orthogonal shift.
2. Method assessing time factor by transforming the regression parameter from time function to numerical coefficients.
3. Method of assessing time factor in the experiment when one of the controlled variables is time.
4. Method of assessing time factor using spectrum-correlation theory of random processes.

This can be partially explained by the fact that the risks theory for complex dynamic systems took their roots from the classic formula introduced by F.R. Farmer R=QC, where both the probability of initial events (emergencies and disasters) Q and the damage caused by them C were understood as sets which are not dependent analytically from time. At present this would seem outdated, but in the 60s of the previous century time parameter was not being given proper attention. Although at that time already it was specially noted that reliability and failure-free operation of complex systems are inherently time related. Considering the above said, the present article is primarily oriented at considering time factor when modelling risk R as a pivotal point in the theory of anthropogenic risk.

3. Mathematical models that allow to consider the time factor in predicting the anthropogenic risk

Class 1. Probabilities of initial events and damage are random time functions (random processes), in general case both dependent and independent.
Then for independent random processes with distributions $f_Q(q, t)$ and $f_C(c, t)$
$R = H_3\{q, c, t\}$;

$$F_R(r) = \iint\limits_{W_3} f_Q(q, t) f_C(c, t) dq(t) dc(t) \tag{8}$$

Class 2. Probability density of initial events are described by partial differential equations.
It is worthwhile to use the methods where the output (complex, generalized) parameter of the object is regarded as a random function. To determine the probability $q_i(t)$ during time t, the random process is $Y = Y(X, t)$ (X – vector of external and internal influences on the object), then $Y(t)$ is described by n-dimensional density, where n depends on the value of $t \in T$ the rate of change of the random process $Y(t)$ and demands precise calculations. The drawbacks of this class of models are very complex input data in the form of multi-dimensional distribution laws, the process of obtaining this data is very difficult. The use of one-dimensional distribution densities instead of multi-dimensional ones can significantly alter the calculation results. That is why, it was suggested in studies [7,10] to use, when determining probability $q_i(t)$, the additional limitations on the random process $Y(t)$.
Suppose $Y(t)$ is a continuous one-dimensional homogeneous Markov process with finite Euclid phase space. This process is described by the function $Q(\theta, y, t, Y)$ - the probability that the object at the time θ ($\theta > 0$) is in state y, then at the time $t(t > \theta)$ it will be in one of the states $Y \subset \Omega$, where Ω – θ is the algebra of subsets of phase space. Function $Q(\theta, y, t, Y)$ satisfies the Chapman–Kolmogorov equation, and the probability density of the transition $f(\theta, y, t, Y)$ satisfies the partial differential equations (both forward and backward Kolmogorov equations).

$$\left.\begin{aligned}
&\frac{\partial f(\theta,y,t,Y)}{\partial\theta} + \sum_{k=1}^{n}\alpha_k(\theta,y)\frac{\partial f(\theta,y,t,Y)}{\partial y_k} + \frac{1}{2}\sum_{i,k=1}^{n}\beta_{i,k}(\theta,y)\frac{\partial^2 f(\theta,y,t,Y)}{\partial y_k^2} = 0\\
&\frac{\partial f(\theta,y,t,Y)}{\partial t} + \sum_{k=1}^{n}\frac{\partial}{\partial y_k}\left[\alpha_k(\theta,y) f(\theta,y,t,Y)\right] - \frac{1}{2}\sum_{i,k=1}^{n}\frac{\partial^2}{\partial y_i \partial y_k}\left[\beta_{i,k}(\theta,y) f(\theta,y,t,Y)\right] = 0
\end{aligned}\right\} \tag{9}$$

where coefficients $\alpha(\theta, y)$ and $\beta^2(\theta, y)$ are drift and diffusion coefficients, correspondingly, that equal

$$\left.\begin{aligned}
\alpha(\theta,y) &= \lim_{t\to 0}\frac{M[Y(t+\theta) - Y(\theta)\big|_{Y(\theta)=y}]}{t};\\
\beta^2(\theta,y) &= \lim_{t\to 0}\frac{D[Y(t+\theta) - Y(\theta)\big|_{Y(\theta)=y}]}{t}.
\end{aligned}\right\} \tag{10}$$

To find the coefficients $\alpha(\theta, y)$, $\beta^2(\theta, y)$ of equation (10) the following system of equations must be solved

$$\frac{\partial m_1(\theta,y)}{\partial\theta}=\alpha(\theta,y)\frac{\partial m_1(\theta,y)}{\partial y}+\frac{\beta^2(\theta,y)}{2}\cdot\frac{\partial^2 m_1(\theta,y)}{\partial y^2};$$
$$\frac{\partial m_2(\theta,y)}{\partial\theta}=\alpha(\theta,y)\frac{\partial m_2(\theta,y)}{\partial y}+\frac{\beta^2(\theta,y)}{2}\cdot\frac{\partial^2 m_2(\theta,y)}{\partial y^2}, \tag{11}$$

where m_1, m_2 are, correspondingly, conditional expected value and dispersion of the process:

$$m_1(\theta,y)=M\ [Y(t)]\Big|_{Y(\theta)=y}=\alpha(t)Y=y\int_{-\infty}^{\infty} ydF_y(\theta,y); \tag{12}$$

$$m_2(\theta,y)=M[Y^2(t)]\Big|_{Y(\theta)=y}=\beta(t)Y-\alpha^2(t)Y^2=$$
$$=y\int_{-\infty}^{\infty}\varphi(\theta,y)y^2dy-y^2\left(\int_{-\infty}^{\infty} ydF_y(\theta,y)\right)^2. \tag{13}$$

It is could be seen from equations (12) and (13) that mathematical expectation and dispersion of the process are functions of time and depend on type and values of the laws of dispersion in the slices of the random process *Y(t)*.
Therefore, infinitesimal characteristics of the random process *Y(t)* allow to find probability of the system transition from one state to another during time interval [t_0, t_k], and calculate distribution of the other functionals of the process. In particular time for process to reach the certain area and distribution of the process *Y(t)* value in the continual area until moment t_k.

Risk models with partial differential equations with leaps of state change of dynamic systems

Class 3. It should be noted that equations (9)–(11) are well-set models of known fundamental preservation laws [10]:

$$\frac{\partial f^{\omega}(x,\,z,\,y,\,t)}{\partial t}+\sum_{j=1}^{n}\frac{\partial A_j^{(\omega)}(f,\,x,\,z,\,y,\,t)}{\partial x_j}=B^{*(\omega)}(f,\,x,\,z,\,y,\,t),$$
$$x,\,y,\,z\in R^n,\ t>0,\ \omega\in\Omega, \tag{14}$$

where $f=\{f^{(\omega)}\}$ is an unknown vector-function (in our case it is $q_i(t)$);

$x,\,y,\,z\in R^n$ spatial coordinates;

A_j и B^* – operators that are considered as specified by the character of modelled physical processes in objects;

Ω – set of parameters ω, numbering equations (14).

Preservation principles (14) reflect the objects functioning, described in the general case by systems of non-linear differential and integral-differential equations.

For the cases when the right part of equation (14) is discontinued, it is necessary to refer to the models of Liouville-Vlasov equations [10]

$$\left.\begin{aligned}&\frac{\partial f(z,\,t)}{\partial t}+\frac{\partial\,[\,f(z,\,t)\,p(z)]}{\partial z}=0;\\&f(z,\,t)\big|_{t=0}=f^0(z),\end{aligned}\right\} \tag{15}$$

where $f\,(z,\,t)$ is probability density of distribution of system state in phase space in time t;
$p(z)$ – field of velocities of state change of the system in phase space;
$f^{\,0}(z)$ – initial probability density of distribution of system state in phase space.

Although Liouville's equation is an equation of continuity and the major conservation principle determining the statistical solutions of equations for dynamic systems, but there are possible applications of this equation with leaps of state change of dynamic systems. In other words, Liouville-Vlasov equation, with leaps of state change, is a solution of a differential equation system with discontinuous right part. The use of the equation (15) with discontinuous coefficient leads to functional solutions. It has been found in [10] that the numerical modelling of equations of Liouville's type with discontinuous coefficients is a significant advantage, in comparison with difference schemes, as the latter in our case are approximating.
The experience of calculating the anthropogenic risk shows that determining the damage $C_i(t)$ does not present any significant difficulties, apart from organizing ones, connected with subjective factors. The majority of problems arise with assigning the values of probabilities of initial events of failures, emergencies, and disasters. Currently, safety theory employs and applies various logical-and-probabilistic models for the assessment of $q_i(t)$. These models are based on the methods of Fault Tree Analysis - Event Tree Analysis, diagrams of functional integrity, general logical-and-probabilistic methodology, with the use of topological methods, logical models and others. Detailed theory of many of these models have been given by scientists both in Russia and abroad. The majority of the models have been automated and implemented in a computerized form [3,5]. They have been recommended by many national and international organizations to be used for practical assessments and calculations in probabilistic safety analysis of complex critically important dynamic systems. However, the overwhelming number of logical-and-probabilistic methods when assessing the risk and safety have to use the equipment reliability parameters in the form of probability or failure rate. This is connected with solving such difficult problems as ensuring high reliability of equipment, low number of failures, heterogeneous and reduced sampling, variability of elements base, differing technological plans, etc.
Equipment elements with lumped parameters are less problematic in obtaining the safety characteristics than the systems with distributed parameters.
There are other possible forms of interrelations between sets Q, C and T. For example, one might consider the previous history of values of anthropogenic risk and others.

4. Postulates of time phenomenon in the theory of anthropogenic risk in in in complex dynamic systems

Postulate evolving from Markov processes theory. Markov process is a stochastic process, the evolution of which after each prescribed value of time parameter t does not depend on the evolution preceding t, given that the process is fixed in time (i.e. 'future' and 'past' of the process do not depend from each other with the given 'present') This postulate is conventionally called Markov postulate [11]. It was first formulated by A.A. Markov in "Proceedings of Physics and Mathematics Society of Kazan University' in 1906.
Markov processes of Brownian motion type are closely linked with differential equations of parabolic type. The transitional density of $f(\theta, y, t, Y)$ diffusion process $Y(t)$ satisfies, with some additional assumptions, Kolmogorov backward equation [9].
In other words, Markov process is a process during which the future evolving of object state depends only from the present current state. For objects with continuous time this means that the process is local in time, that is memory effects are not working.
Shannon's postulate The difficulty of predicting the equipment lifespan of complex dynamic systems lies not only in building the model of changing in time deterioration processes of equipment materials, that will correspond the predicted processes on the interval of previous history, but in preserving this correspondence at the interval of prevention. It is evident, that any mathematical prediction tools render of little use if the physical properties of predicted processes are not taken into account. Determining the regularities of changes in physical processes of equipment deterioration of complex dynamic systems in prediction problems must be based on one of the fundamental laws of physics on preserving the essence of physical processes when inferring the object behavior, that was formulated by C. Shannon that states that major regularities observed in the past will be preserved in the future.

The functioning of complex dynamic systems should be considered, in this situation, as a consecutive change of its states under the influence of external and internal factors (Figure 2).

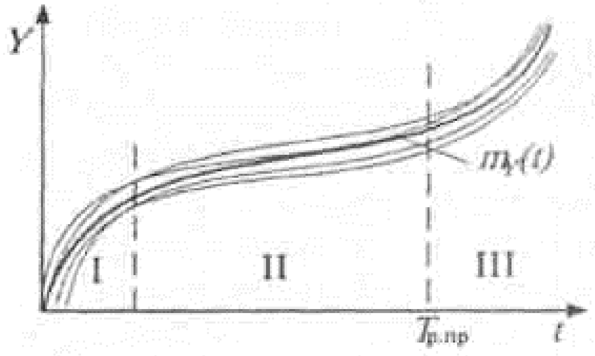

Figure 2. Change of deterioration processes of materials and equipment of complex dynamic systems during operation: my(t) — expected value of the predicted lifespan; I — running in zone; II — area of normal operation period; III — zone of intensive wear and deterioration.

Sedyakin's postulate It is known [4,12], that notwithstanding the law of distribution of random value of object operating time the probability of failure-free operation equals

$$p(t) = e^{-\int_0^t \lambda(\tau)d\tau} \tag{16}$$

where $\lambda(t)$ us the object failure rate.
The right part of equation (16) is the function of the integral, specified by N.M. Sekyakin [12] through

$$r(t) = \int_0^t \lambda(\tau)d\tau \; . \tag{17}$$

"Let us consider the value of this integral as a measure of service lifespan used by the element in the time interval (0, *t*). Evidently, the concept of service lifespan used by the element in the period (0, *t*) agrees with out intuitive understanding. Indeed, if $t = 0$, then $r(0)= 0$. That corresponds the case when the lifespan equals zero.
In another extreme case, when the element works failure-free for indefinitely long period ($t \to\infty$), then, if the function $\lambda(z)$ is nondecreasing, then $r(t) \to\infty$. This means that the elements lifespan is not limited. In actual life, if the definite element is capable of working during finite time $\tau^*=\tau$, and its full available lifespan is

$$r(\tau) = \int_0^\tau \lambda(z)dz \; , \tag{18}$$

where τ is the object failure-free operation time.
As the object's failure-free operation time can not be predicted unambiguously in advance, its full lifespan is a random value.
The element's operation mode is understood as the amount of load.

$$\varepsilon = \frac{H}{H_0}, \tag{19}$$

where H and H_0 are acting and nominal loads of the element.
Depending on the value ε function $w(\tau)$, can change, as a matter of fact, within a wide range. However, if $r(\tau)$ is determined with a definite value ε, then the object failure rate will, according to (16)-(17), present a well-defined function

$$\lambda(t) = \lambda(t, \varepsilon) \; , \tag{20}$$

where ε is determined from equation (19).
Approximate dependency λ(*t*, ε) from *t* for different values of ε is shown in Figure 3.

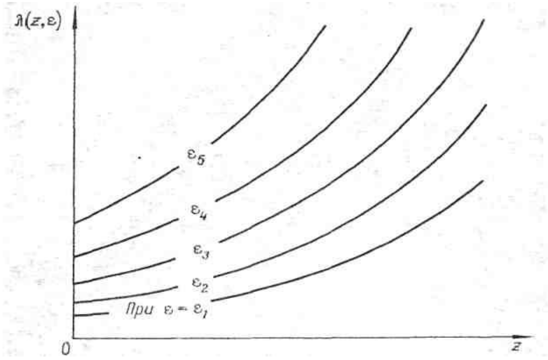

Figure 3. Approximate dependencies of possible failures from time, with operation conditions εk , k = 1,2,3, ...

Using the introduced concept of available lifespan *r*(*t*), it becomes possible to formulate one of the laws of the theory of reliability, Sedyakin's postulate, the meaning of which is that the reliability of an object depends on the value of used lifespan in the past and does not depend on how this available lifespan has been used [12], i.e.

$$P\left(\frac{t}{r}\right) = p^{(1)}\left(\frac{t}{t_1}\right) = p^{(2)}\left(\frac{t}{t_2}\right), \tag{21}$$

where t_1 and t_2 satisfy the integral relation

$$r = \int_0^{t_1} \lambda\left(z, \varepsilon_1\right) dz = \int_0^{t_2} \lambda\left(z, \varepsilon_2\right) dz. \tag{22}$$

It should be noted, that if this law is true, then the sphere of its application has to be limited by those physical processes which do not lead to the qualitative change of the structure of object materials. In following this condition it is natural to expect, that the object reliability in the future must depend on the amount of the lifespan used in the past. Here, the left part of the equation (22) corresponds to the lifespan, used by the object for the period x_1 in conditions $\varepsilon = \varepsilon_1$, and the right part of the equation is the lifespan of the object used for the period x_2 in the conditions ε_2 . It should be born in mind, that equations (21) and (22), being of statistical nature, show the laws of object behavior in mass sense" [12].

Lyapunov's postulate In chaotic dynamic systems the concept of trajectory loses its sense after a certain characteristic time (Lyapunov's time) [13]. Chaos will be understood as the system behavior when the initially close trajectories diverge exponentially in a certain time. The mode is called chaotic if the distance between any two points, however small originally, grows exponentially with time. A.M. Lyapunov's postulate is formulated as follows: the divergence of trajectories is described by the function *exp*(*t/τ*), where 1/τ is, for chaotic systems, a positive value. Value 1/τ is called Lyapunov's index, and τ Lyapunov's time [13, 14].

Prigogine postulates. There are three types of the laws of nature:
1. the first type operates with the trajectories in classic Newtonian mechanics and wave functions in quantum mechanics;
2. the second type deals with statistical framework of laws of nature (J.Gibbs, A.Einstein), it is 'deduced' or 'reduced';
3. the third type of laws of nature states that the laws of chaos are probabilistic, yet unreliable.
The laws that govern the behavior of stable systems are deterministic and reversible in time. And, vice versa, the laws describing the chaotic systems, relate to probabilities and include irreversibility.

The evolution of chaotic systems in time demands irreducible probabilistic description, in terms of ensembles and probability distributions. The evolution of probability distribution has to be described in space that is time-dependent.
The solution of time paradox is only possible that the space becomes 'temporally-related' as the past and the future do not play the same role.
Prigogine postulates can be formulated as follows:
1. Chaos leads to including the arrow of time in fundamental dynamic description of system behavior. The evolution of systems with $t \to +\infty$ and $t \to -\infty$ is different.
2. All systems that allow irreducible probabilistic description are considered chaotic.
3. Laws describing chaotic systems relate to probabilities and are characterized by irreversibility.

5. Conclusion

1. Complex dynamic systems, as a rule, have a long life cycle. That is why, it is of great importance, in the theory of anthropogenic risk, to work out and develop the methods and models of predicting the changes in time of risk quantitative values.
2. The article describes three classes of models for predicting the anthropogenic risk, which, according to the authors' view, are most promising in terms of the solution of the problems described in the first part of the article.
3. Emergencies and disasters risks are characteristic of such critically important complex dynamic objects as nuclear power systems, aircrafts, systems of hydrocarbons transportations, chemical industry plants, and others. That is why, the article focuses on the models of anthropogenic risk, described in terms of non-linear differential and integral differential equations, with jumps and discontinuous coefficients.
4. This is the first time that the postulates have been defined that will allow to work further on time phenomenon application in the theory of anthropogenic risk, which is one of the basic fields of modern mathematical theory of safety of critically important objects.

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