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Taras Boyko[1], Mariia Ruda[1], Mykhailo Paslavsky[2], Volodymyr Lentyakov[2]

[1] Lviv Polytechnic National University, Lviv, Ukraine
[2] Ukrainian National Forestry University, Lviv, Ukraine

Systemic approach to the analysis of ecological reliability of consortive protective ecotones

Abstract
The article presents a methodology for assessing the environmental reliability of consortium ecotones of protective type on the roads of the Lviv railway. It was established that the spatial or morphological structure reflects the compound, structural relations and spatial arrangement of structural elements or ecosystem blocks, which determine the peculiarities of its functioning under certain environmental conditions. The task of the functional structure is to reflect the features of the work (functioning) of the structural components of the ecosystem. It characterizes the pace, amount and effects of substance-energy exchange, stability, performance and other important functions. The totality of the design of protective forest plantations on the railway line operates as a single system or forest-melioration complex — a consortium that performs the functions of an ecological framework, where elements and subsystems interact, providing a synergistic effect. The spatial structure of the consortium ecotones of the protective type of the Lviv railway was constructed. The analysis of the structure of consortium ecotones of the protective type and the indicators of ecological reliability are determined.

Keywords: consortium ecotones, ecological reliability, ecological stability, capacity of ecosystems.

Introduction

Ecosystems of different levels of organization have their own specific features of internal structure, external relations, the scope of material-energy transformation and spatial location. Normally, ecology distinguishes the spatial and functional structure of ecosystems. By the structure is meant the internal constitution of the system and certain connections between its constituent parts. Spatial or morphological structure reflects the composition, structural relations and spatial arrangement of structural elements or ecosystem units which determine the peculiarities of its functioning under certain environmental conditions. The task of the functional structure is to display the features of the operation (functioning) of the structural components of the ecosystem. It describes the pace, volume and effects of substance-energy exchange, stability and resistibility, productivity and other important functions. The aggregate of the structures of protective forest plantations (PFP) on the railway lines functions as a single system or forest-amelioration complex — a consortium that performs the functions of the ecological framework, where the elements and subsystems interact, providing a synergistic effect (Boyko, 2011; Stolyarcuk, 2010; Obshta, 2018).

At the same time, natural ecological systems belong to the class of complex systems. Their features are determined by a number of factors: the impossibility of a clear mathematical description; the presence of many parts of the structural composition; the existence of a significant number of links between individual structural units.

From the standpoint of ecological safety, the objectives of studying the ecological reliability of the ecosystem is to see how its constituent elements function in interaction with each other and why there can be reversible or irreversible changes that bring the threat to the environment. The safety of the ecosystem is taken to mean such a property that determines the risk of loss of its stability, balance and viability, provided its fulfillment of the spatial-functional role.

The objective of the work is to develop a methodology for assessing the ecological reliability of the CPE on the lines of the Lviv railway.

To achieve this objective, it is necessary to achieve the following goals: to construct the spatial structure of the CPE of the Lviv railway; to carry out an analysis of the structure of the CPE; to propose a methodology, in particular, to determine indicators of the ecological reliability.

Analysis of key studies and publications

The idea of a consortium arose in the 1950s due to the works by V.M. Beklemyshev (1951) and L.G. Ramensky (1952), who was the first to define the consortium as an elementary unit of the functioning of the biogeocoenosis structure (BGC) (Stolyarcuk, 2009). Later on, many researchers worked in this field. As of today, among Ukrainian scientists, the greatest contribution to the study of consortive ties was made by Y.V. Tsaryk (2002; 2001; 2008).

In foreign scientific publications, the terms “ecotone” and “geo-ecotone” have been given sufficient attention. An analytical review of these publications is presented in the works by T.V. Bobra (1999; 2000; 2005), M.D. Grodzynsky (2005), P.M. Demyanchuk (2002; 2011), and G.I. Denysyk. However, there are no studies on their ecological functions (Denisik, 1998).

Modern ideas about the multifunctional role of protective-type ecotones in landscapes are related to the ideas in V.V. Dokuchaev’s reports on the harmonic correlation in shelterbelts, forests, meadows, water reservoirs, and the teaching by G.M. Vysotsky about “forest pertinence” — the spatial influence of forests on the environment. Theoretical principles, developed practical and analytical material given in the works by G.M. Vysotsky, V.O. Bodrov, B.Y. Loginov, Y.P. Byalovych, V.I. Koptyev, M.M. Myloserdov, M.Y. Dolgilevich, O.I. Pylypenko, A.P. Stadnyk, G.B Gladun, V.Y. Yukhnovsky and other researchers makes it possible to outline a rather sufficient scientific picture of the spatial and functional role of protective-type ecotones.

Creation of a protective-type ecotone system is one of the most innovative ways to ensure the stability of anthropogenically altered ecosystems, in particular, increasing their buffer zone due to partial regeneration of forest-based BGCs which are an integral part of natural landscapes, as well as the introduction of consortia of these ecotones in the intrazonal for them upland-type forest-typological conditions, which will ensure ecological safety on the railway lines using exclusively natural mechanisms of the natural system protection.

In 1884, the French chemist A. Le Chatelier formulated the principle (later he received the academic status) according to which any external impacts that disrupt the system's state of equilibrium cause in this system processes that try to weaken the external influence and return the system to the initial equilibrium state. It was initially considered that the Le Chatelier principle can only be applied to simple physical and chemical systems. Later on, the studies showed that the Le Chatelier principle can be applied to large systems such as populations, ecosystems and even the biosphere.

Biological objects have extremely high reliability which far exceeds the reliability of any technical systems. This follows, first of all, from the time of the existence of biological systems which significantly exceeds the time of failure-free existence of technical systems. As the definition of the concept of bio-system reliability, the following concept can be proposed: reliability is the fundamental property of biological objects which determines their effective existence and functioning in randomly varying environments and in time. The degree of reliability is the probability of failure-free existence of systems, which can vary from 0 to 1.

Analyzing the works on the reliability of technical systems, we can conclude that the bulk of the scientific works on the reliability issue is devoted to the formulation and solution of a wide range of optimization tasks, as well as tasks related to the problem of interval estimation of reliability indicators by the results of testing or operation (Denisik, 2012; Mazing, 1976; Krendentser, 1978; Golinkevich, 1977).

Spatial structure of consortive protective ecotones

One of the important steps towards reducing or eliminating anthropogenic impact on the natural environment (NE) in accordance with the national environmental strategy of Ukraine is the formation of ecologically balanced system of nature use on the basis of environmentally friendly transport techniques. Therefore, an important role in the mechanism of reduction and neutralization of such effects in the future should be attributed to the formation of highly productive phytocomplexes with a strong potential for phytostabilization and phytoextraction of contaminated soils. Today, protection from snow and sand drifts, avalanches, landslides, earthfalls, talus, and soil erosion is exercised by PFPs along railway lines which have acquired attributes of consortive protective ecotones on the railway lines (Cherkesov, 1974). PFPs are intended, first of all, to protect railway tracks from adverse aerodynamic actions and provide the normal, uninterrupted movement of rolling stock of the railway at any time of the year (Kovalenko, 1975).

The main principle of the establishment and functioning of the PFP on the railway lines is to ensure the continuity and permanence of the protective, nature-conservation, sanitary and aesthetic functions on the railway tracks (Pilipenko, 2004).

The CPEs are protective plantations whose main purposes involve snow-fencing (snow-protective), wind-protective, shielding, sand-control, anti-erosion, soil-fixing, water-bodies protective, water-regulating, greening, sanitary-hygienic, noise-reducing, anti-abrasive functions (Pichkur, 2008).

PFPs have different effects on the microclimate — this depends primarily on the design of forest strips, that is, the structure of the longitudinal profile of the forest strip, which determines its aerodynamic properties. The longitudinal profile of PFP is called the frontal view along the forest strip.

The cumulative ability of the CPE is characterized by a complex environmental impact and has environment-stabilizing and environment-forming functions (Cheksovskaya, 2006). With systemic and balanced spatial distribution, it is possible to achieve significant positive effects on the adjoining territory. Therefore, it is important to determine the potential area of the CPE on the basis of landscape-ecological methods, which will provide maximum efficiency in time and space and will have a significant synergetic effect.

The CPE of a given structure is an integral element of the PFP consisting of several plant species which are different in height, habit, and which grow in parallel in the immediate vicinity and merge into one structural unit of the protection of the railway line (Fig. 1).

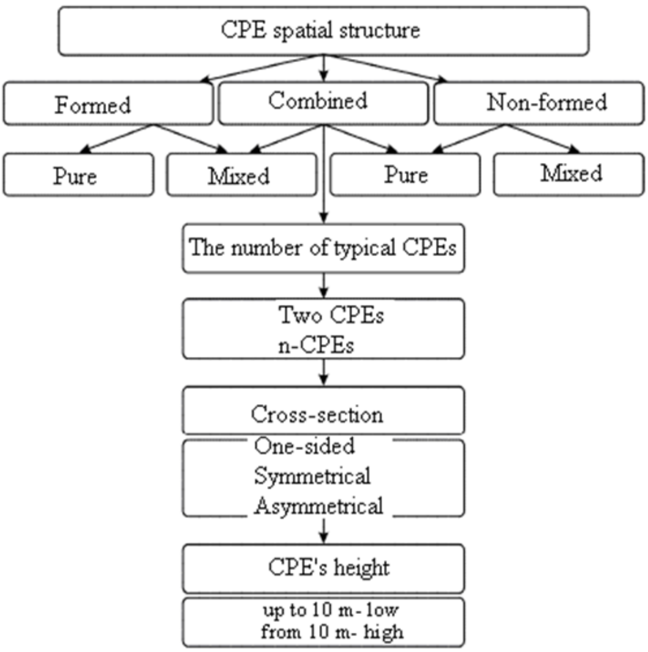


Fig. 1. CPE structure

The spatial and functional role of CPEs on the railway lines is dominant in the optimization of their components, since the location and size of plantations should be subordinated to the windbreak effect and the direction of wind streams harmful for railway lines and adjoining agrocoenoses (dry hot-winds, deflation, blizzard, etc.).

The CPE system is marked by a synergetic effect as to the impact on trophotopes and geochemical processes in the landscape. Within the phytocoenosis of the CPE, there is a close interrelation within the meso-eco-system: plantings provide necessary conditions for the existence of a variety of living organisms which, in turn, interact with the soil cover reproducing and developing. Thus, a relationship is established between the phytocoenosis of the CPE and the soil: there is a cycle of nutrients that are necessary for plant life (salts of nitrogen, potassium phosphorus, etc.).

The structure and composition of the CPE phytocenosis depend on the interrelation of plants between themselves and the relationship between the plants and the environment which consists of a complex of abiotic, biotic, anthropogenic factors. With each element of the system in the railway transport, there are direct and feedback links, as well as certain restrictions on the use of natural, labor and financial resources.

If you express the objects of the railway transport as *x1*, *x2*, *x3*, …, *xn*, CPE as *y1*, *y2*, *y3*, …, *yn*, and relationships that arise between them as *k1*, *k2*, *k3*, …, *kn*, then the quality of the PFP state on the railway (N) at any time (t) can be expressed as a functional dependence (Bedrytsky, 2003):

$$Nt = \Phi[x(t), y(t), k(t)] \tag{1}$$

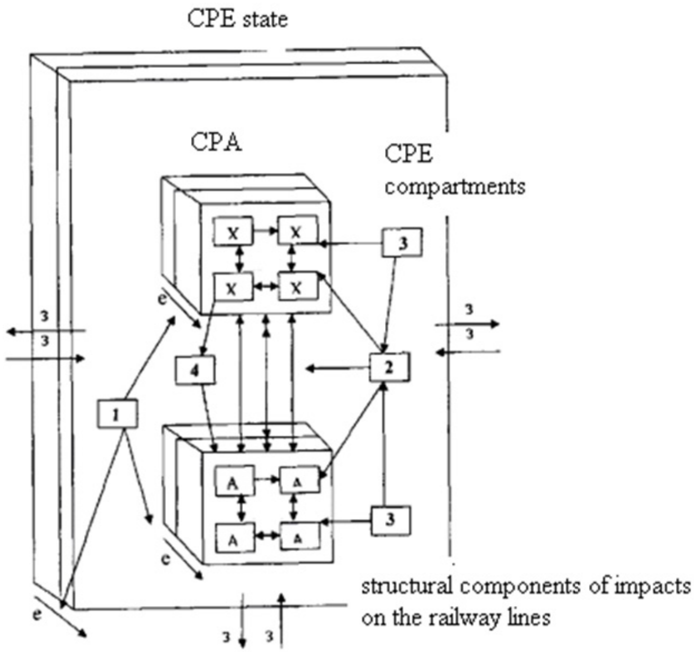
Removal of pollutants from the objects of railway transport ($dp_{МЗТ}/dt$) and other objects of the region ($dp_{фон}/dt$) is limited by the self-purifying ability of the natural environment ($dp_{самооч}/dt$), which is expressed by the formula:

$$\frac{dP_{фон}}{dt} + \frac{dP_{МЗТ}}{dt} \leq \frac{dP_{самооч}}{dt} \tag{2}$$

The difference in the parameters of ecological factors of CPE from those of PFP, inherent in adjacent ecosystems, is a condition for the formation of specific coenoses and changes in the structure of populations, in particular, the specific and unique populations of plants and animals can be formed in the CPE, or a situation may arise when one part of the population is in the same group, the second in the other, and the third — in the ecotone (Plxotnik, 2001).

Optimization of the CPE structure on the railway lines involves analyzing the functional-spatial structure of the protective forest plantations of the railway lines. Long-term research on the lines of the Lviv railway makes it possible to put forward the hypothesis that the functional-spatial structure of protective forest plantations of the Lviv railway is not optimal, which is explained by the small-scale and disproportionate afforestation of the territory of the railway land acquisition by protective forest plantations of polyfunctional importance, as well as forest-typological conditions. On the Lviv railway, protective forest plantations, which have acquired features of the CPE in the geographical space, are formed unevenly in both latitudinal and meridional aspects. The width of the ecotones decreases from west to east and from south to north with significant inclusions of natural forest tracts. Most ecotones of protective type on the Lviv railway, formed on the basis of natural forests, inherent in a particilar territory, perform functions of biocentres and ecosystems, while artificially planted areas become part of the areas of the adjacent territories. However, they have been hardly analysed for compliance with both natural kernels, buffer zones, regenerated territories and territories with specified engineering purposes.

The conducted analysis allows us to imagine the spatial structure of the CPEs on the railway in the form of a principal model of their functional organization (Fig. 2).



1 — unit of coordination and control of biological processes; 2 — unit of positive feedback; 3 — unit of negative feedback; 4 — unit of structural and functional compliance between the CPE and the anthropogenic influence on the part of the railway; e — course of changes in the CPE condition; з — external system links; X — CPE compartments; A — structural parts of the railway lines; arrows indicate the directions of links and influences; double arrows indicate directions and influences of control links

Fig. 2. Model of spatial and functional organization of the CPE (Matveeva, 2014)

Systemic approach to the analysis of ecological reliability of consortive protective ecotones

From the standpoint of environmental safety, a systemic approach to the analysis of possible failures in ecosystems under the influence of external, anthropogenic factors is to see how individual constituent elements of the ecosystem will function in interaction with other parts of it. System analysis of CPE reliability — methodology for the study of any ecosystem by means of their distribution into separate elements and further analysis of these elements — is used for: identification and clear formulation of the problem under uncertainty; the choice of research and development strategy; the precise definition of ecosystems (boundaries, inputs, outputs, links), the identification of the objectives of the development and functioning of the ecosystem.

The CPE is a complex, multilevel and multicomponent entity. Therefore, for the purpose of adequate information and identification of causal relationships, the elements of the CPE are specified. Such an approach allows identifying the hazards and degradation processes that arise on the railway lines. This is provided by the decomposition of the CPE — the dismemberment of the hierarchy and the organization of the CPE into interrelated components (compartments), their subsequent research independently of each other and the coordination of local decisions. Actually, this method is fragmentation of complex ecosystems into simple ones using theorems on conditional probabilities and conditional distributions. In this case, the reliability indicators of simpler subsystems are calculated first, and then the results obtained are grouped in order to obtain the characteristics of the entire ecosystem as a whole.

The considered method is used to simplify the configuration of the CPE and its distribution in space. The effectiveness of the method depends on the choice of the leading element, that is, the element used in the decomposition of the ecosystem. If the element is chosen unsuccessfully, then, despite the identity of the final result, the calculations will be cumbersome. In the case of relatively complex ecosystems, the right choice of key elements to create a simple configuration can be a difficult task.

The difficulties encountered when considering a CPE can be reduced by using the conversion method. It consists in the successive simplification of the CPE with the serial and parallel connection of the elements by converting them into equivalent circuits. The main advantage of this method is its simplicity and accessibility, however, it is not always acceptable in case of gradual failures.

Revealing the mechanisms of sudden and gradual failures and their impact on the degradation of the CPE is of great significance and provides an opportunity to effectively improve the technologies of rehabilitation of contaminated areas in order to increase their environmental reliability on the railway lines.

However, a purely physical approach does not allow direct determination of absolute values of the probability indicators of ecological reliability of the CPE, in particular, to find the time-to-failure law. The reliability models obtained with this approach are of a certain nature — they either simulate any prevailing degradation process of a specific CPE compartment, or exhibit numerous coefficients for a particular state of the CPE. Extending the results of such models of environmental reliability, even to a similar object, but in a different state, can only have a qualitative character.

Methodology for determining ecological reliability of the CPE

In the theory and practice of reliability, the greatest development has become a trend based on the use of only probabilistic concepts (strictly probabilistic theory). In this case, the failures of the CPE are considered as some abstract random events, and the various physical states of complex elements are reduced to two states: operability and malfunction.

Proposed is the methodology of obtaining results on the ecological reliability of the CPE on the railway lines according to the strictly probabilistic (statistical) method. The sequence of calculating the ecological reliability of the CPE is shown in Fig. 3.

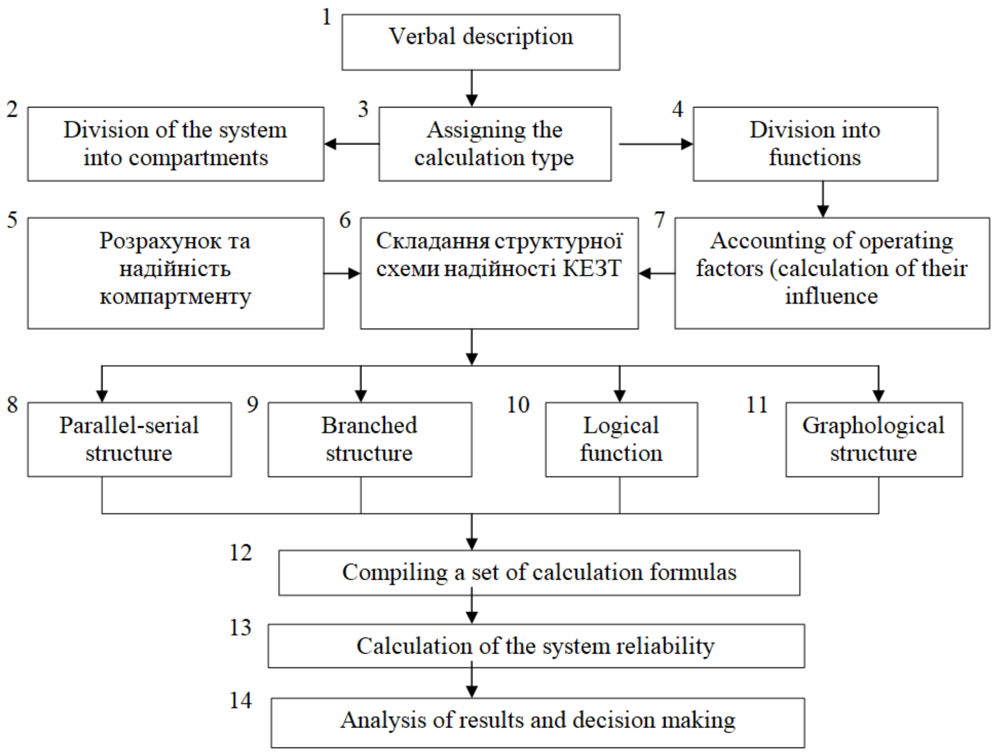


Fig. 3. The algorithm for calculating the ecological reliability of the CPE on the railway lines

Consider the main stages. First of all, we should clearly formulate the task of calculating the ecological reliability of the CPE, where it is necessary to specify: the designation of the CPE, its composition and basic information about its functioning; indicators of environmental reliability and the signs of failure, designated purpose of the calculations; the conditions in which the CPE functions; requirements for the accuracy and reliability of the calculations, for the completeness of accounting the existing anthropogenic factors on the part of the railway.

Thus, a conclusion is made about the nature of future costs. In case of calculating the functional reliability of the CPE, the transition to stages 4-5-7 is carried out. When calculating compartments — to stages 3-6-7.

Based on the results of the studies on the current state of the CPE, statistics of sudden and gradual failures are obtained. The generally accepted division of the failures of ecosystem elements into the so-called "sudden" and "gradual", which lead to ambiguous choice of probabilistic models of failures, has tended to be increasingly rejected in recent years (Plohotnik, 2002; Dylys, 1973; Antonov, 1996).

Usually, a failure is considered "sudden", if the cause of the failure is not identified and it is understood that it arose as a result of some instantaneous change of the parameters under investigation, that is, denied is the existence of any physical degradation processes — the real causes preceding the occurrence of failure. It often turns out that a failure is "sudden" only because it is impossible to monitor the changes of all the determining parameters that can cause a failure (Antonov, 1993; Aronov, 1987).

Next, using the known statistical criteria of agreement, the corresponding random distribution model, developed in the theory of probabilities, is selected and taken as the theoretical model for the probability distribution of failure-free operation of the ecosystem (model of reliability), on the basis of which the necessary quantitative reliability indices of the CPE are determined. Estimation (calculation) of ecological reliability of the CPE is carried out by calculating the probabilities of its operable elements.

Failures in the CPE may arise due to various impacts on the part of the railway. Since each factor depends on many causes, the failures of the compartments that make up the CPE, as a rule, belong to accidental events, and the time of the existence of these factors until the occurrence of failures — to random variables.

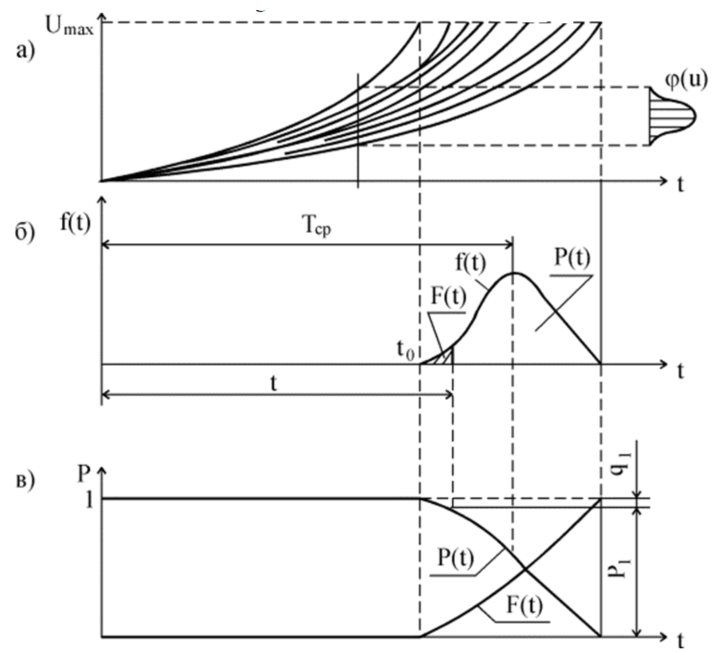
Failures that occur during the period of normal existence of the CPE are called sudden, since they appear at random moments of time, or, in other words, suddenly, unexpectedly.

After analyzing the environmental reliability, it is clear that the object of the study is random events that occur in the CPE on the railway lines. Any continuous distributions which are used in probability theory can be used as theoretical distributions of failures. You can take any curve and use it as a distribution curve of a random variable.

Random event is an event (a fact, a phenomenon) which eventually may or may not occur. Random events (failures, degradation processes, etc.) form random flows and random processes. Flow of events is a sequence of events occurring one after another in any segment of time. For example, failures of an unrestorable CPE form a flow of events (the flow of failures). Under the influence of the flow of failures, the CPE may be in different states (complete failure, partial failure).

The transition of the CPE from one state to another is a random process. The random variable is a value that, as a result of the CPE study, may acquire a certain value, and it is not known in advance which one. The random variable can be discrete (the number of failures over the time t), or continuous (the time of the element development to failure).

In reliability theory, as random variables, usually the system operating time (time before occurrence of failure) is taken. In this case, the function of the distribution density $f(t)$ will serve as a complete characteristic of scattering the elements service life (Fig. 4).



а — realization of degradation function $\varphi(U)$; б — distribution density of the CPE lifetime $f(t)$; в — integral distribution function $F(t)$ and the probability of a failure-free existence of the CPE $P(t)$

Fig. 4. Random value distribution curves with gradual failures in CPE (GOST 27.005-97. Industrial Product depedability)

The pattern of this function depends on the patterns of the process of stability loss by the CPE compartment. The distribution curve $f(t)$ — the failure rate — allows calculating the state of any compartment of the CPE after it has fallen under the influence of the railway T_{CP} (mathematical expectation $M(t)$), dispersion (dispersion D) relative to the grouping centre, and other numerical parameters of the random variable T.

Estimation of environmental reliability indicators

If we take a certain period of time t of a compartment lifetime, the area $F(t)$ of the distribution curve $f(t)$ will characterize the probability of failure (loss of function) of the compartment of the CPE for this period of time (Fig. 4б). Therefore, the left branch of the distribution curve $f(t)$, which belongs to the area of low probability of failure, is usually used to characterize the reliability P of the CPE, while the whole curve $f(t)$ and its parameters are necessary for the estimation of its durability.

The ordinates of the integral distribution function $F(t)$ (Fig. 4в) characterize the probability of the failure of CPE compartment to the given moment of time. In many cases, there is no need to use the functions $F(t)$ or $f(t)$, it will suffice to know the numerical characteristics of these curves. The main characteristic of the position of the curve $f(t)$ is the mathematical expectation $M(t)$ which, in this case, is the average lifetime of the CPE T_{CP} (operating time before failure):

$$T_{cp} = \int_0^{\infty} tf(t)dt \tag{3}$$

The main characteristic of the dispersion of a random variable is the dispersion D or the mean square deviation:

$$\sigma = \sqrt{D}, \quad D(t) = \int_0^{\infty} \left(T_{cp} - t\right)^2 f(t)dt \tag{4}$$

The higher the value of D (or, respectively, σ), the greater the dispersion of the lifetime with respect to its mean value $M(t)$.

In order to assess the ecological reliability of the CPE compartments, the time before failure has been selected as the main random value. Also, the probability of a failure-free lifetime of the CPE $P(t)$ is determined within a given period t. To this end, the value of the integral function is used:

$$P(t) = \int_0^{t} f(t)dt \tag{5}$$

The probability of a failure-free existence of the CPE $P(t)$ refers to the event opposite to the appearance of the failure $F(t)$. That is why $F(t) + P(t) = 1$ or $P(t) = 1 - F(t)$. In this case, the failure distribution function $F(t) = P(t < t_{зад}) = Q(t)$; distribution density $f(t) = dQ(t) / dt$; probability of CPE failure-free in time t: $P(t) = 1 - Q(t)$. The distribution density is determined by the formula:

$$f_n(t) = \frac{1}{n\sigma} \sum_{i=1}^{n} V\left(\frac{t - \xi_i}{\sigma}\right) = \frac{1}{n\sigma\sqrt{2\pi}} \sum_{i=1}^{n} \exp\left[-\left(\frac{t - \xi_i}{\sqrt{2}\sigma}\right)^2\right] \tag{6}$$

where

$$V(t) = \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-x^2}{2}\right)$$

is Gaussian kernel; n is sample size; σ is locality parameter (rating width, experimental parameter).

The experimental random variable in the considered problem is time. Domain of this parameter — $[0, \infty]$. Thus, it is a priori known that the random variables considered belong to the class of non-negative values.

For positive random variables, we propose to use the Gaussian distribution:

$$\hat{f}(t,\sigma)=\frac{1}{n\sigma}\sum_{i=1}^{n}\left[V\left(\frac{t-\xi_i}{\sigma}\right)+V\left(\frac{t+\xi_i}{\sigma}\right)\right] \quad (7)$$

The probability of a fault-free existence of a CPE is the probability that within a given operation time *t,* there will not be a gradual failure in the compartments, that is, the random failure-free operation time ξ will be not less than *t*:

$$P(t)=P(\xi\geq t)=\bar{Q}(t),\quad t\geq 0. \quad (8)$$

If you know the distribution density, you can calculate the distribution function by numerically integrating the density:

$$\hat{F}(t,\sigma)=\int_0^t f(u,\sigma)du=\frac{1}{n\sigma}\sum_{i=1}^{n}\left[\int_0^t V\left(\frac{u-\xi_i}{\sigma}\right)du+\int_0^t V\left(\frac{u+\xi_i}{\sigma}\right)du\right]=$$
$$=\frac{1}{n}\sum_{i=1}^{n}\left[\Phi\left(\frac{t-\xi_i}{\sigma}\right)+\Phi\left(\frac{t+\xi_i}{\sigma}\right)-\Phi\left(\frac{\xi_i}{\sigma}\right)-\Phi\left(-\frac{\xi_i}{\sigma}\right)\right]=\frac{1}{n}\sum_{i=1}^{n}\left[\Phi\left(\frac{t-\xi_i}{\sigma}\right)+\Phi\left(\frac{t+\xi_i}{\sigma}\right)\right]-1, \quad (9)$$

where $\Phi(u)$ is error function integral.

Further, the probability of failure-free operation of the CPE is calculated:

$$P(t)=1-F(t). \quad (10)$$

The average direct remaining time of the ecological state of the CPE is the mathematical expectation of the time left for the existence of the CPE until the next failure, starting at the time *t*, when the CPE was functional. The average reverse remaining time is the mathematical expectation of the CPE lifetime from the beginning of operation, or its restoration after the last regeneration, by the time *t* in which the CPE is capable of performing protective functions. These indicators are calculated only for renewable CPEs.

Defined are the processes $\{V_t, t\geq 0\}$ and $\{R_t, t\geq 0\}$ which are, respectively, called the processes of direct and reverse remaining time:

$$V_t=\tau_{N(t)+1}-1; \quad (11)$$

$$R_t=t-\tau_{N(t)+1}, \quad (12)$$

where (11) is direct remaining time п, or the age, and (12) is reverse remaining time, or remaining failure-free operation of the system by the time *t*; τ_i is the moment of *i*-th failure.

Fig. 5 shows the process of functioning of a renewable object, where τ_i are moments of failures (restorations); ξ_i is operation time between failures; V_t is direct remaining time; R_t is reverse remaining time.

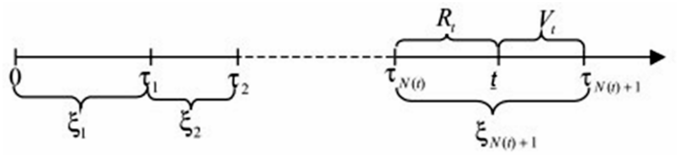


Fig. 5. The process of functioning of a system that is being restored (Kapur, 1980)

In this case, {*Ri*} and {*Vi*} are homogeneous Markov's processes with a multiple states on the time axis [0, ∞].

The intensity of failures of compartments in the CPE is the ratio of the conditional probability that the random time-to-failure will acquire values from the half interval [*t*; *t* + *Δt*] of infinitely small length Δ*t*, provided that a failure until the time *t* did not take place, to the length of this half-interval Δ*t*. In other words, the intensity of failures in the CPE is the ratio of the distribution density of the operation-to-failure to the probability of its failure-free existence:

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{P\left(t \le \xi < t + \Delta t / t \le \xi\right)}{\Delta t} = \frac{f(t)}{1 - Q(t)} = \frac{f(t)}{P(t)} \tag{13}$$

The failure rate is often called the *λ*-characteristic, it shows which part of the CPE compartments fails per unit time relative to the average number of well-functioning CPE compartments.

Conclusions

The studies have shown that the developed methodological approach can be an integral part in conducting environmental studies and enables the authorities responsible for environmental safety to improve the efficiency of preventive and ongoing supervision in order to prevent environmental pollution. Transferring the developed approach to software in a personal computer can serve as the basis for creating a decision-making support system as well as an appropriate information system for managers of different levels.

For a qualitative assessment of the state of the CPE on the railway lines, a cluster analysis of the theory of recognition of radiation safety images should be used, where techniques and methods are developed that allow assigning the object of study to this or that class and characterize its state by some, often very insignificant, attributes.

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