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CONTENTS

Research in behavior of the centre of failure free performance distribution density for redundant complex technical systems

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Abstract. Aim. *For complex highly-integrated technical systems that contain elements that vary in their physical nature and operating principles (combination of mechanical, electrical and programmable electronic components), complex dependability analysis appears to be challenging due to both qualitative and quantitative reasons (large number of elements and performed functions, poorly defined boundaries of interfunctional interaction, presence of hidden redundancy, static and dynamic reconfiguration, etc.). The high degree of integration of various subsystems erodes the boundaries of responsibility in the cause-and-effect link of failures. Thus, the definition of the strength and boundaries of interfunctional and cross-system interaction is of great value in the context of complex system analysis from the standpoint of locating bottlenecks, as well as reliable evaluation of the complex dependability level.* **Methods.** *In order to solve the tasks at hand, the authors propose a method that is based on the research of the behavior of the centroid of an area bounded above by the failure density function graph, below by the coordinate axis, from the right and left by the boundaries of the considered operation interval. Graphical analysis with construction of centroids is performed for each subsystem or structural unit of a complex technical system. After that, based on the partial centroids of the respective subsystems/units, the average centroid for the whole complex system is constructed. The authors suggest using the average centroid as a conditional universal measure of the average dependability level of highly-integrated technical systems that can be used in the development of specific design solutions. In this case, in particular, it is suggested to use the presented method for identification of the subsystem that, when redundant, ensures the highest all-around growth of dependability of the complex technical system as a whole. This condition is fulfilled by the subsystem/unit of which the partial centroid is situated at the longest distance from the average centroid. The assumptions presented in this article and the results obtained are tested by means of a short verification consisting in the calculation of the probability of no-failure of the system and subsystems, construction and analysis of respective graphs.* **Results.** *The method's implementation is presented using the example of a conventional mechatronic system. For the sake of briefness and focus the information is given in a simplified and abstract form. The application of the proposed method for analyzing complex technical systems dependability through the research of density function centroid introduced in this article was the target criterion of the method's development, i.e. identification of bottlenecks and areas with the highest potential for increasing the overall dependability. Further publications will be dedicated to proving the applicability of such entity as a centroid as a dependability evaluation criterion, as well as other applications of the presented method in complex technical systems dependability analysis.*

Keywords: *dependability, complex technical system, mechatronic system, failure density, probability of no-failure, centroid, Weibull-Gnedenko distribution law, redundancy.*

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Introduction

In the beginning, we should provide a description of the mathematical models used herein. Let us consider a conventional technical system of which the failure distribution $\lambda(t)$ is described with the Weibull-Gnedenko law:

$$\lambda(t) = \alpha\lambda_0 t^{\alpha-1},$$

$f(t)$ is the time to failure density function

$$f(t) = \lambda_0 \alpha t^{\alpha-1} \exp\left(-\lambda_0 t^{\alpha}\right)$$

or

$$f(t) = \left(\frac{\alpha}{\beta}\right)\left(\frac{t}{\beta}\right)^{\alpha-1} \exp\left(-\left(\frac{t}{\beta}\right)^{\alpha}\right),$$

where λ_0 is the initial failure density (if $t = 0$);
α is the parameter of the distribution shape;
β is the parameter of the breadth of distribution;

Table 1 Distribution law parameters of primary system units

Parameter	Electronic components	Software	Mechanical components
λ_0, h^{-1}	1×10^{-4}	0,005	1×10^{-7}
α	1	0,5	1,8
β	10000	40000	7742,6368
$\lambda(t)$	$\lambda_{el}(t) = 0{,}0001$	$\lambda_{SW}(t) = 0{,}0025\cdot t^{-0,5}$	$\lambda_{mech}(t) = 1{,}8\cdot10^{-7}t^{0,8}$
$f(t)$	$f_{el}(t)=10^{-4}e^{-10^{-4}t}$	$f_{SW}(t)=0.005*0.5t^{-0.5}e^{-0.005t^{0.5}}$	$f_{mech}(t)=10^{-7}*1{,}8t^{0,8}e^{-10^{-7}t^{1,8}}$

$$\beta = \lambda_0^{-1/\alpha}.$$

The first step is the definition of the time interval $[t_1;t_2]$ and bounding of the studied domain under the graph D_i (fig. 1).

After the limits of the operation period and thus the area D_i have been defined, the subsequent analysis consists in the identification of the area S_i

$$S_i = \iint_{D_i} df dt = \int_{t_1}^{t_2} f_i(t)dt$$

and calculation of the coordinates $(\bar{t}_i;\bar{f}_i)$ of the centroid of the respective domain D_i

$$\bar{f}_i = \frac{1}{S_i}\iint_{D_i} f\, df dt,$$

$$\bar{t}_i = \frac{1}{S_i}\iint_{D_i} t\, df dt.$$

A number of important observations must be made:

The area under curve *f(t)* within the interval $[t_1;\ t_2]$ is the realization probability of a random value of which the distribution is described with the corresponding function *f(t)*. Therefore, from the dependability theory point of view, area S_i of domain D_i is the probability of system failure within the specified time of operation and possesses associated properties, in particular,

$$\lim_{t\to\infty} S_i = 1;$$

Let us call the X-axis coordinate $\bar{t}$ of the centroid of the area under graph *f(t)* calculated for the time interval $[0;\ t_i]$, the "**relative mean time to failure**" of which the limit tends to the true value of the mean time to failure if $t_i\to\infty$:

$$\lim_{t_i\to\infty}\left(\frac{1}{S}\int_0^{t_i} tf(t)dt\right) = \frac{1}{1}\cdot\int_0^{\infty} tf(t)dt = T_1,$$

where T_1 is the mean time to failure [1].

A numerical evaluation of the mean time to failure can be performed by limiting the T_1 range of calculation to t_i, then the mean time to failure will be defined with a certain error even subject to integral expansion by parts:

$$T_1 = \int_0^{t_i} tf(t)dt = -tP(t)\Big|_0^{t_i} + \int_0^{t_i} P(t)dt.$$

Thus, within the interval $[0;\ t_i]$, the centroid X-axis coordinate is the ratio between mean time to failure and probability of such failure.

The centroid Y-axis coordinate $\bar{f}$ characterizes the «**relative failure density of a facility near the mean time to failure**".

Part 1. Input data for calculation

For complex technical systems that contain elements that vary in their physical nature and operating principles (e.g. combination of mechanical, electronic and software components), complex dependability analysis appears to

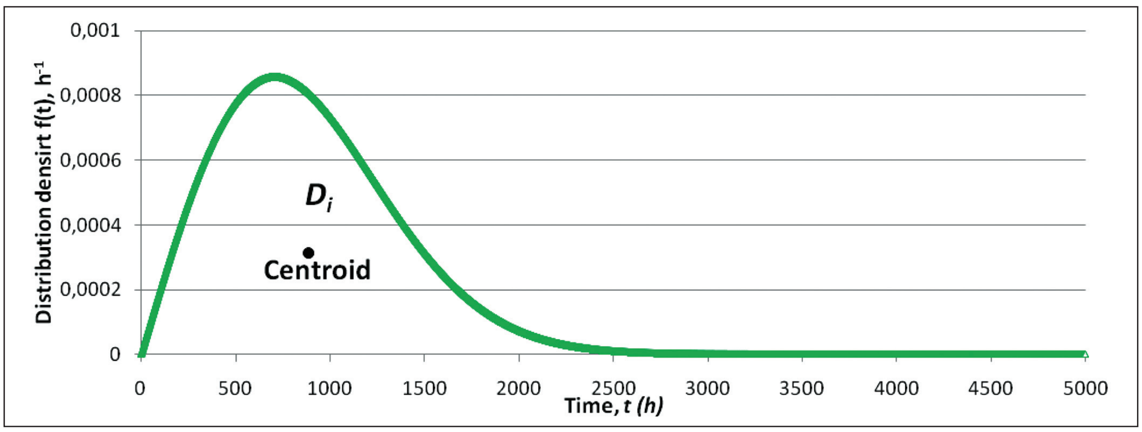

Figure 1 – Failure density of a technical system and location of centroid D_i

Table 2 – Centroid coordinates of a mechatronic system units

#	Parameter	Operation time range, h				
		0 – 2500	**0 – 5000**	**0 – 7500**	**0 – 10 000**	**0 – ∞**
Electr.	S_i	0.2212	0.3935	0.5276	0.6321	1
	$\bar{f}$, h^{-1}	4.447×10^{-5}	4.016×10^{-5}	3.6811×10^{-5}	3.4198×10^{-5}	6.412×10^{-6}
	$\bar{t}$, h	1198	2292	3285	4180	10000
SW	S_i	0.2212	0.2978	0.3514	0.3935	1
	$\bar{f}$, h^{-1}	1.0637×10^{-4}	7.5797×10^{-5}	6.2311×10^{-5}	5.4285×10^{-5}	4.5914×10^{-5}
	$\bar{t}$, h	781.7	1521	2234.4	2925	80000
Mechan.	S_i	0.1225	0.3656	0.611	0.795	1
	$\bar{f}$, h^{-1}	2.9855×10^{-5}	4.2475×10^{-5}	4.5175×10^{-5}	4.3353×10^{-5}	3.7695×10^{-7}
	$\bar{t}$, h	1584.55	3054.64	4324.27	5328.75	6885.42

Table 3 – Coordinates of the average centroid of a mechatronic system

Parameter	Operation time range, h				
	0 – 2500	**0 – 5000**	**0 – 7500**	**0 – 10 000**	**0 – ∞**
$\bar{f}$, h^{-1}	6.023×10^{-5}	5.281×10^{-5}	4.8099×10^{-5}	4.39453×10^{-5}	1.75677×10^{-5}
$\bar{t}$, h	1188	2289.21	3281.22	4144.5	32295.14

be challenging due to both qualitative and quantitative reasons (large number of performed functions, poorly defined boundaries of interfunctional interaction, presence of hidden redundancy, static and dynamic reconfiguration, etc.) [2, 3]. This property manifests itself in the forced transition from design to function analysis when each individual function is submitted to analysis, while system dependability as a whole is characterized with the vector of dependability indicators of all the functions [4, p. 91]. In practice, a combination of structural and functional study of system dependability is used, as well as analysis of various special situations caused by functional failures and/or external events, combination of deductive and inductive methods of analysis (e.g. a combination of failure mode, effects and criticality analysis (FMECA) and failure/fault tree analysis (FTA).

Let us consider the method that involves the identification of failure density centroids for a conventional mechatronic system that in a single device contains an electronics unit, software (SW) and mechanical components.

It is suggested to study the centroid behavior successively within the operation time intervals [0; 2500], [0; 5000], [0; 7500], [0;10000] hours and individually within the interval [0; +∞]. The research will assume that the system operates

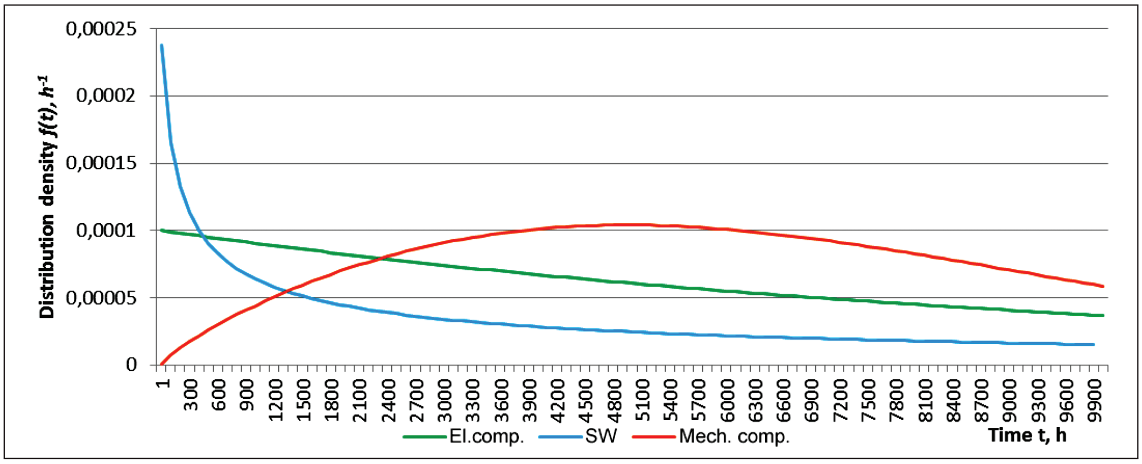

Figure 2 – Failure density functions of a mechatronic system's units

Table 4 – Location of partial centroids of a mechatronic system's units with rate 1 hot redundancy

#	Parameter	Operation time range, h				
		0 – 2500	0 – 5000	0 – 7500	0 – 10 000	0 – ∞
Electr.	S_i	0.04893	0.1548	0.2784	0.39958	1
	$\bar{f}$, h^{-1}	1.23×10^{-5}	1.849×10^{-5}	2.1255×10^{-5}	2.2162×10^{-5}	1.6666×10^{-5}
	$\bar{t}$, h	1613.74	3119	4512.56	5793.2	15000
SW	S_i	0.04893	0.08869	0.12351	0.15482	1
	$\bar{f}$, h^{-1}	9.8646×10^{-6}	9.0145×10^{-6}	8.439×10^{-6}	7.9991×10^{-6}	2.94458×10^{-6}
	$\bar{t}$, h	1187.8509	2321.9787	3422.724	4495.5467	140000
Mech.	S_i	0.015	0.1337	0.37338	0.63207	1
	$\bar{f}$, h^{-1}	6.023×10^{-6}	2.4287×10^{-5}	3.9767×10^{-5}	4.4709×10^{-5}	6.0746×10^{-11}
	$\bar{t}$, h	1937.86	3768.7818	5406.2758	6762.2095	9086.04

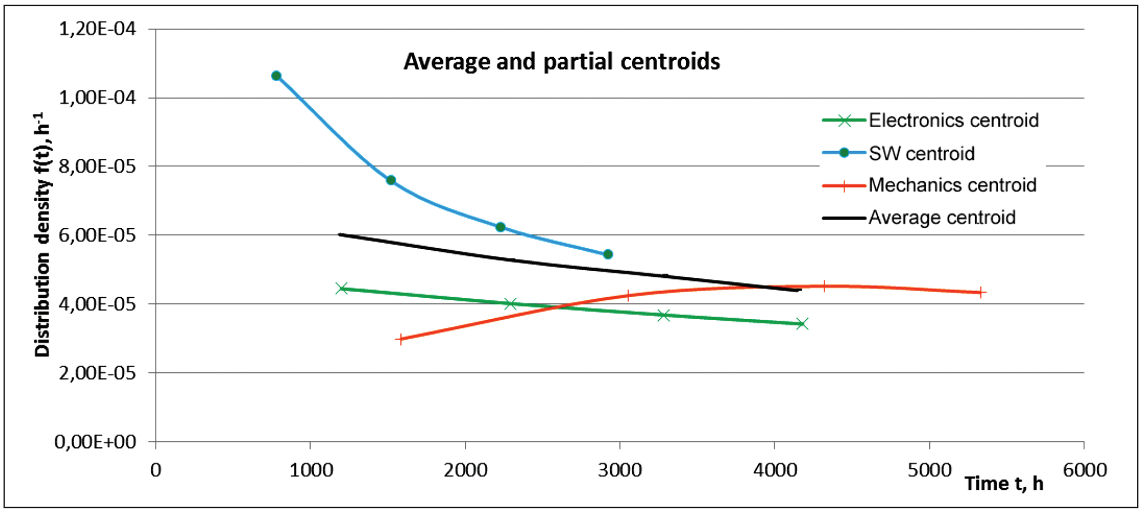

Figure 3 – Location of the average and partial centroids for a mechatronic system

without recovery. The calculation results are presented in table and graphs (fig. 3 – fig. 6).

Now, we suggest considering the system comprehensively by defining the «average centroid» using the formula:

$$\bar{f}_0 = \frac{\bar{f}_{el} + \bar{f}_{SW} + \bar{f}_{mech}}{3},$$

$$\bar{t}_0 = \frac{\bar{t}_{el} + \bar{t}_{SW} + \bar{t}_{mech}}{3}.$$

Part 2. System redundancy

Let us analyze the behavior of the average centroid subject to changing reference parameters. In order to achieve equivalent changes for each of the three subsystems, it is suggested to modify the dependability parameters in such a way as if the system had a rate 1 hot redundancy (dual redundancy). The time to failure density function of a redundant system appears as follows:

$f(t) = 2\lambda e^{-\lambda t}\left(1 - e^{-\lambda t}\right)$ for exponential law,

$f(t) = 2\alpha\lambda_0 t^{\alpha-1} e^{-\lambda t^{\alpha}}\left(1 - e^{-\lambda t^{\alpha}}\right)$ for the Weibull-Gnedenko law

or

$$f(t) = \left(\frac{\alpha}{\beta}\right)\left[\frac{t}{\beta}\right]^{\alpha-1} e^{-\left[\frac{t}{\beta}\right]^{\alpha}}\left(1 - e^{-\left[\frac{t}{\beta}\right]_{\alpha}}\right).$$

The area under the redundant system graph must be equal to the square of the corresponding area of a non-redundant system.

Part 3. Research of centroid behavior

Let us make and verify the assumption that at each specific operation time interval the subsystem (or unit)

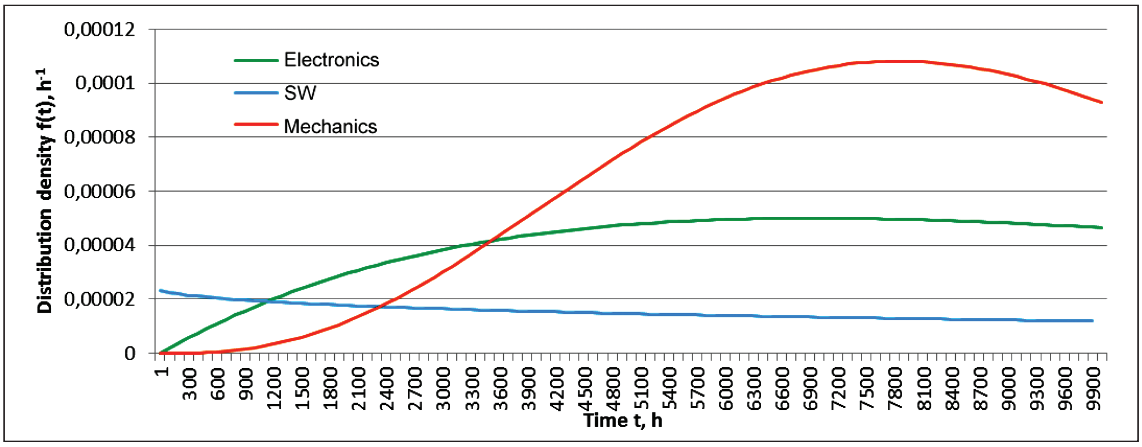

Figure 4 – Failure density functions of a mechatronic system's units for the case of rate 1 hot redundancy

Table 5 – Distance between the partial and average centroids BEFORE redundancy

Subsystem		Operation time range, h			
		0 – 2500	0 – 5000	0 – 7500	0 – 10 000
Electronics	$\rho_{\bar f}$	1.57617×10^{-5}	1.26507×10^{-5}	1.1288×10^{-5}	9.74733×10^{-6}
	$\rho_{\bar t}$	9.916666667	2.786666667	3.776666667	35.41666667
SW	$\rho_{\bar f}$	4.61383×10^{-5}	2.29863×10^{-5}	1.4212×10^{-5}	1.03397×10^{-5}
	$\rho_{\bar t}$	406.3833333	768.2133333	1046.823333	1219.583333
Mechanics	$\rho_{\bar f}$	3.03767×10^{-5}	1.03357×10^{-5}	2.924×10^{-6}	5.92333×10^{-7}
	$\rho_{\bar t}$	396.4666667	765.4266667	1043.046667	1184.166667

Table 6 – Coordinates of the average centroid of a mechatronic system with rate 1 hot redundancy

Redundant subsystem		Operation time range, h			
		0 – 2500	0 – 5000	0 – 7500	0 – 10 000
Electronics	$\bar f$, h^{-1}	4.95083×10^{-5}	4.55873×10^{-5}	4.29137×10^{-5}	3.99333×10^{-5}
	$\bar t$, h	1326.663333	2564.88	3690.41	4682.316667
SW	$\bar f$, h^{-1}	2.80632×10^{-5}	3.05498×10^{-5}	3.01417×10^{-5}	2.85167×10^{-5}
	$\bar t$, h	1323.466967	2556.206233	3677.331333	4668.0989
Mechanics	$\bar f$, h^{-1}	5.22877×10^{-5}	4.6748×10^{-5}	4.62963×10^{-5}	4.43973×10^{-5}
	$\bar t$, h	1305.853333	2527.2606	3641.891933	4622.403167
Full redundancy	$\bar f$, h^{-1}	5.22877×10^{-5}	4.6748×10^{-5}	4.62963×10^{-5}	4.43973×10^{-5}
	$\bar t$, h	1579.816967	3069.920167	4447.1866	5683.652067

of which the partial centroid is the most remote from the average centroid has the highest influence of the location of the average centroid and thus the highest potential on local changes of the whole system's dependability level

The distance between the points is found according to the known formula:

$$\rho_{\bar t} = \left|\bar t_i - \bar t_0\right|,$$

$$\rho_{\bar f} = \left|\bar f_i - \bar f_0\right|.$$

According to the results given in table 5, the partial centroid most remote from the average one both on the

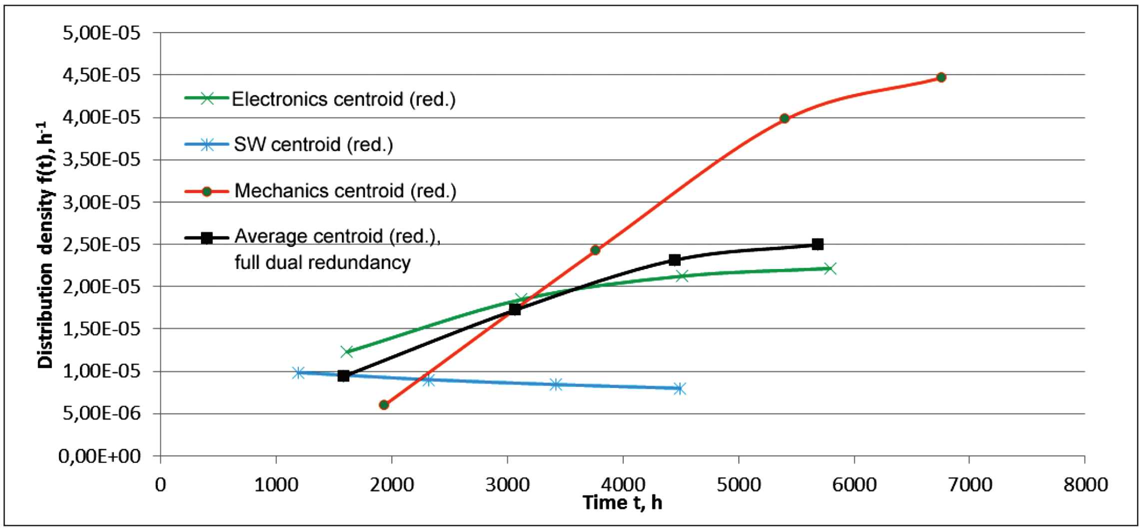

Figure 5 – Location of the average and partial centroids for a mechatronic system with rate 1 hot redundancy

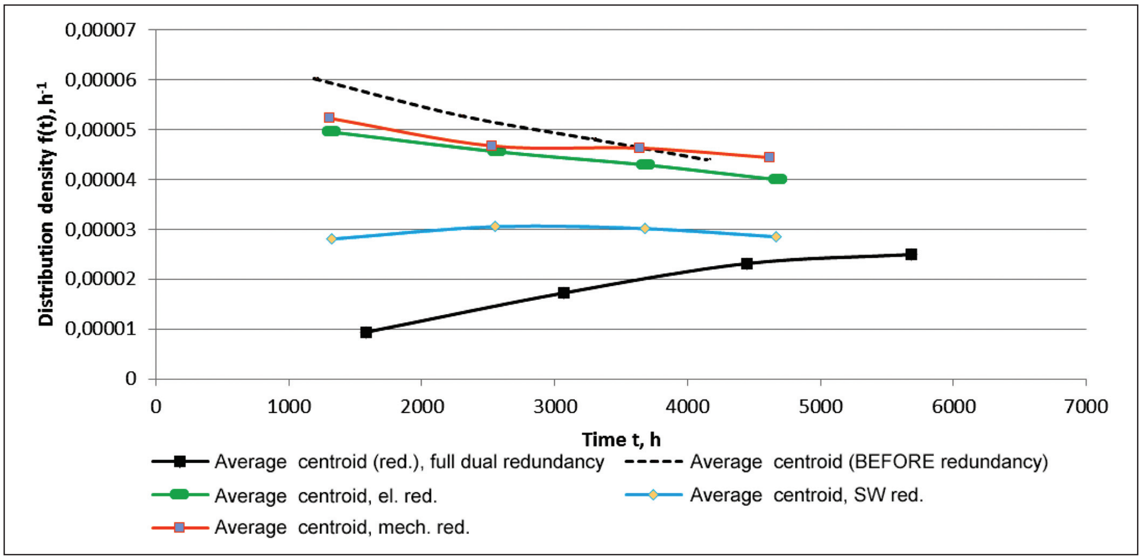

Figure 6 – Coordinates of the average centroid of a mechatronic system with redundancy of one unit

X-axis and Y-axis belongs to the software unit. Let us evaluate the change of location of the average centroid of a mechatronic system depending on the redundancy of either individual or all units.

The calculation results given in table 6 and fig. 6 show that the most significant position change of the average centroid in a mechatronic system is achieved through redundancy of the subsystem of which the partial centroid was most remote from the average one, i.e. the software unit. That is how the biggest growth of dependability of a mechatronic system in general is achieved.

The study of centroid behavior allows evaluating the contribution of varied system elements into the overall dependability through superposition and, most importantly, identifying the subsystem that most contributes to the overall dependability level of the product.

Let us express the result in terms of the probability of no failure (PNF) parameter *P(t)*:

$$P(t)=\exp\left(-\lambda_0 t^{\alpha}\right)=\exp\left(-\left(\frac{t}{\beta}\right)^{\alpha}\right),$$

$$f(t)=-\frac{d}{dt}P(t)=\frac{d}{dt}Q(t).$$

A mechatronic system is an integrated complex of electromechanical, electrohydraulic, electronic elements and computer devices that continuously and dynamically exchange energy and information united by a common system of automated control that includes elements of artificial intelligence [5]. As it is labor intensive and often incorrect to reflect the interconnections between electronic, software and mechanical elements of a complex system at the system level (diversity of performed functions, intrinsic time of subsystems' operation, hidden redundancy, static and dynamic reconfiguration, etc.), in our reasoning in order to express the resulting probability of no-failure of a mechatronic system as a whole as the limits of the confidence interval we will be using a “corridor” of the TBF functions of serial and parallel connection of electronic, software and mechanical units, as well as their arithmetical mean value.

Conclusion

According to the graph given in fig. 7, by the end of the operation time range the TBF function of the software unit is the highest out of all the systems, therefore it is not obvious that the redundancy of the software unit has the highest

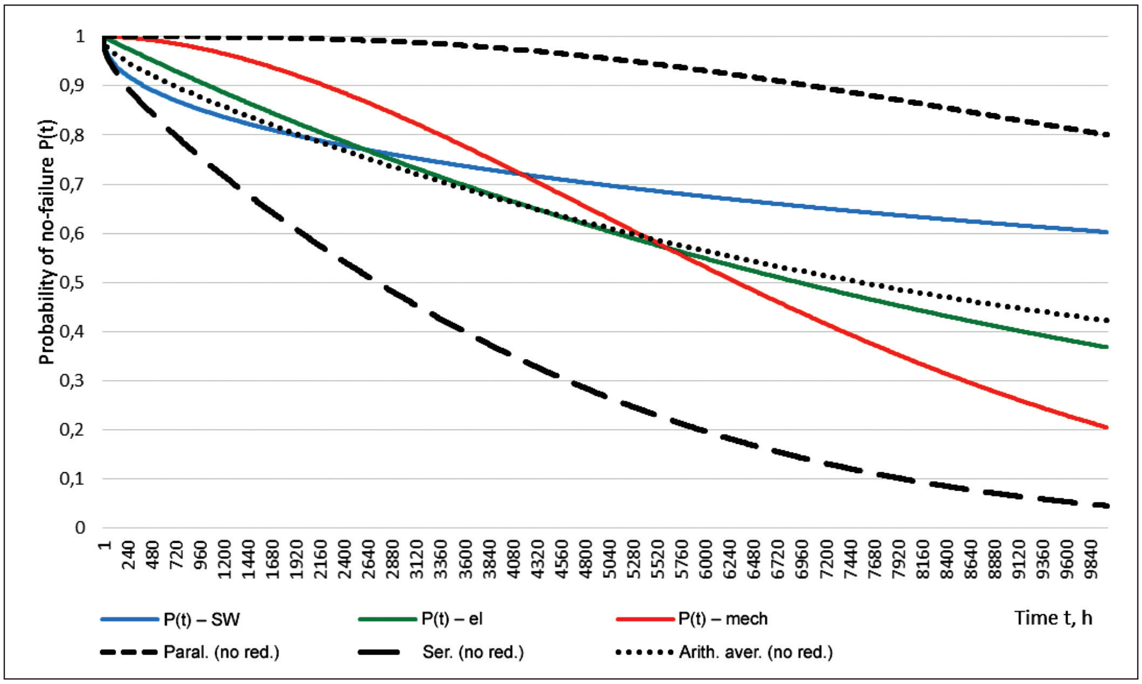

Figure 7 – Probability of no-failure of mechatronic system units without redundancy

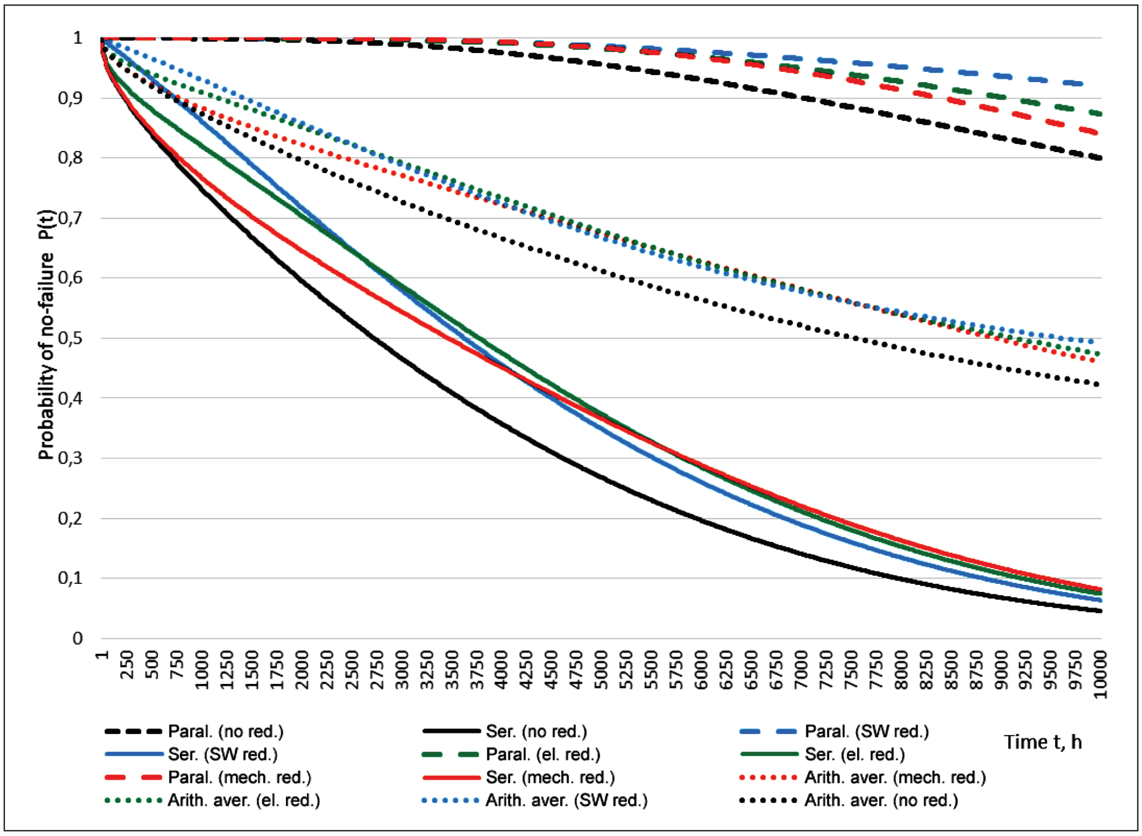

Figure 8 – Probability of no-failure of mechatronic system with one redundant unit

impact on the overall level of dependability.

The calculation results of the probability “corridor” for cases of individual units’ redundancy are presented in fig. 8. It can be seen that the largest upward shift of the “corridor” is achieved by software unit redundancy. The highest total difference between the arithmetic averages of the partial “corridor” and the mechatronic system without redundancy also belongs to the software unit.

The research of the behavior of failure density centroids for components of complex technical systems allows evaluating the degree of mutual influence of subsystems and identifying their contribution into the overall level of dependability of a complex technical system.

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Evaluation of dependability indicators of NK, NKV and NPS type pumps

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Abstract. *One of the strategic areas of development of all oil refineries (OR) in the Russian Federation is the improvement of equipment dependability and safety. The regulatory framework often does not take into consideration the design features of devices which, on the one hand, standardizes the service conditions, but, on the other hand, may cause inefficient maintenance of individual types of equipment. Due to the unpreparedness of the Russian oil refining complex to migration from scheduled preventive maintenance to condition-based maintenance, a large number of obsolete equipment and unceasing growth of technology complexity in modern ORs, it is required to improve and update the statistical and analytical base of dependability indicators of the equipment in operation. Russian and foreign experience of OR operation shows that damaged OR pump equipment can cause significant material damage and human casualties. A fair share of faults and failures that can cause accidents in ORs is concentrated in pump and compressor facilities. Ensuring safety of equipment operation and ORs as a whole requires reducing the probability of accidents. To that effect, technical condition monitoring facilities are deployed and equipment diagnostics are performed. A priori information analysis is also an option.* **Results.** *The article presents the results of documental inspection of performed maintenance of NK, NKV and NPS type pumps of a Russian OR conducted for the purpose of improving dependability and safety of pump operation. Probabilistic and statistical methods were used. The article presents an analysis of dependability indicators based on Gomertz-Makeham parametric distribution. This distribution is widely used in survival analysis and characterizes both system deterioration, and the influence of factors that do not depend on operation time. The authors analyze maintenance operations and repair cycles, identify the least dependable pump components and most frequent repair operations, show the influence of total operation time on pump dependability indicators. For the inspected pumps, the availability factors, utilization factors and average time between maintenance have been defined. The analysis identified that the availability factor of pumps depends not only on the average time between maintenance (that in turn depends on the frequency of required maintenance), but also on the utilization factor of the pumps. Beside the conventional dependability indicators, i.e probability of no-failure and failure rate, based on pump failure rate analysis ultimate times to failure for the inspected pumps were identified. Ultimate time to failure is the operation time beyond which gradual deterioration process significantly accelerates and causes a growth of the number and/or quality of partial failures. A significant accumulation of partial failures results in the loss of function or destruction of equipment. This dependability indicator is the most important in insuring the normal operation from the point of view of operating services.* **Conclusions.** *The article shows taht the identification of the ultimate time to failure for improved dependability and reliability of equipment operation must involve regular updates of input data in order to identify the beginning of the process of equipment "aging" for prevention of accidents caused by out-of-limit tear and wear of equipment.*

Keywords: *oil pumps, dependability, probability of no-failure, failure rate, availability factor, utilization factor, expected time to failure, average time between maintenance.*

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Introduction

In the Russian Federation, there are a large number of oil refineries of various purpose and oil conversion rate. The rising demand for refined products stimulates the growth of the existing ORs and construction of new ones.

The state of the art of pump equipment operation is characterized by the following trends:

- most equipment failures are caused by its unsatisfactory condition;
- inadequacy of obsolete equipment modernization and reconstruction mechanisms causes its significant inferiority to foreign counterparts;
- unreliable operation of pump equipment is also due to non-optimal operating modes: for years, most pumps

output 50 – 60 % of the nominal value with increased pressure.

Therefore, there is a growing necessity to accumulate and analyze statistical data on pump failures.

Analysis of the scope of activities

In total, the inspection covered 37 NK type pumps, 25 NKV type pumps and 24 NPS type pumps. Picture 1 shows the percentages of the total number and types of the considered repair operations on NK, NKV and NPS type pumps. Table 1 shows the scope of the analyzed repair operations on pumps of various types.

NK and NKV are centrifugal horizontal overhung pumps designed for oil and oil products pumping with horizontal and vertical upstream ends respectively. NPS are centrifugal horizontal injection pumps with flat barrel connectors for oil and oil products pumping.

Evaluation of pumps availability factor

For preliminary evaluation of maintenance quality and dependability of pumps, the availability factor has been calculated. This is a composite indicator that characterizes an element's readiness for intended use at a random moment of time except planned maintenance periods when the element's intended use is impossible [1]:

$$K_G = \frac{T}{T + T_R},$$

whereT is the mean time to failure, h;

T_R is the mean failure recovery time, h.

Due to unavailability of pump recovery time records at the inspected refinery, the indicator has been evaluated based on guideline values [2-4].

The matters of oil refinery centrifugal pumps repair are presented in [5-7]. The analysis of the performed repair operations and evaluations of the availability factor of NK, NKV and NPS type pumps are presented in figure 2. Pumps 1-33 are of the NK type, 34-46 of the NKV type, 47-60 of the NPS type.

The minimal values of mean time between failures for the NK type pumps and thus low dependability factors are observed in the following pumps:

- No. 2 on the list – N-11a of installation TK-1 (mean time between repairs is 1 003 h, availability factor is 0.964);

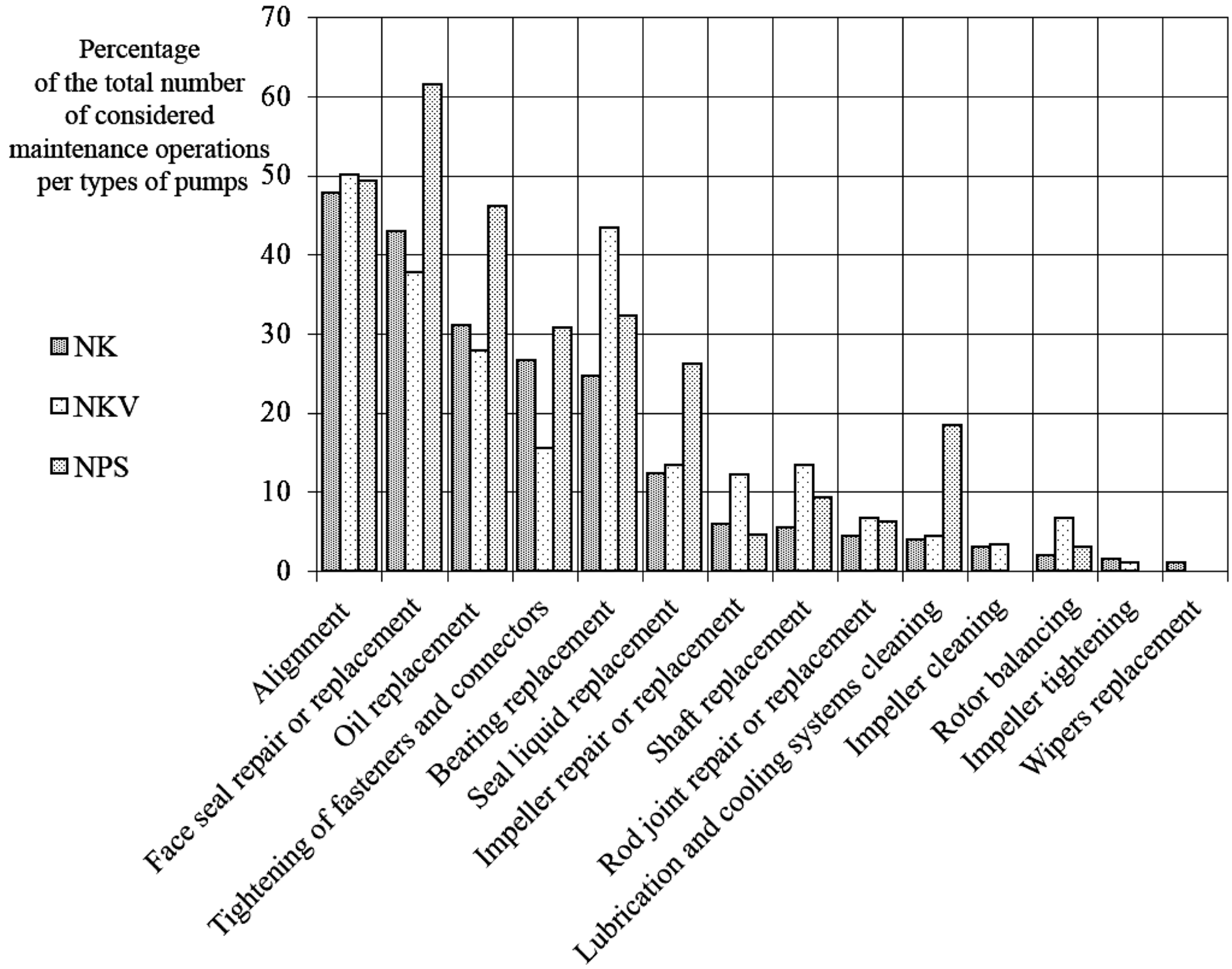

Figure 1 – Percentages of types of pump repair operations

Table 1. Scope of the analyzed repair operations on pumps of various types

Type of repair operation	Repairs of NK type pumps		Repairs of NKV type pumps		Repairs of NPS type pumps	
	Q-ty, units	Percentage	Q-ty, units	Percentage	Q-ty, units	Percentage
Total number of considered repair operations, incl.:	203	100.0	90	100.0	65	100.0
- current	110	54.2	44	48.9	42	64.6
- medium	77	37.9	39	43.3	17	26.2
- overhaul	16	7.9	7	7.8	6	9.2

- No. 3 on the list – N-11b of installation TK-1 (1 117 h and 0.968);
- No. 19 on the list – N-39 of installation AVT-3 (504 h and 0.947);
- No. 30 on the list – N-2 of installation AT-6 (797 h and 0.968);

Pump N-39 of installation AVT-3 is paired with pump N-20 of AVT-3 and pumps desalted oil into column K-1 in three flows. According to the provided data for the year 2013, the pump operates without rapid changes in process parameters: oil temperature is 94.7 °C – 115.0 °C (104.9 °C average), fluid usage is 420.0– 489.4 m^3/h (464.6 m^3/h average), upstream pressure is 4.3 – 6.0 kg/cm^2 (5.3 kg/cm^2 average). Total time of operation at the end of the analyzed period is 51 260 h. The pump's operating pattern within the analyzed range (time to failure with subsequent repair is given within brackets) is: T – C (344) – T (548) – T (509) – T (1 493) – C (75). According to the work and repairs schedule, current repairs are to be conducted after 4 680 h, medium repairs must be conducted after 14 040 h (after last repair operation). Non-observance of the schedule and frequent shutdowns for maintenance can be explained by poor maintenance or lack of quality control of spare parts.

Similar analysis can be provided for pump N-2 of installation AT-6 and pumps N-11a and N-11b of installation TK-1. In all cases there are no objective reasons for low time to failure.

An analysis of figure 2 brought out a connection between the utilization factor and availability factor. The correlation factor for the utilization and availability factors of NK type pumps is 0.753 (0.536 for all considered pumps). The cor-

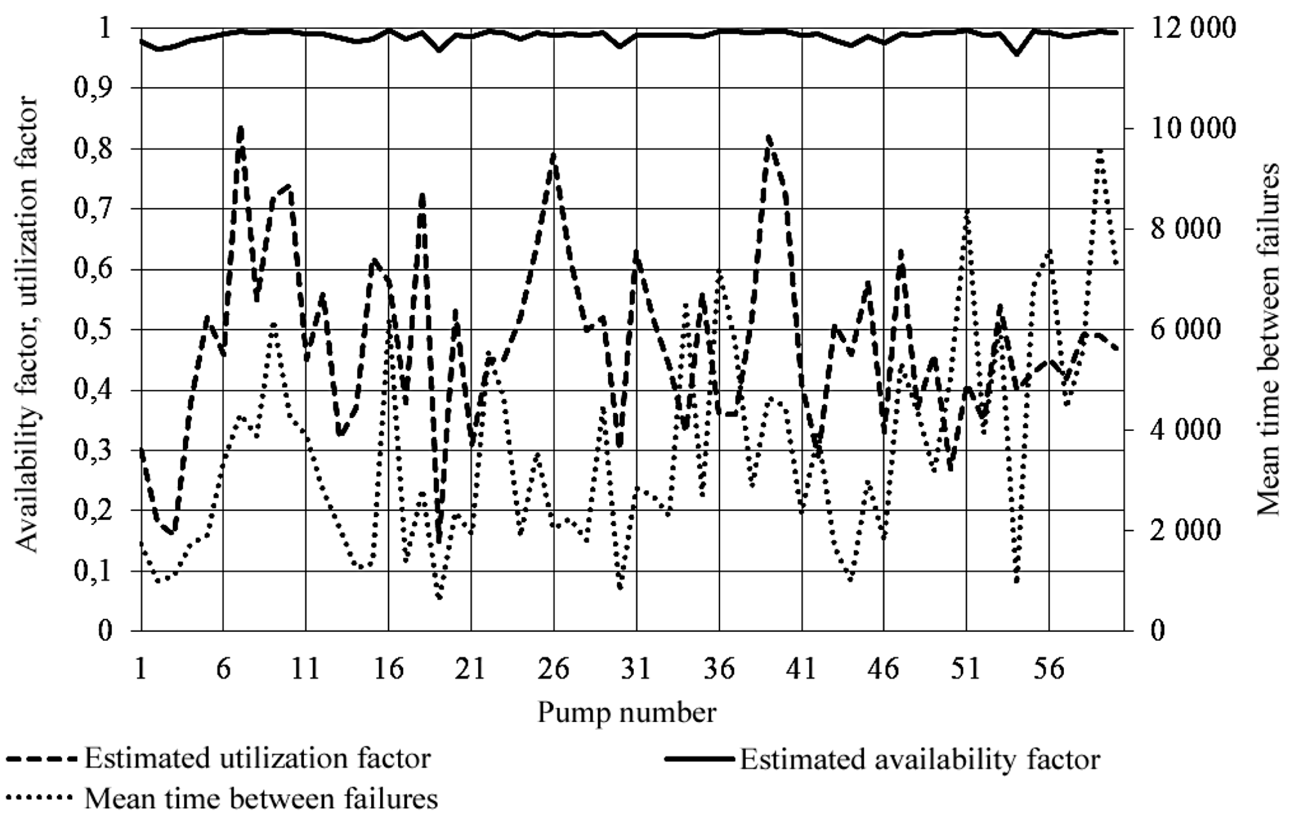

Figure 2. Evaluation of the availability factor, utilization factor and average time between pump failures

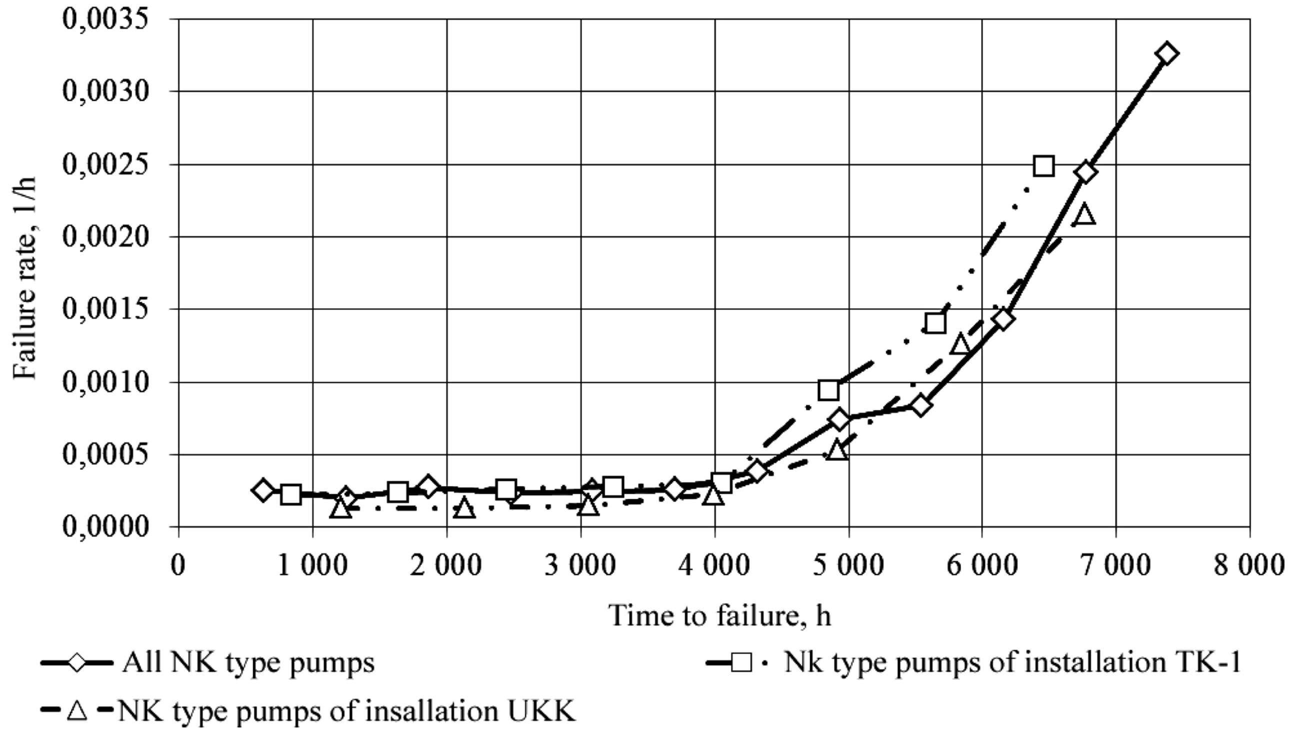

Figure 3. Failure rate of pumps

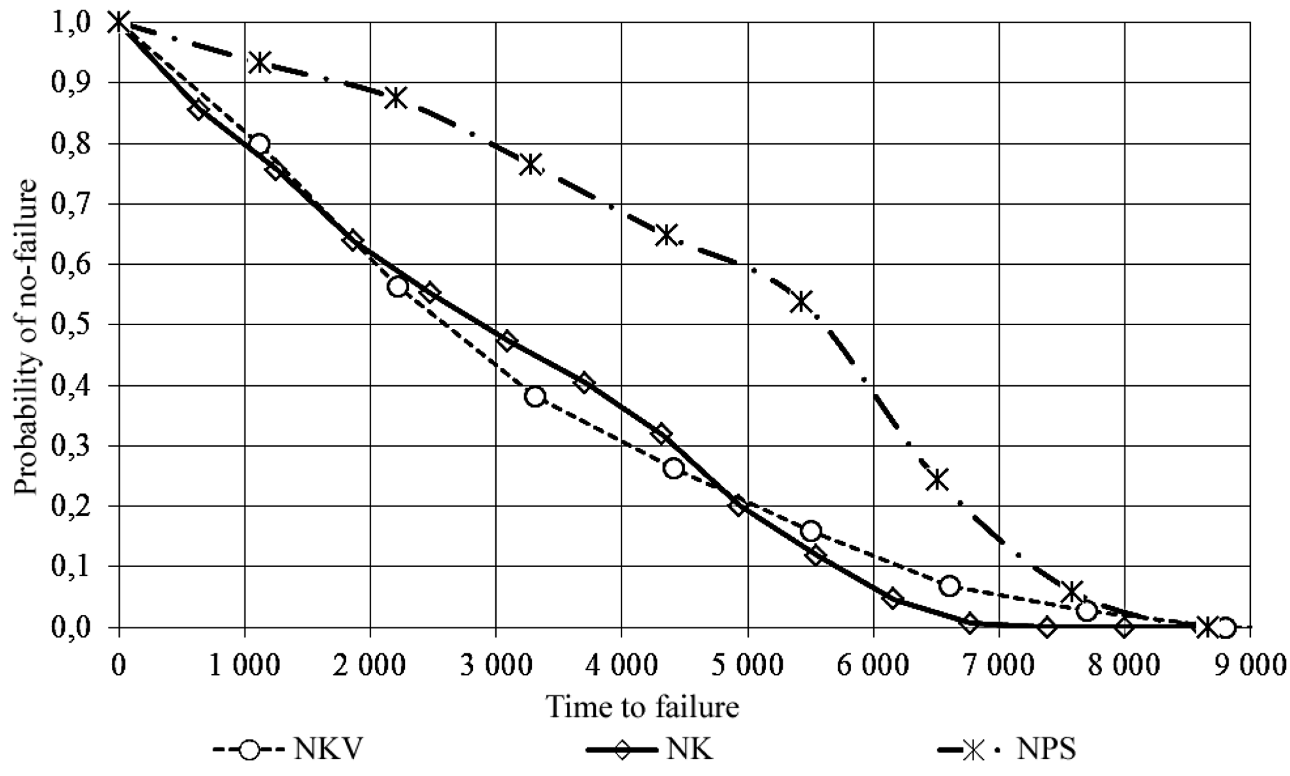

Figure 4. Probability of no-failure of pumps

relation factor for the availability factor and mean time to failure of NK type pumps is 0.737 (0.623 for all considered pumps).

The high correlation factor for the utilization factor and availability factor allows predicting an increase of the availability factor as the utilization factor grows.

Identification of probability of no-failure and ultimate time to failure

Figure 3 shows the failure rate of the analyzed pumps.

In Figure 3, it can be seen that the failure rate of the pumps in different installations matches the failure rate of all pumps

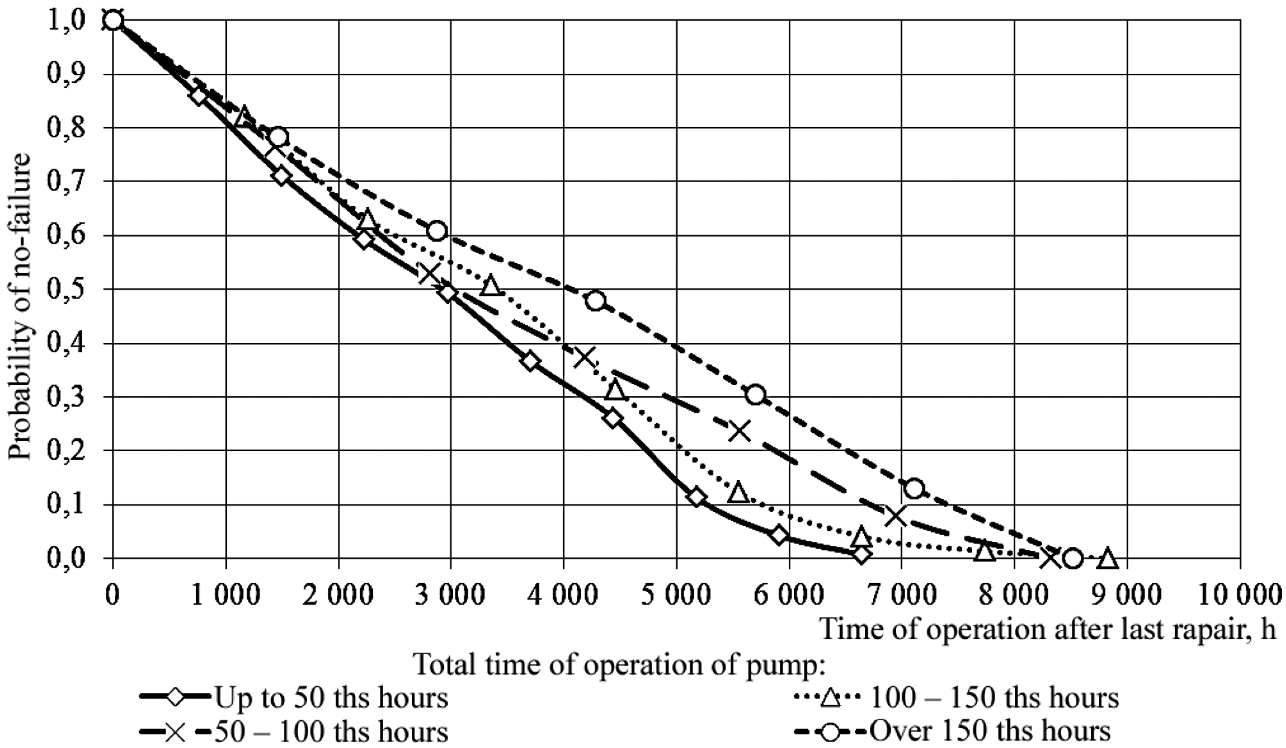

Figure 5. Probability of no-failure of NK type pumps

of this type. We can also identify the time of operation that is characterized by the beginning of abrupt growth of failure rate: 4 100 h for NK type pumps, 4 400 h for NKV type pumps and 5 400 h for NPS type pumps. The above abrupt growth characterizes the expected time to failure.

The probabilities of no-failure of pumps are presented in figure 4. NPS type pumps have a higher probability of no-failure.

The parent distribution of time to failure can be described with a Gomertz cumulative distribution factor. In this case the no-failure operation time is described with the following equation [8, 9]:

$$P(t) = \exp\left(-\int_0^t \lambda(t)dt\right),$$

where

$$\int_0^t \lambda(t)dt = K_1 t + K_2\left(\exp(K_3 t) - 1\right),$$

$$\lambda(t) = K_1 + K_2 K_3 \exp(K_3 t),$$

where K_1, K_2 and K_3 are positive constants that define the impact of environmental factors and system deterioration, h^{-1};

λ is the failure rate, h^{-1};

t is the time to failure, h.

The resulting distributions are presented in Table 2.

If the amount of analyzed data is sufficient, Gompertz-Makeham distribution allows analyzing the influence of time of operation on the probability of no-failure (Figure 5). For the purpose of the analysis, the sample was divided into 4 ranges.

Table 2. Resulting factors K_1, K_2, K_3

Parameter	NK type pumps	NKV type pumps	NPS type pumps
K_1, h^{-1}	0.00017	0.00017	0.00005
K_2, h^{-1}	0.024	0.100	0.015
K_3, h^{-1}	0.00070	0.00040	0.00065

Probability of no-failure and failure rate of NK type pumps under exponential distribution K_2 and linear distribution K_3 can be found according to the formulas:

$$P(t) = \exp\left[-(0,00017 \cdot t + 0,066 \cdot \exp(-2,733 \cdot 10^{-5} \cdot T) \cdot \cdot \exp\left((1,9 \cdot 10^{-5} \cdot T + 6,7 \cdot 10^{-4}) \cdot t - 1\right)\right],$$

$$\lambda(t) = 0,00017 + (0,125 \cdot 10^{-5} \cdot T + 0,440 \cdot 10^{-4}) \cdot \cdot \exp\left(-2,733 \cdot 10^{-5} \cdot T + (1,9 \cdot 10^{-5} \cdot T + 6,7 \cdot 10^{-4}) \cdot t\right),$$

where T is the total time of operation of piston compressor, h; t is the time to failure, h.

Figure 5 clearly shows the equipment «wearing in». Reliable prediction of ultimate time to failure requires regular updates of the statistical database.

Conclusion

The performed analysis has shown that the availability factor of pumps depends not only on the average time between maintenance (that in turn depends on the frequency of required maintenance), but also on the utilization factor of the pumps. The average time between maintenance can be extended by improving the quality of maintenance and quality control of spare parts. Optimal utilization factor can be obtained by mothballing excessive redundant pumps or evening the utilization of the pumps that operate in identical roles within the operational diagram (paired, standby operation, etc.).

The article set forth the dependences between failure rates and probabilities of no-failure for NK, NKV and NPS type pumps. Those characteristics did not depend on the installations they were fitted on which indicates similar operating conditions of the considered pumps of each type.

Expected time to failure without regard to total operation time is 4 100 h for NK type pumps, 4 400 h for NKV type pumps, 5 400 h for NPS type pumps. As soon as this time is reached, sudden failures become probable as components deterioration shows itself.

The identification of the ultimate time to failure for improved dependability and reliability of equipment operation must involve regular updates of input data in order to identify the beginning of the process of equipment “aging” for prevention of accidents caused by out-of-limit deterioration of equipment.

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Practical application of continuous distribution laws in the theory of reliability of technical systems

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Aim. *One of the stages of dependability analysis of technical systems is the a priori analysis that is usually performed at early design stages. This analysis a priori has known quantitative dependability characteristics of all used system elements. As unique, non-mass produced or new elements usually lack reliable a priori information on quantitative dependability characteristics, those are specified based on the characteristics of technical elements already in use. A priori information means information retrieved as the result of dependability calculation and simulation, various dependability tests, operation of facilities similar in design to the tested ones (prototypes). From system perspective, any research of technical object dependability must be planned and performed subject to the results of previous research, i.e. the a priori information. Thus, the a priori analysis is based on a priori (probabilistic) dependability characteristics that only approximately reflect the actual processes occurring in the technical system. Nevertheless, at the design stage, this analysis allows identifying system element connections that are poor from dependability point of view, taking appropriate measures to eliminate them, as well as rejecting unsatisfactory structural patterns of technical systems. That is why a priori dependability analysis (or calculation) is of significant importance in the practice of technical system design and is an integral part of engineering projects. This paper looks into primary [1] continuous distributions of random values (exponential, Weibull-Gnedenko, gamma, log normal and normal) used as theoretical distributions of dependability indicators. In order to obtain a priori information on the dependability of technical systems and elements under development, the authors present dependences that allow evaluating primary dependability indicators, as well as show approaches to their application in various conditions.* **Methods.** *Currently, in Russia there is no single system for collection and processing of information on the dependability of diverse technical systems [3] which is one of the reasons of low dependability. In the absence of such information, designing new systems with specified dependability indicators is associated with significant challenges. That is why the information presented in this article is based upon the collection and systematization of information published in Russian sources, analysis of the results of simulation and experimental studies of dependability of various technical systems and elements, as well as statistical materials collected in operation.* **Results.** *The article presents an analysis of practical application of principal continuous laws of random distribution in the theory of technical systems dependability that allows hypothesizing the possible shape of system elements failure models at early design stages for subsequent evaluation of their dependability indicators.* **Conclusions.** *The article may be useful to researchers at early stages of design of various technical systems as a priori information for construction of models and criteria used for dependability assurance and monitoring, as well as improvement of accuracy and reliability of derived estimates in the process of highly reliable equipment (systems) development.*

Keywords: *dependability, distribution, failure, operation time, density, mathematical expectation, dispersion.*

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Introduction

System failures can be described using models designed for application in various dependability-related tasks that treat differently the system of factors that are intrinsic to the nature of failure.

The random nature of failures over the course of technical systems and components operation allows describing those using probabilistic statistical methods. The most commonly used failure models are based on distributions of associated random values, i.e. times to failure of non-repairable items and times between failures of repairable items.

As the primary types of distributions of item times to failure we should emphasize the following ones [1]:

- exponential

- Weibull-Gnedenko
- gamma
- lognormal
- normal.

A review of the available literature sources on technology dependability resulted in the evaluation of practical application of those laws in the context of studying various technical objects. Based on the performed analysis, an appropriate a priori distribution of corresponding dependability criterion or indicator can be selected.

Exponential distribution

While being a special case of the Weibull-Gnedenko distribution (if α=1), the exponential distribution is of significant interest in itself as it adequately describes the distribution of element operation time within the period of normal operation. The practical popularity of the exponential law is explained by not only its various potential natural physical interpretations, but its exceptional simplicity and convenience of its simulation properties. Below are the formulas for identification of density and probability of no-failure over the time t as per this law:

$$f(t)=\lambda\cdot e^{-\lambda t};$$

$$P(t)=e^{-\lambda t},$$

where λ is the failure rate.

The expectation m and mean-square deviation m for the exponential distribution are expressed through its parameter:

$$m=1/\lambda,$$

$$\sigma=1/\lambda.$$

Mean time to first failure is equal to

$$T_{ave}=m=1/\lambda.$$

The exponential distribution is often used at the design stage when information on the dependability of the elements of the system in development is limited or absent. That is why it is often called the principal law of dependability [2]. The limiting factor of this law's application is the requirement of utmost simplicity of the failure and renewal streams (they must be ordinary, stationary and devoid of consequences) [3].

According to [4 – 12], exponential distribution provides a good description of the dependability of technology operated after the end of the wear-in until significant degradation failures, i.e. within the period of normal operation when sudden failures take place. In [2, 7], it is said that the time to failure of technical systems with large numbers of serially connected elements can be described with this distribution if each of the elements individually does not significantly contribute to system failure. In case the failures of serially connected elements have an exponential distribution, then the system's own failures will be subject to that law and its failure rate will be equal to the sum of the elements' failure rates. Regard must be paid to the fact that systems that contain elements connected non-serially dependability-wise will not display exponential distribution despite the exponentiality of probabilities of failure free performance of its component elements [3].

As each element of a system in turn is itself a subsystem comprising several or commonly a larger number of elements, the total failure rate of the system's elements depends only on the number of faulty elements, while the time of repair of each faulty element has an exponential distribution. A failure of such subsystem is a failure of one of its elements that in maintenance is replaced with a new one. The net operating time of a subsystem defines that its failure flow is a sum of a large number of flows and, according to the Khinchin limiting theorem, it is asymptotically a Poisson stream. Therefore, we can conclude that the time interval between adjacent failures will have exponential distribution [13, 14].

The exponential law should be applied to those complex technical systems in which there are many different destructive processes that unfold simultaneously at different rates. However, as the difference in the rates at which the processes develop declines, the distribution approaches normal, if same-type destructive processes prevail, the distribution is exactly normal [11].

The authors of [2, 4, 6, 15] believe that in the context of solving problems related to complex system maintenance, if the renewal stream is simple, the exponential law should be applied when describing the renewal rate, labor intensity of current maintenance and failure recovery. In mass service, the intervals between repairs of equipment are also describable in terms of the exponential law [3].

As during normal operation sudden failures normally occur due to external effects, the replacement of an old element with a new one cannot influence the failure cause. Due to that, under exponential failure law there is no need for preventive measures, e.g. replacement of elements or their scheduled maintenance [16].

Some believe [2, 3] that if we consider the physical nature of sudden failures, the exponential law can be used to approximate the probabilities of no-failure of a large number of technical objects, primarily electronic equipment, electrical and electronic devices, hardware and software systems, etc.

However, despite the simplicity and universality the exponential law has a number of limitations. In particular, some papers [3, 13, 17] question the applicability of the exponential distribution law to sustained operation systems and over long intervals of time due to the following considerations:

– due to the fact that this distribution is characterized by "memorylessness", it has a significant disadvantage, i.e. contradiction with natural physical representations. This property means the absence of aging, i.e. a technical object does not age or, upon a certain time of operation will have a failure distribution identical to the one of a new object, which is inappropriate for the operation of many technical objects, especially over long periods of time [3,13, 17].

– in [3] it is claimed that the exponential distribution law is not applicable to complex technical systems, as due to non-simultaneity of the elements' operation and presence of failure aftereffects, the failure rate of a complex system cannot be permanent even if the failure rates of its elements are permanent. Therefore, this law cannot be used for dependability analysis of actual long-term operation technical systems, and the basic premises in the models are not adequate to the physical processes within the systems.

That points to the fact that you need to have sufficiently valid reasons to use exponential distributions, just like any other. Nevertheless, this distribution is common, which is due to the following:

– simplicity and dependence on only one parameter λ. This and the absence of aftereffect allow solving many tasks of the dependability theory and deliver solutions in an explicit analytical form;

– it has been proven that the time before failure of complex high-dependability repairable systems can be described with an exponential distribution under certain conditions (e.g. possibility to disregard the effect of materials "aging");

– under certain conditions the application of the exponential law in the cases when it is not appropriate allows achieving low dependability indicators, i.e. lower estimate, which is often acceptable.

Normal distribution law (Gaussian law)

The completeness of the theoretical research regarding the normal law, as well as comparatively simple mathematical properties make it the most attractive and easy to use. If the studied empirical data deviates from the normal law, there are the following ways it could be used:

- use it as the initial approximation. In many cases this assumption yields sufficiently accurate results;

- fit a transformation of the studied random value ξ, that would change the initial "non-normal" law into a normal one [14].

An important property of this law is its "self-reproducibility" that consists in the fact that the sum of any number of normally distributed random variables also follows the normal distribution law.

The distribution density of this law is defined by the formula:

$$f(t)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(t-m)^2}{2\sigma^2}}.$$

Normal distribution dependability function is calculated using the following formula:

$$P(t)=\int_t^{\infty}\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-m)^2}{2\sigma^2}}dx=0,5-F_0\left(\frac{t-m}{\sigma}\right),$$

where $F_0(t)=\frac{1}{\sqrt{2\pi}}\int_0^t e^{-\frac{x^2}{2}}dx$ is the Laplace's function of which the values are tabulated.

The mean time before failure is equal to $T_{ave}=m$, and the relation between the time to first failure $\overline{T}_1$ and value T_{ave} is expressed with the formula:

$$\overline{T}_1=T_{ave}+\frac{\sigma\sqrt{2/\pi}}{\left[1+F\left(\frac{T_{ave}}{\sigma\sqrt{2}}\right)\right]}e^{-\frac{T_{ave}^2}{2\sigma^2}}.$$

The failure rate for the normal distribution is the increasing function that is defined by formula:

$$\lambda(t)=\frac{\sqrt{\frac{2}{\pi}}e^{-\frac{(t-T_{ave})^2}{2\sigma^2}}}{\sigma\left[1-F\left(\frac{t-T_{ave}}{\sigma\sqrt{2}}\right)\right]},$$

where $F(\;)$ is the function integral of the form

$$F(x)=\frac{2}{\sqrt{\pi}}\int_0^x e^{-x^2}dx.$$

The normal law is used to describe the dependability of technical facilities over the period of aging [2, 4, 6, 18]. In a number of sources [6 – 9, 19 – 22] it is stated that it is used in the cases when the failures are gradual and are caused by directional physicochemical changes due to deterioration (aging), and the coefficient of variation $\upsilon \le 0{,}3 \div 0{,}4$ [7, 23]. Under stable conditions and modes of operation during this period the Gaussian distribution matches well with the mean and gamma-percentile life distribution [7], as well as machine's original life [4].

It is important to note that normal distribution of time before failure comes from the uniformity of technical objects quality, permanent average rate of deterioration and realization of deterioration as they long move and intertwine until failures start occurring [16].

The particular feature of the normal law application is as follows: if σ values are low compared to mean time before failure m, the density is fairly close to zero within a significant time interval, which lets us conclude that within this interval the probability of failure is very low. That reflects the fact that granted the deterioration level is high and accumulated deterioration is low the probability of failure is low. That is exactly the reason for the forced replacements (repairs) at low levels of deterioration that enable a low probability of failure between repairs [16]. In turn, for the exponential distribution that reaches maximum density if $t = 0$, most failures occur at the beginning of operation.

The statistical analysis, e.g. in [2, 11] of the test and operation results of mechanical units and metal structures subject to intense deterioration, aging and fatigue, shows that strength and load distribution are described with the normal law with associated probability densities. In some units a combination of exponential and normal distributions was observed. Such composed distribution is possible if units and parts of a device are simultaneously subject to sudden and deterioration failures. In hydraulic carrying systems and geared pumps the normal law describes the time between failures [11]. It must be noted that such random values as measurement and manufacturing errors, etc. also follow the Gaussian law. [16].

Logarithmically normal distribution

A random value ξ is lognormally distributed when its logarithm is distributed normally. A lognormal random value is affected by a large number of mutually independent factors, while the effect of each individual factor is "uniformly insignificant" and equally possible in sign. Unlike in the case of normal distribution, the sequential nature of the effect of random factors means that the random gain caused by the action of each further factor is proportional to the already achieved studied value.

The distribution density is defined by the formula

$$f(t) = \frac{1}{st\sqrt{2\pi}} e^{-\frac{(\ln t-\mu)^2}{2s^2}},$$

where μ and s are the parameters evaluated by the results of n tests to failure;

$$\mu = \frac{1}{n}\sum_{i=1}^{n} \ln t_i;$$

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\ln x_i - \mu\right)^2}.$$

For the lognormal law, the dependability function is as follows:

$$P(t) = \frac{1}{\sqrt{2\pi}} \int_{\frac{\ln\left(t/\mu\right)}{s}}^{\infty} e^{-t^2/2}\, dt.$$

The expectation of the time before failure and mean-square deviation are determined from the formula:

$$T_{ave} = m = e^{\left(\mu + s^2/2\right)};$$

$$\sigma = \sqrt{e^{2\mu+s^2}\left(e^{s^2} - 1\right)}.$$

In the case of lognormal distribution the failure rate will be equal to [23]

$$\lambda(t) = \frac{0,4343 e^{-\frac{(\lg t-\mu)^2}{2s^2}}}{st\sqrt{2\pi}F\left(\frac{\mu - \lg t}{s}\right)}.$$

A lognormal distribution is a distribution of positive variables, hence it is somewhat more accurate than the normal distribution [2]. It describes the behavior of the time between failures of objects that «strengthen» over time. The «strengthening» causes a slow decrease of deterioration rate. That is why before using the lognormal distribution it is necessary, on the basis of the physical nature of the deterioration process and, if possible, analysis of deterioration realizations behavior, to establish whether the studied technical objects have a tendency for «strengthening» [16].

This distribution also describes the following: renewal processes; longevity of products operating during the aging period when the deterioration increment is proportional to instantaneous deterioration [7, 14, 19]; operation times in the situation of rapid «burnout» of undependable elements; failures occurring as the result of material fatigue, in particular, description of operation time of ball bearings [3, 7].

In general, lognormal distribution adequately describes the times to failure of complex technical systems (tractors, automobiles, special heavy-duty vehicles, etc.), as well as electronic equipment [2].

Gamma distribution

Gamma distribution has a two-parameter distribution with the shape parameter ($\alpha>-1$) and scale parameter ($\beta>0$):

$$f(t) = \frac{t^{\alpha}}{\beta^{\alpha} G(\alpha)} e^{-\frac{t}{\beta}}.$$

The probability of no-failure is defined using the formula:

$$P(t) = \int_{t}^{\infty} \frac{x^{\alpha-1}}{\beta^{\alpha} G(\alpha)} e^{\frac{x}{\beta}} dx = 1 - I\left(\alpha, \frac{t}{\beta}\right),$$

where $G(\alpha) = \int_0^{\infty} x^{\alpha-1} e^{-x} dx$ is the gamma function;

$I(\alpha, t) = \frac{1}{G(\alpha)} \int_0^{t} x^{\alpha-1} e^{-x} dx$ is the incomplete gamma function.

The expectation (mean time between failures) and mean-square deviation for the gamma distribution are equal to:

$$T_{ave} = m = \alpha\beta;$$

$$\sigma = \sqrt{\alpha}\beta.$$

The failure rate formula is as follows:

$$\lambda(t) = \frac{t^{\alpha} e^{-t/\beta}}{\int_t^{\infty} x^{\alpha-1} e^{-x/\beta} dx}.$$

Gamma distribution serves to describe deterioration failures; failures due to damage accumulation; description of operation time of complex technical systems with redundant elements; renewal time distribution [2, 7, 10, 16]. It can also be used for longevity (lifetime) analysis of certain technical objects [17].

Gamma distribution has a number of useful properties:

1. If $\alpha<1$ the failure rate monotonically decreases which corresponds to a rapid "burnout" of undependable elements.

2. If $\alpha>1$ the failure rate increases, gradual deterioration and aging of elements takes place.

3. If $\alpha=1$ gamma distribution matches the exponential one and can be used to describe the probability of failures in normal operation of a technical system [18].

Given the above, we can conclude that gamma distribution may be used at all stages of the lifecycle: wearing-in ($\alpha<1$), normal operation ($\alpha=1$) and aging ($\alpha>1$) [20].

4. If $\alpha>10$ gamma distribution practically matches the normal one and therefore can be used to describe the probability of failures of aging units, mechanisms and other elements [16, 18]. Also, if $P(t)\to\infty$ the gamma distribution approaches the normal distribution law. For this reason it is often used for approximation of those unimodal, but nonsymmetrical distributions that are poorly approximated with normal distribution [9, 12].

5. If α is a positive integer, then in [2, 7] the gamma distribution is also called Erlang distribution.

6. If $\lambda=1/2$ and α is divisible by 1/2, then the gamma distribution matches the ch-square distribution [2, 7].

On the assumption of [13] in respect to the tasks solved in terms of the Laplace transformation the gamma distribution can be conveniently used to approximate natural distributions.

In [11, 12], the following definition is given: gamma distribution is the characteristic of the time of failure occurrence in complex electromechanical systems in cases when sudden failures of elements take place at the initial stage of operation or system debugging, i.e. it is a convenient characteristic of the time of failure occurrence in the equipment during the wear-in period.

In complex technical systems that consist of elements of which the probability of no-failure has an exponential distribution, the probability of no-failure of the system as a whole will have a gamma distribution [11].

The distribution of the failure occurrence time in complex technical systems with redundancy (granted that failure flows of the primary and all backup systems are simple) can also be described with a gamma distribution [12]. Similarly, in cases of cold or combined redundancy the probability of no-failure of the system follows the generalized gamma distribution [3]. That said, it has been established [24] that in redundant systems (both repairable and non-repairable) there are always hidden failures, while the efficiency of their detection is quite limited. Those factors have a significant effect on system dependability and require more detailed model design (e.g. using Markov or semi-Markov process).

Weibull-Gnedenko distribution

The Weibull-Gnedenko distribution is a two-parameter distribution with the shape parameter α and scale parameter β that is characterized by the probability density function:

$$f(t) = \frac{\alpha t^{\alpha-1} e^{-\left(\frac{t}{\beta}\right)^{\alpha}}}{\beta^{\alpha}}.$$

The connections between dependability indicators appear as follows:

$$P(t) = e^{-\left(\frac{t}{\beta}\right)^{\alpha}},$$

$$T_{ave} = \beta G\left(1+\frac{1}{\alpha}\right),$$

$$\sigma = \beta\sqrt{G\left(1+\frac{2}{\alpha}\right) - G^{2}\left(1+\frac{1}{\alpha}\right)},$$

$$\lambda(t) = \frac{\alpha}{\beta^{\alpha}} t^{\alpha-1}.$$

This law has a wide range of use as it bridges over the fields of application of a number of other distributions, but is described with more complex formulas [4]. It can be used to describe:

- lifetimes of ball bearings, threads, splined shafts and other parts with simultaneous deterioration of several working faces [4];
- times to failure with simultaneous occurrence of sudden and deterioration failures [4];
- probability of no-failure of mechanical elements during aging or deterioration [3, 11, 12];
- lifetime of components of metal structures, supporting systems, support and rotation systems, hydraulic and electric drive systems in connection with fatigue and sudden failure (coefficient of variation of 0.35 – 0.70) [22].
- failure distribution during wear-in [2, 3, 21];
- operation times of special-purpose complex technical systems (mobile installations) in operation [2, 18];
- operation times of parts and components of automobiles, handling and other machinery subject to fatigue failures, ball bearings times to failure [2, 3];

- distribution of mean and gamma-percentile life subject to fatigue failure in stable conditions and modes of operation [7].

In a number of cases [3, 8, 10] the Weibull-Gnedenko distribution is universal due to the following properties;

– if α=1 it transforms into exponential distribution;

– if α<1 failure density and rate functions decrease;

– if α>1 failure density and rate functions increase;

– if α=2 function $\lambda(t)$ is linear, the distribution transforms into the Rayleigh distribution with density $f(t) = 2te^{-\lambda t^2}$;

– if α=3,3 the distribution is close to normal.

Due to its universality the Weibull-Gnedenko distribution is recommended for priority application when processing experimental data on the dependability of technical facilities in situations when the type of the distribution function is not initially known [15]. Additionally, all natural distributions are approximated much better with this distribution rather than the exponential distribution [9].

Like the gamma distribution, the Weibull-Gnedenko distribution well suits the approximation of natural distributions at various lifecycle stages: wear-in (α<1), normal operation (α=1) and aging (α>1) [2, 14, 20].

Also, a complex technical system that is considered as a single structural entity comprising a large number of elements in each of which the time before failure is subject to gamma distribution, but the parameters of such distributions slightly vary from element to element, will have a distribution close to the Weibull-Gnedenko distribution [16, 20]. It should be noted that many technical objects contain large numbers of identical or similar in design elements that operate in similar conditions (e.g. an internal combustion engine has a number of cylinders, electronic equipment has a large number of capacitors, resistors, etc.). If the repeating elements of a technical system define the time before failure of the system, that produces a structure that would have the Weibull-Gnedenko distribution [16].

From the point of view of the physical nature of failures, the Weibull-Gnedenko distribution adequately describes the time before failure of many electronic equipment elements in case the failure of such elements is considered [16] as a deviation of a parameter beyond the specified limits.

Conclusion

In conclusion, it should be noted that beside the above mentioned types of distributions, solving some tasks involves special types (several dozen in total), as well as discontinuous distributions that are not covered in this article. Distributions have various transitions and connections. Despite the existing goodness measures of the chosen theoretical and empiric distributions, all of them provide the answer to the following question: whether or not there are good grounds for discarding a hypothesis for the chosen distribution? The authors note that any data can be made to fit the multi-parametric law even if it does not correspond to real physical phenomena [7]. Thus, while choosing the type of distribution and its parameters one must first take into consideration the physical nature of the occurring processes and events.

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Special aspects of estimating the probability of fire occurrence on diesel locomotives of various types

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Abstract. Aim. *The paper considers the problem of estimating the probability of fire occurrence on diesel locomotives of various types and the ways to solve it. The problem arises due to JSC RZD locomotive fleet special aspects. Thus, the operating fleet presents diesel locomotives designed and constructed in the 20th century as well as in 21st century, and this accounts for different causes of fire owing to design differences. The biggest contribution to differences in fire numbers on new and old type locomotives is made by the construction of a diesel engine as well as the fire resistance of cables. Researches show that substantial difference in fire statistics for diesel locomotives of various types for the same period of observation are caused by the volume of operating diesel locomotive fleet. For instance, volumes of operating fleet for some types of diesel locomotives amount to thousand units (loco-days), while for other types they make up just a couple of hundreds. This raises questions about whether a period of observation and a volume of operating fleet are enough for estimating the probability and what methods should be used to estimate it. Furthermore, we need an interval estimation of probability which is caused by reliability considerations, by getting "the worst scenario". Again, this is influenced by above differences in types of diesel locomotives. The paper also analyzes the necessity of estimating "the worst scenario" and problems arising in reference with its calculation. To solve the problem of enhancing the reliability of calculations is to calculate the upper boundaries of probabilities. In this case some types of diesel locomotives will have a lower boundary of probability rather than "the worst scenario" as interval estimation. The necessity of such estimation is specified for diesel locomotives of specific designs with materials complying with modern standards in terms of reliability and fire resistance or having scarce statistics for applying approximation methods of calculation because of limited operating fleet.* **Methods.** *Researches into statistics of fires on diesel locomotives of types 2TE10, 3TE10, 2TE116, 2M62, TEP70, ChMEZ, TEM2 made by the authors began with application of a "classic" statistics tool, i.e. check of statistical hypotheses about a law of distribution of a random value "fire" belonging to known discrete laws. While at this, a minimum amount of tests was defined for making sure that targeted estimates of probability are of certain reliability. The condition of a diesel locomotive during operation is not stationary, so a classic estimation of probability of fire occurrence would lead to uncertainty in applying the results of estimation for the purposes of planning and prediction. To evaluate "the worst scenario", we used both precise and approximate methods for defining confidence boundaries based on "double approximation". Further, to enable transition from estimation of probability of fire occurrence on diesel locomotives of a certain type to estimation of fire probability for certain units, a sufficient amount of rolling stock was researched. The authors have found that the amount of operating fleet should be not less than 610 loco-days to ensure the precision of probability calculation with an error not exceeding* ε. *The authors have also identified the method and the necessity of separately estimating the probability of fire on locomotives with operating fleet less than 610 loco-days.* **Results. Conclusions**. *In fine, for each type of locomotive we have defined a law of random value occurrence, calculated interval estimates of probability of fire occurrence considering an amount of operating fleet. Tools of statistical analysis for calculating probabilities of fire occurrence on diesel locomotives of various types have been also identified. We have determined methods for calculating interval probability estimates taking into account an available amount of observations with an error not exceeding a specified value* ε *at the level of* $0{,}2p_j^*$. *This research and related calculations have enabled us to obtain one of the primary elements for estimating a fire risk, i.e. the probability of fire on diesel locomotives of various types.*

Keywords: *fire risk, probability, diesel locomotive.*

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Introduction

Calculation of probability of an undesirable event is vital part of risk analysis. For analysis of fire risk, an undesirable event is a case of fire. The paper tackles analysis of fire cases as random events and estimation of probability of their occurrence. Probability of fire occurrence is a mathematical value of possibility of occurrence of necessary and sufficient conditions for fire breakout (catching fire) [1]. Conditions for fire break-out presents a set of direct fire causes or, in terms of probability theory, elementary outputs, whose set favors occurrence of fire event. That said, the set of elementary outputs will differ for different objects. The most obvious example is such: on diesel locomotives 12% of fires happen due to failures of a turbo charger. For electrical locomotives a share of fires due to this cause is 0%, since electrical locomotives do not have turbo chargers. Diesel locomotives of various types also have design differences. However, design is not the only criterion of difference between types of diesel locomotives. Not lesser influence on an amount of fires is made by a volume of diesel locomotives operation or, in other words, operating fleet. Therefore, as a random event of fire on different types of locomotives is caused by different sets of elementary outputs, the probability of fire on a locomotive of each type should be calculated separately. This paper deals with consideration of special aspects of available fire statistics, choice of statistical tools for estimating fire probabilities with each type of locomotives taken into account.

The paper uses a mathematical apparatus for calculating probabilities of fire on diesel locomotives of such types as 2TE10, 3TE10, 2TE116, 2M62, TEP70, ChMEZ, and TEM2 (based on statistics for the period of 2008-2015). The process of calculating probability includes consideration and description of the process of selection of a distribution law, check of compliance of chosen distribution conditions.

The second part of the paper deals with enhancement of reliability of calculation results. This task was solved by estimating upper boundaries of probabilities of catching fire on various types of diesel locomotives. The calculation allowed estimating the weight of probability as a value above which the weight of probability will not rise with a high reliability. The estimate of upper boundaries of probability is used not so widely as an explicit estimation of probability. The task solving was complicated by the fact that for some types of diesel locomotives the sample was small, and that was shown as a small operating fleet and as the fact that it was impossible to apply classical formula for estimating upper boundaries of parameters of known distributions. A precise method of calculation was used for estimating such probabilities.

Selection of distribution

For estimating the probability of fire occurrence it is necessary to select a mathematical model of estimation. In this case estimation of probability was made by using a Bernoulli distribution (binominal trial model) [2]. A Bernoulli distribution is called a consequence of tests satisfying to certain conditions. Table 1 provides the analysis of conditions for application of a Bernoulli distribution for analyzing fire cases as to empirical data (observations).

According to the accepted model, a trial is assumed as a month wherein we witness cases of fire or no fire on locomotives that have N volume of operating fleet.

Using a Bernoulli formula, the occurrence probability of exactly k of successes $P_n(k)$ is equal to[1]:

$$P_n(k) = C_k^n p_j^{*k} (1 - p_j^*)^{n-k} = \frac{n!}{k!(n-k)!} p_j^{*k} (1 - p_j^*)^{n-k} \quad (1)$$

Furthermore, we have analyzed other known discrete distribution laws, including a Poisson distribution. Below one can find checking the extent to which observed statistics is described by the chosen law.

Check of statistical hypotheses

For checking assumptions related to definition of compliance of a sample with a certain distribution law, a mechanism of checking statistical hypotheses is used.

A statistical hypothesis is called an assumption about a type of distribution law or values of unknown parameters of a distribution law in the population.

Below is the procedure of checking a statistical hypothesis about compliance of fire occurrence with a binominal distribution law:

1. Statement of a null and alternative hypothesis.

A hypothesis stated about compliance with a binominal distribution law with confident likelihood α is called a null hypothesis H_0: $\{P=P_0\}$. As a result of statistical check, a null hypothesis is either accepted (assumed as true) or rejected (assumed as false).

In addition to a null hypothesis, we define an alternative hypothesis H_1: $\{P \neq P_0\}$ that will be accepted in case a null hypothesis is rejected – a hypothesis about incompliance with binominal distribution:

2. Selection of a criterion for checking a hypothesis and calculation of its observed value.

For checking hypotheses, one applies special criteria which are calculated using observed data (based on a sample) and comply with one of the standard distribution laws (Student's, χ^2 etc.) [8]. This paper uses Pierson's criterion χ^2.

Supposing that $\overrightarrow{X_n}$ is a random sample of n volume (8 years) from the population of a continuous random value X [7]. Let then one observe a discrete random value X (number of months with fires per year) taking on i of various values $u_1, \ldots, u_i$ with positive probabilities $p_1, \ldots, p_i$, (2) and (3):

$$P\{X = u_k\} = p_k, \; k = \overline{1,i}, \quad (2)$$

[1] Here and elsewhere j index with p^* defines a type of locomotives and i index characterizes a parameter of distribution within the type.

Table 1. Compliance of conditions for application of a Bernoulli distribution and calculation data

Conditions of distribution applicability	Observations	Condition compliance
Each trial has only two outcomes: «success» and «failure»	Each trial has only two outcomes: «fire occurred» and «no fire occurred»	Compliant
Independence of trials: the result of a next trial should not depend on the results of previous experiments	Independence of trials: fire occurrence does not depend on whether a fire has occurred before or not. Fire occurrence depends on maintenance	Compliant
Probability of success should be permanent (fixed) for all trials (p^*_j).	Probability of fire occurrence is a permanent value for a given type (p^*_j), in accordance with statistical observations	Compliant

Table 2. Example of check for diesel locomotives of 2TE116 type

u_i	$n_k(\overrightarrow{x_n})$	p_k	np_k	$(n_k(\overrightarrow{x_n})-np_k)^2$	$\frac{(n_k(\overrightarrow{x_n})-np_k)^2}{np_k}$
0	0	$2{,}09 \cdot 10^{-5}$	$1{,}67 \cdot 10^{-4}$	$2{,}8 \cdot 10^{-8}$	$1{,}67 \cdot 10^{-4}$
1	0	$3{,}65 \cdot 10^{-4}$	$2{,}92 \cdot 10^{-3}$	$8{,}54 \cdot 10^{-6}$	$2{,}92 \cdot 10^{-3}$
2	0	$2{,}92 \cdot 10^{-3}$	$2{,}34 \cdot 10^{-2}$	$5{,}46 \cdot 10^{-4}$	$2{,}34 \cdot 10^{-2}$
3	1	$1{,}42 \cdot 10^{-2}$	0,11	0,79	6,94
4	1	$4{,}64 \cdot 10^{-2}$	0,37	0,39	1,07
5	1	0,11	0,86	$1{,}88 \cdot 10^{-2}$	$2{,}18 \cdot 10^{-2}$
6	1	0,18	1,46	0,22	0,15
7	2	0,23	1,82	$3{,}06 \cdot 10^{-2}$	$1{,}68 \cdot 10^{-2}$
8	0	0,21	1,66	2,75	1,66
9	1	0,13	1,07	$5{,}22 \cdot 10^{-3}$	$4{,}87 \cdot 10^{-3}$
10	1	$5{,}85 \cdot 10^{-2}$	0,47	0,28	0,6
11	0	$1{,}55 \cdot 10^{-2}$	0,12	$1{,}53 \cdot 10^{-2}$	0,12
12	0	$1{,}87 \cdot 10^{-3}$	$1{,}5 \cdot 10^{-2}$	$2{,}25 \cdot 10^{-4}$	$1{,}5 \cdot 10^{-2}$
	$\sum_{k=1}^{i} p_k$	1		χ^2_v	10,62
				$\chi^2_{\alpha,v}$	19,67

$$\sum_{k=1}^{i} p_k = 1. \quad (3)$$

To check a hypothesis about a binominal distribution, p_k is calculated by formula (1).

Supposing that u_k number in a sample comes across $n_k(\overrightarrow{x_n})$ times, $k=\overline{1,i}$. Note that $\sum_{k=1}^{i} n_k(\overrightarrow{x_n}) = n$.

Then Pierson's theorem is true for $v=i-1$ of freedom degrees (4):

$$\chi^2_v = \sum_{k=1}^{i} \frac{(n_k(\overrightarrow{x_n})-np_k)^2}{np_k}. \quad (4)$$

If inequation (5) is satisfied:

$$\chi^2_v \le \chi^2_{\alpha,v}, \quad (5)$$

Then a hypothesis about compliance with a binominal distribution law is accepted with confident probability α (α=0,95).

An example of calculation of check for locomotives of 2TE116 type is given in Table 2.

Let us assume that α=0,95. In our case a number of freedom degrees $v=i-1=12-1=11$ (i is a number of various values u_i). Hence $\chi^2_{\alpha,v} = 19{,}67$. Therefore, inequation (5) is satisfied, and we have confirmed a hypothesis about compliance of fire occurrence with a binominal distribution law at this level. This means that selection of a hypothesis is in line with experimental data.

Estimation of sufficiency of a testing volume

For each type of diesel locomotives, the sufficiency of a testing volume is estimated so that estimated probabilities would have certain reliability. Let us exemplify it by diesel locomotives of 2TE116 type. Let us state this task as follows: how many trials should be made in order to define an unknown parameter of a binominal distribution with an error not exceeding a specified value ε [5]. Let us accept an error ε at the level of $0,2p_j^*$.

The volume of a sample is calculated by formula (6):

$$n = \frac{u_\alpha^{\ 2}}{\varepsilon^2} p_j^* (1 - p_j^*), \tag{6}$$

Where u_a is a quantile of standard normal distribution, α is confident probability, p_j^* is a parameter of binominal distribution.

For α=0,9, u_a=1,645. Substitute values in formula (6), we have (7):

$$n = \frac{1,645^2}{(0,2*0,495)^2} 0,495(1-0,495) = 69, \tag{7}$$

This testifying to the sufficiency of a trial volume as the number of months based on which a conclusion was made about p_j^* amounted to n=96.

Estimation of probability of fire occurrence on diesel locomotives of 2TE10, 2TE116, ChMEZ, TEM2 types

As it was already said, estimation of fire probability on diesel locomotives of 2TE10, 2TE116, ChMEZ, TEM2 types was made by using a binominal distribution. In this case a Bernoulli trial consisted in observation of at least one fire per month. The probability of fires occurring per year was calculated by formula (8):

$$P(B) = 1 - P(k=0), \tag{8}$$

Where $P(B_0)$ is a probability that no month will witness any fires to be calculated by formula (9):

$$P(B_0) = C_k^n p_г^{*k} (1 - p_г^*)^{n-k} = \frac{n!}{k!(n-k)!} p_г^{*k} (1 - p_г^*)^{n-k} = \\ = \frac{12!}{0!12!} p_г^{*0} (1 - p_г^*)^{12}, \tag{9}$$

Where $p_г^*$ is a parameter of binominal distribution considering upper boundaries calculated depending on the type of statistics. An upper confident boundary corresponds to such parameter of binominal distribution $p_г^*$, for which it is unlikely to obtain that distribution parameter $p_j^* (p_j^* = \frac{n_{months\ with\ fire}}{n})$, which we got by experience or even smaller parameter of distribution. This means that a parameter of binominal distribution definitely does not exceed an upper value, and consequently we consider the worst variant.

Estimation of a binominal distribution parameter

Calculation of upper boundaries of a distribution parameter $p_г^*$ [6,7] was made by formula (10):

$$p_г^* = p_j^* + u_\alpha \left(\frac{p_j^*(1 - p_j^*)}{n} \right)^{1/2}, \tag{10}$$

Where u_a is a quantile of standard normal distribution, p_j^* is a j-th binominal distribution parameter, $p_j^* = \frac{n_{months\ with\ fire}}{n}$, n is a number of months, α is confident probability, i.e. the probability of p^* being in the interval constructed for it.

For confident probability α=0,95, u_a = 1,96.

Calculation by this formula is approximate and can be applied for rather a big volume of samples. Application is actually related to "double approximation": a law of distribution of $p_г^*$ parameter estimation is substituted by a normal distribution law, and an approximate value is calculated instead of a precise value. For small and medium volumes of samples, application of formula (10) can cause substantial errors. Therefore, application of this formula is just a first approximation.

Based on a resulting upper boundary of a distribution parameter and information about operating fleet, we calculated an upper boundary of fire probability by formula (9).

Calculation of fire probability and restrictions for operating fleet

The probability of fire occurrence per year on one of operating fleet locomotives was calculated by using a theorem of probabilities multiplication [2] (events being independent) by formula (11):

$$P(AB) = P(A)P(B), \tag{11}$$

Where P(A) is the probability of choosing one locomotives from operating fleet, $P(A) = \frac{1}{N}$, where N is operating fleet per month; $P(B)$ is the probability that there will be fire during a year.

Table 3 presents the main values of operating fleet.

Table 3. Value of operating fleet of various types

Type	Operating fleet (loco-days), N
2TE116	630
2TE10	1041
3TE10	153,75
2M62	237
TEP70	338
ChMEZ	2332
TEM2	1118
Average operating fleet	835

Then the average value

$$P(A)=\frac{1}{N}=\frac{1}{835*30}=3{,}99\cdot 10^{-5}.$$

Let us estimate constraints for operating fleet. We shall consider the task: what volume of operating fleet is necessary to define probability $P(A)$ with an error not exceeding a given value ε. The task is solved by equation (12) [9]:

$$N=\frac{u_\alpha{}^2}{\varepsilon^2}\frac{P(A)(1-P(A))}{(30)^2} \quad (12)$$

For α=0,9, u_a=1,645.

Value ε will be set as 0,35$P(A)$. Then N will take a value:

$$N=\frac{1{,}64^2}{(30)^2(0{,}35*11{,}98\cdot 10^{-4})^2}11{,}98\cdot 10^{-4}\left(1-11{,}98\cdot 10^{-4}\right)=610.$$

Therefore, a minimum requisite volume of operating fleet is the value of 610 (loco-days).

Estimation of fire occurrence probability for 2M62, TEP70, 3TE10 diesel locomotives

2M62, TEP70, 3TE10 diesel locomotives presented the following features different from those of 2TE10, 2TE116, ChMEZ, TEM2 diesel locomotives:

- small operating fleet not exceeding the value of 610 and substantially smaller in numbers than other types;
- small numbers of fires during the whole observed period.

In relation to it, the calculation for 2M62, TEP70, 3TE10 diesel locomotives differed from the calculation for 2TE10, 2TE116, ChMEZ, TEM2 diesel locomotives.

For demonstration of necessity of other estimate, we'll give values obtained in calculation by method used for 2TE10, 2TE116, ChMEZ, TEP70 diesel locomotives. Table 4 presents values for an initial parameter of binominal distribution p^*, Δ of a binominal distribution parameter $\left(u_\alpha\left(\frac{p_j^*(1-p_j^*)}{n}\right)^{1/2}\right)$, and a parameter of binominal distribution with upper boundaries $p_г^*$ taken into account.

Table 4. Values for calculation of probability for ChMEZ, TEP70, 2TE116, 2TE10

Type	p_j^*	Δ	$p_г^*$	Operating fleet
2M62	0,041667	0,05653	0,007535	236,8919
TEP70	0,0625	0,06848	0,01748	337,975
2TE116	0,495	0,097	0,592	630
2TE10	0,693	0,089	0,783	1041,3

As seen from Table 4, Δ of 2M62 and TEP70 diesel locomotives is comparable to or exceeds a binominal distribution parameter, whereas the value Δ of 2TE10, 2TE116 diesel locomotives is considerably less than that of a binominal distribution parameter. The value Δ of 2M62 and TEP70 diesel locomotives comparable to the parameter considerable increases it when calculating a binominal distribution parameter with upper boundaries taken into account, while it gives a negative value when calculating with lower boundaries taken into account. Furthermore, for small and medium volumes of samples, as said before, substantial errors can be caused by the application of formula (10). And in this case a sample is influenced by a small operating fleet.

Therefore, the calculation of $p_г^*$ for 2M62, TEP70, 3TE10 diesel locomotives due to their difference from other types of locomotives was made by using a precise estimate [3,5].

Precise definition of confident boundaries was carried out by the following formulas. A binominal distribution parameter with upper boundaries taken into account was calculated by formula (13):

$$p_в^* ==\frac{m}{nR_2}, \quad (13)$$

Where m is a number of months with fires, n is a number of months.

The parameter R_2 is calculated by formula (14):

$$R_2=\frac{m(2n-m+\frac{1}{2}\chi_\alpha)}{n\chi_\alpha}, \quad (14)$$

Where χ_α is a quantile of chi-squared distribution with k=2(m+1) of freedom degrees, α is confident probability accepted at the level of 0,95.

A binominal distribution parameter with upper boundaries taken into account is calculated by formula (15):

$$p_н^* ==\frac{m}{nR_1}, \quad (15)$$

Where m is a number of months with fires, n is a number of months.

The parameter R_2 is calculated by formula (16):

$$R_1=\frac{m(2n-m+1+\frac{1}{2}\chi_{1-\alpha})}{n\chi_{1-\alpha}}, \quad (16)$$

Where $\chi_{1-\alpha}$ is a quantile of chi-squared distribution with k=2m of freedom degrees, α is confident probability accepted at the level of 0,95.

Because of a small volume of operating fleet, as a resulting parameter of binominal distribution for calculating a probability for 2M62, TEP70, 3TE10 diesel locomotives, we accepted a binominal distribution parameter with upper boundaries taken into account and calculated by formula (15). Further calculation was made by analog with the calculation for 2TE10, 2TE116, ChMEZ, TEP70 by formulas (1), (11).

Conclusion

1. The paper has defined tools of statistical analysis for calculating probabilities of fire catching on diesel locomotives of various types. It has demonstrated the necessity of application of various statistical tools for calculating probabilities of fire catching on diesel locomotives of various types, with special aspects of various types taken into account: design, operating fleet. The paper has defined groups of types whose probabilities it is possible to estimate through estimating a binominal distribution parameter: 2TE10, 2TE116, ChMEZ, TEM2. For 2M62, TEP70, 3TE10 diesel locomotives, the probability of fire catching has been estimated by precisely defining confident boundaries.

2. The paper has defined a number of observation sufficient for estimating an unknown parameter of binominal distribution with an error not exceeding a given value ε at the level of $0,2p_j^*$.

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Aspects of information support in ensuring the survivability of spacecraft under electrophysical effects

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Abstract. *In order to improve the operational efficiency of decision-making in the context of spacecraft (SC) endurance in operation, the task was set to increase the efficiency of adaptation of its control system to the environmental effects. The instruments installed on most Russian SCs in many cases do not provide for identification and timely elimination of accident sources due to delays in the identification of faults and failures. A technology is proposed that involves intellectualization of control systems. It is suggested to complement the SC control circuit with an expert system that includes a "prognostic decision support system", a "control simulation and correction module". Due to the ambiguity and common uncertainty of cosmic phenomena, it is suggested to predict the reaction of SC equipment to external effects rather than monitor such effects. The intelligence of the expert system is to be ensured through the analysis of the communication medium that defines the possibility to ensure SC survivability. The correction of control is suggested to be performed not on the basis of process parameters monitoring, but rather knowledge. This knowledge is held by experts who possess experience in SC flight mission performance. The results of the audit of external factors and development of SC functional units reactions represent the input data. After clearing, sorting and statistical analysis of data, it is suggested to regard it as information resources. The results of such resources analysis and design of messages based on expert conclusions transforms such resources into knowledge that is used in decision making and control correction. The diversity of architectures and processes of SC functional units design has defined the requirement to involve experts with diverse professional backgrounds. It was proposed to generate forecasts of SC equipment reactions development in the form of description of the dynamics of multifactor combination of the results of intersubject audit of functional units operations and subjective expert evaluations. In order to ensure agility of information analysis within the knowledge base, it was suggested to use the OLAP comprehensive multidimensional analysis technology. In particular, that regards fast analysis of shared multidimensional information that includes requirements for multidimensional analysis applications. The proposed model of systematic accumulation and processing of knowledge will enable flight control officers to timely identify inadequacies in the control inputs. The logical and statistical analysis capabilities ensured by this application will enable the delivery of analysis results to the experts within a time period sufficient for elimination of the causes of faults and failures in SC equipment operation. Multidimensional conceptual representation of data including the support of multiple hierarchies will define the capability to refer to any required information regardless of its size and place of storage. The proposed method of information support of SC equipment reactions forecasting is addressed in the light of the analysis of electrophysical effects that affect SC in near-Earth orbits. Combining the methods of computer data processing and intersubject analysis of functional units operation must insure efficient decision-making based on increased accuracy and agility of data processing and, consequently, selection of SC operation adaptation scenario subject to flight control officer's preferences.*

Keywords: *spacecraft survivability, electrophysical factors, intellectualization of controls, expert system, prognostic decision support system, simulation and correction of control, networked expert environment, knowledge management, intersubject audit, subjective expert evaluation, comprehensive multidimensional analysis technology.*

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Introduction

The experience of near-Earth activities shows that the effects of space factors, as well as the dynamics of near-object effects may significantly impact the efficiency of spacecraft operation. Therefore, along with the requirement to improve the dependability of SC design on the ground, of great relevance is the matter of operational support of its survivability under external effect in flight. This article suggests a research of mechanisms to ensure SC resilience to electrophysical effects (EPE).

Conventional electrophysical effects measurement facilities use data received from standard raw information instruments (RII)[1]. However, the instruments installed on most Russian SC do not provide for identification of faults and failures which complicates the detection of accident sources. As a result, due to low adaptability to environmental effects stable of SC operation may be disrupted.

The approach proposed in this article is geared toward the intellectualization of control and command through the introduction of an Expert system that allows compensating the development of SC reaction to electrophysical effects. It is suggested adding messages on the errors of electronic, mechanical and electromechanical equipment to the standard RII instruments information that is contained in the database and defines the control and command signals. The diagram of intellectualization of SC control systems is given in Figure 1.

Expert system functions

The system is to be built on the basis of the Prognostic decision support system (PDSS) and the Control simulation and correction module (CSCM). The coordinated operation of the Expert system and the standard control circuit is to be insured by the Database of external EPE and real-time messages regarding the compliance with technical documentation and the results of SC functional modules operation audit.

Updates to the database can be made as follows:

- automatically:

1) acquisition of information from RII and SC functional modules sensors;

2) collection of statistical data on the SC reaction to environmental effects;

3) analysis of the messages on the changes in the SC equipment put into the database;

- semi-automatically:

1) reading of the barcodes on the installed equipment;

2) by the cosmonaut responsible for the operation of a specific functional unit;

3) by control center employees.

The Control simulation and correction module is to be a unit of the Expert system intended for adaptation of the Standard control circuit signals to the SC characteristics that change under the influence of external effects. The adaptation can take the form of modification of control signals or module configuration. It is suggested to implement the second type of adaptation by introducing a new functional unit to address faults and failures of devices in the existing control channel.

In any case, shaping the signals that ensure SC resistance to external effects requires an analysis of the combination of information received from the Standard control circuit and the Expert system. An important feature of the suggested procedure of such signal generation is the information support of the SC reaction to EFE forecasts. To that effect we propose introducing the Intelligent control module to enable stable SC functional modules operation under external effects.

Due to the diversity of the internal factors that define the SC reactions to external effects, let us assume that the information received by the Expert system must be analyzed by experts in various fields. Therefore, such system can only operate using the intersubject audit technology.

Another important factor in ensuring SC survivability consists in the fact that the quality of control and command is significantly affected by the reliability of incoming information that cannot be verified directly, as well as the speed of its delivery to the decision-maker (DM). In other words, the matter of decision efficiency is closely connected with the speed of relevant information delivery to the experts. Therefore, the computer-based Prognostic decision support system (PDSS) must inevitably be part of the suggested Expert system.

In practice, in order to ensure efficient control and command the following factors must be taken into consideration:

- the distribution of PDSS, i.e. whether group or individual decision making is used;
- types of structures of external factors compensation tasks, i.e. availability of analytical models, quantitative evaluations or qualitative characteristics;
- nature of decision efficiency evaluation, i.e. possibility of objective evaluation of the results of corrective input;
- nature of the situation in which decisions are made, i.e. stressfulness, DM's experience, etc.

For the purpose of improving the agility of control and command it is suggested to ensure SC adaptivity to external effects based on predicted operating modes. The forecast is to be generated in the form of dynamics description of multifactorial situations. A situation shall be understood as a SC survivability characteristic under the chosen strategy of corrective inputs generation.

Strategic model of a multifactor situation

The mission tasks define the requirements to SC survivability. However, this task is ill-posed, as SC design usu-

[1] This regards, for example, electrical and magnetic field sensors, energetic particle flow of solar and galactic source sensors, etc.

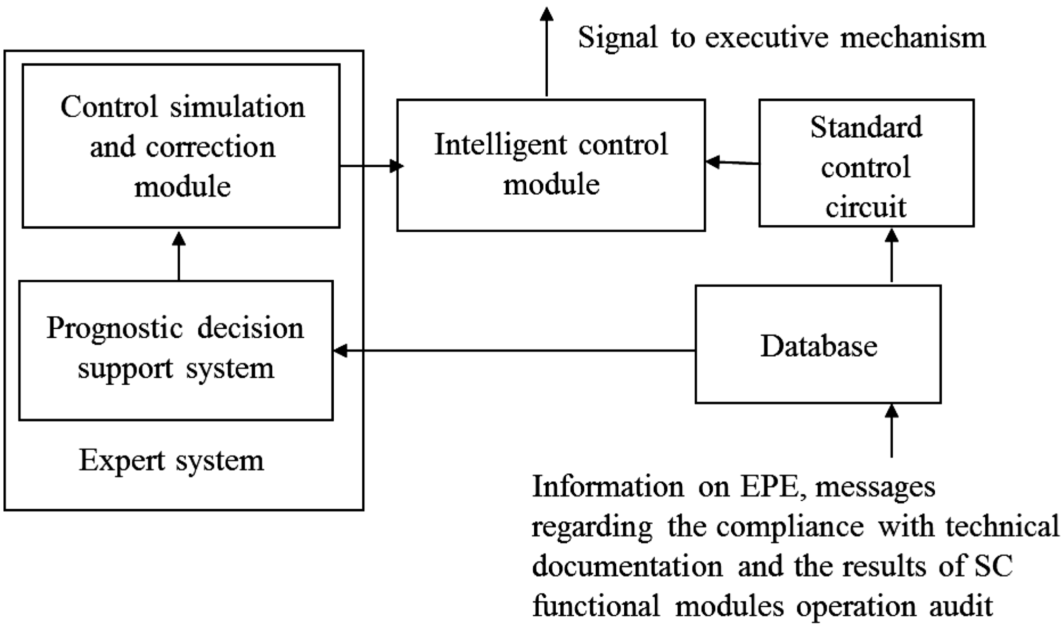

Figure 1. Diagram of intellectualization of SC control

ally allows for a multitude of possible solutions for control adaptation under identical external factors. To that effect we propose evaluating the operational stability of a functional module using the following model (1):

$$<S, k_1, \ldots, k_m, R> \quad (1),$$

where $S=\{s_i, i=1,2,\ldots, m\}$ is the set of strategies for generating corrective inputs that are defined by the characteristics of the hardware and software included in the considered module. It is assumed that such signals would enable SC survivability under environmental effects. Hereinafter we shall name the EFE adaptivity processes the multiple choices and confine them with the conditions of mission survivability.

$k_1, \ldots, k_m$ are expert evaluations of the probability of SC module operation without deviations from parameter values as per the mission task in case the *i*-th strategy has been adopted;

R is the preference-indifference relation.

Let the SC survivability strategy be chosen by experts[1]. In model (1), the value of each variant s_i out of the set *S* of all (possible) variants is characterized by the values of expert evaluations k_i.

Evaluation k_i should be understood as the value defined on set *S* and taking on the value out of set X_i that is called the scale. The the considered task such scale is defined by the set of levels of productivity of the means to ensure adaptivity of SC operation to external effects.

Without loss of generality, we suggest that all evaluations are expressed numerically and larger values are preferable to smaller ones. Thus, each variant s_i is characterized with values $k_i(s)$, that form the evaluation vector of this variant $x(s) = (k_1(s), \ldots, k_m(s))$. In the model the variants are compared based on the preferability through comparison of their vector evaluations. The set of all evaluation vectors: $X = x_1 \ldots x_m$.

It is assumed that the evaluations are homogenous, i.e. they have an identical (common) scale $x_0 = x_1 = \ldots = x_m$. If the evaluation k_j is replaced with $\xi(k_j)$, where $\xi$is an allowable transformation defined by the type of scale, then all the other evaluations k_i should be replaced with $\xi(k_i)$. Let us also assume that the set x_0 finite: $x_0 = \{1, \ldots, q\}$. Elements of this set will be called scale gradations.

Expert preferences are modeled by the relation of preference *R* by *X*: *xRy. That* means that the evaluation vector *x* is not less preferable than *y*. The relation *R* generates the indifference relation *I* and (strict) preference *P*: *xIy,* i.e. the following exressions are true: *xRy* и *yRx*. *xPy* is completed when *xRy,* is true and *yRx is not true.*

For generality, we will use the preference relation accepted for the modeling of the weighted total R^V [1]. For modeling of preferences defined using the value function we will use the preference relation R^f. Additionally, it is suggested to consider not the "weights" of the evaluations as it is done in the method of weighted sums, bit the importance of their numeric values using the terminology of the evaluation significance theory. The concepts of "weight" and evaluation importance are somewhat different, but in terms of practical conclusions of this study it is insignificant.

We evaluate the significance of changes in the SC operational performance in the form of paired comparison of values *б* (importance of first evaluation) and *в* (importance of second evaluation). It is assumed that the values of evaluation importance are whole numbers from 1 to *m*.

Let us assume that it is easier to the expert to identify the relation of the evaluation values importance as a relation of several whole numbers. We suggest defining the value function in the additive form by comparing by each scale grade *k* its value *v*(*k*). Let *w* represent the difference quotient of

[1] In this article, the experts should be cosmonauts and control center employees.

scale grades values. It shows the measure of “waning” of an expert’s preference growth.

$$d_k \le \frac{\nu(k+1)-\nu(k)}{\nu(k+2)-\nu(k+1)} \le u_k, k=1,\ldots,q-2.$$

It is assumed that d_k and u_k are constant for all grades and $w=u_k$, as well as that $w>1$, $\alpha=1/w$.

Due to the variety of external effects SC is considered to be a complex system, i.e. as an object that is characterized by the functions performed by by its modules, as well as those functions’ relation algorithms. In this case the set $\{k_1, ..., k_m\}$ that characterizes the SC survivability will be considered as a sum of evaluations of SC functional dependability.

An important feature of the considered task is the absence of unambiguous numerical characteristics that would describe the environmental effects. Therefore, it is suggested to solve the task of ensuring SC survivability under external effects in term of fuzzy logic (fuzzy sets).

For the purpose of this study it is suggested to apply the term fuzzy to sets of ordered couples: $A=\{u, \mu_A(u)\}$ composed of elements of the ground set U coupled with the function $\mu_A(u)$, $u \in A$ that defines the measure of membership or membership function. The function $\mu_A(u_i)$ indicates the assumed measure if membership of the element u_i in the set A. The primary feature of this function consists in the fact that it characterizes an expert’s subjective idea of the nature of the evolution of SC reaction to external effects. It is also assumed that another expert’s function $\mu_A(u_i)$ would have another formula.

A qualitative description of such quantitative concepts within the considered task would require a linguistic variable. A linguistic variable shall be a variable defined on the qualitative scale and possessing the values of words and phrases of a natural language.

In this article the advantage of fuzzy logic over the classic approach consists in the fact that under the fuzzy approach the analytical representation of external effects can be avoided. In many cases it suffices to provide a description of the SC reaction to such effects, while under the classic approach it is required to formalize the description of the external effects and internal factors that define the SC reaction to such effects.

It should be noted that as the diversity of deviations in the SC operation under external effects grows (growth of the value m in the formula (1)) the ability of the experts to make accurate meaningful assertions decreases. There can be a threshold beyond which the accuracy and meaningfulness become almost mutually exclusive characteristics.

Identifying such threshold requires the use of the law of requisite variety. It is known [3] that in respect to our task the variety of external factors can be compensated only by the variety of the signals that adapt the SC operation. In this case let us assume that in order to choose a strategy using the model (1) an expert must have the required experience and knowledge, be able to analyze situations, predict the dynamics of SC reaction to environmental effects.

The condition of information transmission without distortion proved by C. Shannon for noise-free signals [4], is the absence of excessive power at the source over the channel capacity. In the considered systems an evaluation of information source power and channel capacity is very complicated. However, in our case the efficiency of SC adaptation to external effects can be evaluted based on the importance of errors in the messages exchanged by functional modules. Let us assume that the measure of deviation from the standard mode of controlled module operation is defined by the value of distortion of the information received from the controlling module.

With regard to the considered task let us assume that those distortions correspond to the excess of power of the information flow over the channel capacity. In this case based on the above mentioned C. Shannon’s condition let us define the condition of functional dependability of the control system in the absence of interference: *If the functional dependability of the controlled module is not lower than the functional dependability of the controlling module, then in the absence of interference the operation of the system of such modules can always be organized in such a way that its functional dependability will match the functional dependability of the controlling module without additional correction and conversion.*

The understanding of the control system dependability suggested in this article is based on the evaluation of the probability of no-failure in SC operation [5]. The model (1) allows choosing the strategy of ensuring SC survavability under environmental effects. The analysis of SC modules reaction variations is the basis for forecasting the consequences in such changes.

It is assumed that the characteristics of the SC survivability systems, requirements for the evaluations of the degree of adaptivity of functional modules, as well as the requirements for the form of control input results delivery are defined by the mission task. In this case it can be believed that the efficiency of control signals correction largely depends on the efficiency of computer support of forecasting.

Prognostic decision support system (PDSS)

There are over two hundred known software suites that can be used in forecasting the changes in the condition of complex objects or processes [6]. They work comparatively well when the development is stationary, i.e. process dynamics characteristics don’t significantly change over time. Those programs also work well when the characteristics change function of a process or object is known.

In this context operational decision-making is required in order to ensure functional modules adaptivity to external factors subject to SC specific reactions to effects of unknown nature and unknown intensity dynamics. In this case it is suggested preparing expert forecast of SC reactions based on intersubject audit of its functional modules operation.

Let us identify the three primary tasks related to such PDSS operation:

Search, analysis and processing of current information:

- express analysis of subject areas with identification of key changes in SC functional modules operation;
- identification of information on specific functional modules in the database;
- identification of the most significant effects that define the developments at the SC;
- clusterization of information with possibility of reducing the dimensions of correcting signal's components;

The PDSS must enable:

- automatic offloading and transformation of information into the specified format;
- separation of dynamic links to information source (technical documentation data, RII information, functional modules operation monitoring results);
- simultaneous monitoring of independent modules that provide data on the development of SC reaction to external effects;
- setting time of repeated look-up of each of the modules for new messages;
- generation of reports within the time of operation as per the mission task specifying the number of downloaded messages;
- adding the name of source and date of receipt at the beginning of each message;
- specifying the format of the output file;
- downloading new messages without operator's involvment;
- setting the download mode at request (disabling automatic lookup);
- enabling automatic download;
- notification of new messages;
- monitoring of accidents;

2. Data logging:

- document archiving and development of internal documents with elaborate information search functions;
- creation of the archive of formal profiles (with elaborate search functions) for each functional module;
- automation of regular monitoring of functional modules;
- identification of relations between module reactions, correlations between external effect;
- automation of reports and analytical notes preparation;
- capability to modify the database sructure (adding new properties and generic objects over the course of system operation);
- organization of single storage for information on monitored objects, events, data from external databases;
- automated identification of mentions of objects, connections and events;
- visualization of knowledge as a semantic network;
- capability of searching for implied (indirect) connections between modules reactions;

3. Condition analysis and providing recommendations on managerial decision-making.

PDSS must ensure the compatibility of calculated preferences and expert evaluations obtained based on conventional (or newly developed) mathematical methods implemented within software and hardware.

The first two tasks are not managerial ones, yet SC survivability depends on the efficiency of the hardware and software subsystems that perform those tasks. Those tasks are classic, therefore in order to solve them it is suggested to use software available on the market. Practice shows that the third task can be solved with existing software products, but the combination of fuzzy logics and the requirement for fast decision-making within the time limited by the development of destructive processes in SC as the result of external EPE makes for a unique situation.

It is suggested to design PDSS as a distributed system. Hierarchically it is to be divided into several levels of forecasting process. *Sun Management Center* is an example of such system structure division that comprises the monitoring level, servers and agents. In our case the experts can be considered to be agents.

<u>At the monitoring level</u> it is required to take into consideration the interface between expert requests and the results of intersubject audit of the development of SC reactions to external effects. At this level, we can use the Java monitor, network monitor and call level interfaces. For the same server such monitors must ensure:

display of functional modules performance, e.g. in the form of tables and graphs;

capability to manage characteristics and properties that control functional modules operation, e.g. provide information on the proximity of the threshold of allowed change of operational performances;

capability to initialize control tasks, e.g. dynamic reconfiguration of modules' performance.

<u>The server level</u> receives requests via the monitor and sends them to a specific expert. Then it returns the expert's reply to the monitor. Additionally, by means of the interface the server provides the monitor with a secure entry point for communication with experts.

<u>The purpose of the expert level</u> is to collect information and generate corrective inputs to control commands. The experts shall apply the rules for defining the statuses of controlled modules. In case of rules infringements, the software automatically generates alerts and performs actions predefined by the respective rule of SC survivability.

Modern current information analysis systems widely use the concept of "knowledge management". According to this concept, in the proposed Expert system the main purpose of knowledge management (*Knowledge management – KM*) is the creation of an efficient communication medium that allows finding and using not information, but knowledge held by the experts experienced in the performance of SC mission tasks.

This approach is due to the fact that in practice the results of the audit of EPE and SC functional modules reactions development represent only the initial data. After clearing, sorting and statistical analysis they become information resources. The results of such resources analysis and design of messages based on expert conclusions transforms such resources into knowledge that is used in decision-making on control correction.

With regard to the considered task, in order to ensure agility of information analysis within the database, it is suggested to use the *OLAP* comprehensive multidimensional analysis technology. In particular, that includes the *FASMI* (*Fast Analysis of Shared Multidimensional Information*) test that includes requirements for multidimensional analysis applications:

1) provision of the analysis results to the expert within an acceptable time (usually, not more than 5 sec) even at the cost of less detailed analysis;

2) capability to perform any logical and statistical analysis specific to the given application and save its results in a form available to the end user;

3) multiple user access to data with support for mechanisms of authorized access and blocking;

4) multidimensional conceptual representation of data including full support of hierarchies and multiple hierarchies;

5) capability to refer to any required information regardless of its size and place of storage.

It should be noted that in respect to the considered task the *OLAP* functions can be implemented by various means, from the most simple data analysis tools in applications to complex distributed analytic systems [7].

Conclusion

Consideration of the opportunities presented by information technology in ensuring SC survivability under external effects has brought to light the capabilities enabled by the intellectualization of computer-based support of command. Based on forecasted development of SC functional modules' reaction to EPE, the proposed model of systematic accumulation and processing of data will enable FCOs to timely identify inadequacies in control actions.

The distinctive feature of the suggested method of information support of forecasting the development of SC functional modules' reaction to EPE is the combination of the methods of computer data processing and intersubject analysis of functional units operation. This approach must insure efficient decision making based on increased accuracy and agility of data processing and, consequently, selection of the scenario of SC operation adaptation to EPE subject to flight control officer's preferences.

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On the matters of increasing the dependability of first stage pumping stations power supply

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Abstract. *First stage pumping stations are first category power consumers that usually have back-up power supply. Additionally, the engine room of the pumping station is equipped with synchronous or asynchronous high-voltage motors that in transient states may create unforeseen problems in the power supply system not only within the station, but beyond. The dependability of plant and equipment is defined by many factors, e.g. start-up procedures, stopping-down, operational changes, equipment shutdown. [6]. The primary factors that reflect the impact of the transient states are mechanical overload, voltage slumps in load centers, voltage slumps in switchgear busbars, etc. The value of voltage slump associated with start-up of high-voltage synchronous motors that does not last more than 30 seconds is neglected, though the impact of start-up voltage slump is a negative factor that affects adjacent consumers on the grid [7]. The dependability of the power supply system has an effect not only on pump station operation, but also on the service life of the facility's electrical equipment. An undependable power supply system can also contribute to higher electric loss and deterioration of power quality. Improving the dependability of power supply systems of the considered facilities requires first and foremost specific tasks to be solved. To that effect, this article specifies and analyzes primary causes of faults in first stage irrigation pumping plants. The authors clarify the dynamic stability of high-voltage synchronous motors and its dependence on short interruptions of power supply. They also analyze the impact of start-up currents of synchronous motors on the operation of pumping units and electrical equipment in general. The article substantiates the efficiency of soft starters (SSs) in start-up procedures of high-voltage synchronous motors of pumping units of irrigation pumping stations. The article also establishes the inefficiency of frequency converters in pumping units of irrigation pumping stations using specific examples. It was found that automatic transfer equipment in the considered facility does not ensure the speed of operation required for fault recovery and negation of water hammers in pumping units. The article sets forth the tasks and possible solutions related to improving the dependability of power supply systems of first stage irrigation pumping plants.*

Keywords: *pumping station, soft starter, frequency converters, automatic reserve input, synchronous motor, water hammer, dynamic stability, inrush current, short circuit.*

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High-voltage synchronous motors are the primary power consumers of first stage irrigation pumping plants. This machinery has high capacity factor and inrush current. Among the causes of pumping station failures are loss of dynamic stability of synchronous motors that in turn may be caused by unreliable performance of power supply systems and standby infeed automatics [5]. Another failure-causing factor is inrush current of large synchronous motors causing kinetic force in stator winding which can weaken the end-winding and induce unacceptable local heating in the rotor [4]. In powerful vertical synchronous machines with large active length, the start-up procedure causes uneven heating of bars that causes thermodynamic force and subsequently the destruction of starting winding. Additionally, at start-up busbar voltage may slump. The quality of power delivered to consumers connected to substations that feed pumping stations currently only defined by the provisions of GOST 13109-97 [7]. In the Russian Federation, voltage slumps shorter than 30 seconds are disregarded, whilst high-voltage synchronous motor start-up usually does not exceed 10 to 15 seconds. This problem, as well as the problem of start-up thermodynamic force is partially mitigated by starting-up large synchronous motors with partial voltage. In this case the start-up voltage is lower and the start-up time is longer. Therefore, in each particular case the start-up procedure for large synchronous motors varies [2, 3]. For example, when a powerful synchronous motor is started-up using

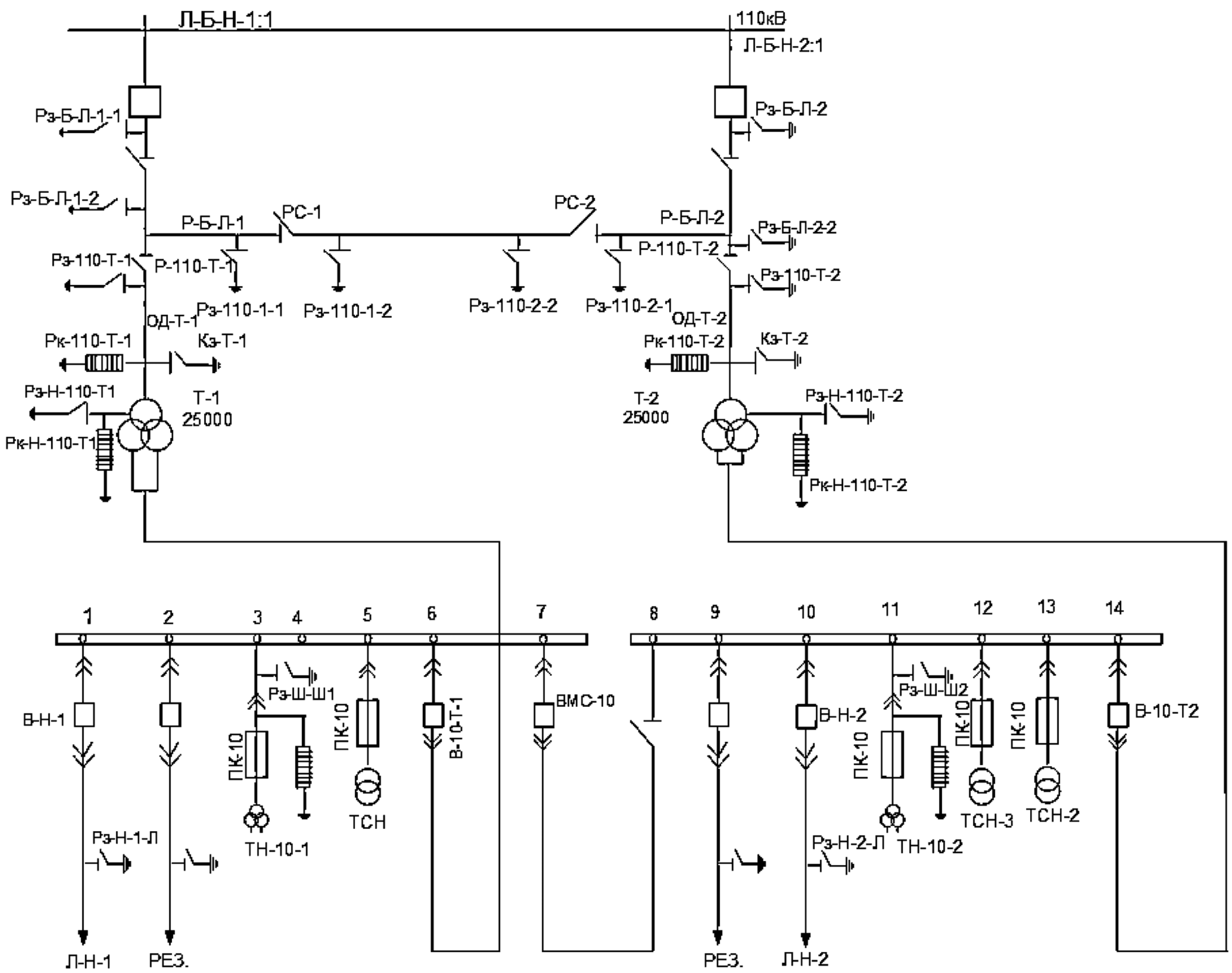

Fig. 1. First stage pumping station (ANS-1) power supply diagram

insufficiently powerful voltage source, a significant voltage slump may occur at motor output.

In this article the research object is the Asht pumping station cascade, namely ANS-1 situated in the Asht District of the Republic of Tajikistan. The design pumping power of the ANS-1 station is 1,7712 mil m^3 of water a day. As of today, only two pumping units of ANS-1 with total output of 0,88 mil m^3 of water a day are operational. Figure 1 shows the ANS-1 power supply diagram [1].

The ANS-1 pumping station is a first category power consumer, thus it is powered by two independent substations [1]. Power to ANS-1 is supplied from the Bulok-2 central power distribution station with the power of 2Ч63 MVA. Via two 110 kV power lines voltage from Bulok-2 is delivered to the power substation of ANS-1. The power substation of ANS-1 is equipped with two 25000 kVA 110/10 kV TRDN-type transformers.

Main and auxiliary pumping units are fed with 10 kV voltage. The station's control and lighting system is fed with 0.4 kV voltage.

The primary power consumers in ANS-1 are:

- 4 main pumping units with total power of 32 MW,
- 3 auxiliary pumps with total power of 4.8 MW,
- two TM 400 10/0,4 type transformers for internal requirements that power a 0,4 kV power network [1].

ANS-1 pumps stations consume around 250000 kWh a day. Water feed is 0,88 mil m^3 a day. In maximum feed mode, ANS-1 simultaneously runs four pumping units. As it was mentioned above, ANS-1 has 4 pumping units with synchronous drives. The pumping units are powered by vertical synchronous motors of the VDS-325/69-16 UKhL4 series of which the technical features are given in table 1.

Disruptions in pump station power supply cause significant water hammers in pipelines and, consequently, failures and breakdowns of pump station equipment. As the research shows, short interruptions of power supply are one of the primary causes of water hammers [5]. In order to prevent major water hammers it is required to reduce the action time of power supply recovery automatics. Previously conducted research has demonstrated that if the duration of power supply disruption is below 0,3 sec, the effect of static to total pressure ratio is in-

Table 1. Technical features of VDS-325/69-16 UKhL4 series of vertical synchronous motors

№	Type of motor	VDS-325/69-16 UKhL4
1	Power, MW	8
2	Stator current, A	540
3	Rotor current, A	400
4	Stator voltage, kV	10
5	Rotor voltage, kV	0,16
6	Speed, rev/min	375
7	Efficiency, %	0,959
8	cos, ц	0,9
9	I_{start}/I_{nom}	4-4,8
10	M_{start}/M_{nom}	0,32
11	$M_{0,05}/M_{nom}$	1,2
12	M_{max}/M_{nom}	1,8
13	Rotor moment of inertia, $t{\cdot}m^2$	24,5
14	Step bearing load, tnf	125
15	Number of pairs of poles	8

significant, and as the power supply interruption time decreases this effect declines, while the conditions for maintaining dynamic stability of synchronous motors improve [5].

For the purpose of synchronous motor start-up current reduction and thereby improvement of the voltage slump situation, as well as reduction of water hammer in pipelines, a number of technical measures have been developed, e.g. soft starters, frequency converters. Frequency transformers have a number of advantages over other startup systems, the main one being the adjustment of the motor speed and thus power-saving. But frequency transformers are only efficient if the range of speed adjustment is significant. If the range is narrow they do not provide any positive effect, while being very costly. In the context of the considered ANS-1 facility, frequency converters are not efficient, therefore the authors suggest using soft starters. Those devices are simple voltage regulators based on power semiconductors, i.e. thyristors and symistors. Soft starters are only used in the start-up procedures, after which they are shut down or used to start-up another motor. If a soft starter is used up to 3 to 4 times, the start-up current can be limited with insignificant voltage slump. Another advantage of soft starters over the frequency transformers consists in the fact that they are several times cheaper and have a simpler design.

Another factor that affects the operation of pumping station power equipment is the fault conditions, i.e. short circuit conditions. Corresponding research has shown that in case of three-phase short circuits the allowable time of power supply interruption is 0,09 – 0,11 sec for the pumping units in question under condition of short circuit duration of 0,07 – 0,08 sec [5]. During this time dynamic stability of synchronous motors is maintained. But the problem is that existing standby infeed automatics cannot provide required response time.

Therefore the problem of ensuring dynamic stability of high-voltage synchronous motors in the context of improving the dependability of pump station power supply system is relevant and in order to solve it, a number of tasks must be set and carried out:

- using soft starters in start-up procedures of high-voltage synchronous motors with low control ranges,
- developing fast-acting microprocessor-based standby infeed automatics,
- researching the application efficiency of soft starters in order to improve the dependability of power supply systems of first stage irrigation pumping plants,
- in order to reduce the equipment costs, researching less expensive methods of improving the dynamic stability of high-voltage synchronous motors, e.g. inclusion of a resistor in the exciting circuit, cyclic superexcitation, etc.,
- performing feasibility studies of deployment and application of intelligent power supply system supervision and monitoring solutions in first stage pumping stations.

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Efficient estimation of mean time to failure

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Abstract. *Product testing plan of type NMT has been chosen as the subject of research plan. This plan's time between failures is subject to the exponential law where N is the number of same-type tested products; T is the time to failure (same for each product); M is a feature of the plan meaning that after each failure the working condition of the product is recovered over the course of the test. In this case, the time to failure is defined according to formula $T_{01} = NT/\omega$, where ω is the number of observed failures, $\omega > 0$, that occurred within the time T. This estimate is biased. Besides that, if it is required to solve a problem that involves achieving a point estimation of mean time to failure (T_0) of products based on tests that did not produce any failures, estimate T_{01} cannot be used. If over the time of testing the number of observed failures is small (the number does not exceed several ones), the estimate can contain a significant error due to the bias. In order to solve the above problem, it suffices to find an unbiased efficient estimate T_{0ef} of the value T_0, if such exists, in the class of consistent biased estimates (the class of consistent estimates that includes all estimates generated by method of substitution, of which the maximum likelihood method, contains estimates with any bias, including those with a fixed one, in the form of function of parameter or constant). In general, there is currently no rule for finding unbiased estimates, and their identification is a sort of art. In some cases, the generated unbiased efficient estimates are quite lengthy and have a complex calculation algorithm. They are also not always sufficiently efficient in the class of all biased estimates and not always have a considerable advantage over simple yet biased estimates from the point of view of proximity to the estimated value.* **The aim** *of the article is to find the estimate of value T_0 that is simple and more efficient in comparison with the conventional one and negligibly inferior to the estimate T_{0ef}, if such exists, in terms of proximity to T_0 when using the NMT plan.* **Methods.** *In obtaining an efficient estimate integral characteristics were used, i.e. total relative square of the deviation of expected realization of estimate T_0 from various values T_0 per various failure flows of the tested product population. A sufficiently wide range of class estimates was considered and a functional built based on the integral characteristic, of which the solution finally allowed deducing a simple and efficient evaluation of mean time to failure for the NMT plan.* **Conclusions.** *The achieved estimate of mean time to failure for the NMT plan is efficient within a sufficiently wide range of estimates and is not improvable within the considered class of estimates. Additionally, the achieved estimate enables point estimation of mean time to failure based on the results of tests that did not have any failures.*

Keywords: *mean time to failure, exponential law, efficient estimation.*

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In modern manufacturing of complex high-dependability products, it has become fairly common when it is required to produce a point estimate of product dependability indicator based on tests that did not result in failure. In compliance with [1], mean time to failure is chosen as the indicator that characterizes reliability as a dependability property of complex restorable itemsT_0. From managerial and economic points of view, the *NMT* plan is optimal for testing restorable (replaceable) products (hereinafter referred to as products) under condition that time between failures is subject to the exponential law, where *N* is the number of same-type tested products; *T is* the time to failure (same for each product); *M* is a feature of the plan meaning that after each failure the working condition of the product is recovered over the course of the test [2]. In this case, the mean time to failure is defined according to formula $T_{01} = NT/\omega$, where $\omega > 0$ is the number of observed failures that occurred within the time *T*. This estimate is biased [2]. Besides that, estimate T_{01} cannot be used for the purpose of solving the above problem. If over the time of testing the number of observed failures is small (the number does not exceed several ones), the estimate can contain a significant error due to the bias.

The above entails the problem of defining the value of relative confidence error δ of the evaluated value T_0, as the solution requires the results of point and confidence estimation [3, 4]. Solving this problem is impossible by using T_{01} if the tests did not produce any failures. In case the number of observed failures is small, the solution has a significant bias of error δ. Therefore, conventional estimation must be used in order to eliminate said shortcomings.

In order to solve the above problem, it suffices to find an unbiased efficient estimate T_{0ef} of the value T_0, if such exists in the class of consistent biased estimates (the class of consistent estimates that also includes all estimates generated by method of substitution, of which the maximum likelihood method, contains estimates with any bias, including those with a fixed one, in the form of function of parameter or constant [5]). In general, there is no rule for finding unbiased estimates, and their identification is a sort of art. In some cases, the generated unbiased efficient estimates are quite lengthy and have a complex calculation algorithm [6-8]. They are also not always sufficiently efficient in the class of all biased estimates and not always have a considerable advantage over simple yet biased estimates from the point of view of proximity to the estimated value [9].

The purpose of the article is to find the estimate of value T_0 that is simple and more efficient in comparison with the conventional one and negligibly inferior to the estimate T_{0ef}, if such exists, in terms of proximity to T_0 when using the *NMT* plan.

In order to find the efficient estimate we will use integral characteristics [10, 11]. Let us use the total relative square of the deviation of expected realization of estimate $T_{0\omega}$ from various values T_0 per various failure flows of the tested product population [11]:

$$AT_{0\omega} = \int_0^{\infty} 1/T_0^2 \left\{\Theta T_{0\omega} - T_0\right\}^2 \partial\Delta, \qquad (1)$$

where Δ indicates the Poisson failure flow with parameter NT/T_0 [12], while $\Theta T_{0\omega}$ is the expectation of the suggested estimate. By using the properties of the Poisson flow with parameter NT/T_0 [12] we will deduce

$$\Theta T_{0\omega} = \sum_{\kappa=0}^{\infty} T_{0\omega\kappa} E^{-\Delta}\, \Delta^{\kappa}/\kappa!. \qquad (2)$$

Let us represent estimate T_{01} as

$$T_{01} = \frac{NT}{\omega+1} + \frac{NT}{\omega(\omega+1)}. \qquad (3)$$

Given that ω is sufficient statistic [13] let us consider the estimate class $T_{0\omega}$ that can be represented as (3), i.e.

$$T_{0\omega} = \frac{NT}{\omega+1} + NTf(\omega). \qquad (4)$$

This estimate class includes the efficient estimate from [11].

The expectation of estimates of class (4) according to (2) will be expressed by formula

$$\Theta T_{0\omega} = T_0\left(1-E^{-\Delta}\right) + T_0 E^{-\Delta}\sum_{\kappa=0}^{\infty}\Delta f(\kappa)\Delta^{\kappa}/\kappa!. \qquad (5)$$

Let us denote $B = \sum_{\kappa=0}^{\infty} \Delta f(\kappa)\Delta^{\kappa}/\kappa!$. After substituting (5) into (1) we deduce

$$AT_{0\omega} = \int_0^{\infty} E^{-2\Delta}(B-1)^2\,\partial\Delta = B_2 - 2B_1 + 1/2, \qquad (6)$$

where $B_2 = \sum_{\iota=0}^{\infty}\sum_{\kappa=0}^{\infty} f(\iota) f(\kappa) 0,5^{\iota+\kappa+3}(\iota+\kappa+2)!/(\iota!\kappa!)$,

$$B_1 = \sum_{\kappa=0}^{\infty} f(\kappa) 0,5^{\kappa+2}(\kappa+1).$$

Let us identify the lower limit of the functional (6) for which purpose let us assume

$$B_2 = \sum_{\iota=0}^{\infty} f(\iota) 0,5^{\iota+1}\sum_{\kappa=0}^{\infty} f(\kappa) 0,5^{\kappa+2}(\kappa+1)(\kappa+2)\ldots(\kappa+\iota+2)/\iota!$$

and note that

$$\begin{gathered}(\kappa+2)\ldots(\kappa+\iota+2)/\iota! = (\kappa/2+1)\cdot(\kappa/3+1)\cdot\ldots\cdot\\ \cdot(\kappa/(\iota+2)+1)\cdot 2\cdot 3\cdot\ldots\cdot(\iota+1)\cdot(\iota+2)/\iota! =\\ (\kappa/2+1)\cdot(\kappa/3+1)\cdot\ldots\cdot(\kappa/(\iota+2)+1)\cdot 2\cdot 3\cdot\ldots\cdot\\ \cdot(\iota+1)\cdot(\iota+2) \geq 2(\iota+1).\end{gathered}$$

Therefore

$$B_2 \geq 2\cdot 0,5\sum_{\iota=0}^{\infty} f(\iota) 0,5^{\iota+1}(\iota+1) 2\cdot B_1 = 4B_1^2.$$

By substituting the right side of the inequality into (6) we deduce $AT_{0\omega} \geq 4\cdot B_1^2 - 2B_1 + 1/2$. By deriving the right side with respect to B_1 and equating it to zero we deduce the lower limit $AT_{0\omega} \geq 0.25$.

Let us identify the composite estimate that belongs to the class under consideration, i.e.: $T_{02} = 2NT$ if $\omega = 0$ and $T_{02} = NT/(\omega+1)$ if $\omega > 0$. Out of general $T_{0\omega}$ follows $f(\omega) = 1$ if $\omega = 0$ and $f(\omega) = 0$ if $\omega > 0$. As is easy to see, in this case $B_2 = 0.25$ and $B_1 = 0.25$. By substituting the resulting values into (6), we deduce $AT_{02} = 0.25$, i.e. the estimate T_{02} affords to the functional $AT_{0\omega}$ a minimum equal to 0.25. Given the above deduced estimate of the lower limit of the functional $AT_{0\omega}$ we can suppose that the estimate T_{02} is not improvable within the considered class of estimates.

Therefore T_{02} is the desired estimate. Let us use it to solve the above problems.

Example. Over a 1000-hour reliability testing of 50 modules no failures were observed. Based on the test results, point estimation of parameter T_0 must be performed.

Solution. For $\omega = 0$ we deduce $T_{02} = 2NT = 2\cdot 50\cdot 1000 = 100000$ h.

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Definitions of dependability

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Abstract. *The article analyzes dependability-related definitions that have been used so far in a number of regulatory documents, the majority of which have been borrowed into Wikipedia. The analysis shows the shortcomings of said terminology, while more correct definitions of primary dependability-related terms are suggested for dependability, reliability, maintainability, durability, survivability, storageability, operation time, limit state. For instance, the generic term "science" instead of "property of object" is suggested for the definition of "dependability", as the former better complies with the modern understanding of the term "dependability", as it has a subject matter, research methods and quite specific goals. It is also shown that this definition of "dependability" may be taken as a basis and then all dependability characteristics should be defined not as "properties of objects", but rather as dependability indicators, while specifying what properties they characterize. For example, reliability is a dependability indicator that characterizes the time from the start of object operation to its expected failure. Another example: storageability is a dependability indicator that characterizes the time during which an object can be stored under certain storage conditions with no loss of required quality. It is suggested to define in this manner all the required dependability characteristics. Further it is shown that there is an error in the dependability-related definitions with the generic term "property of object", as the definition in those notions is incorrectly associated with the term it refers to. For instance, the existing definition of dependability: "property of an object to maintain in time and within the set limits the values of all parameters that characterize the ability to perform the required functions in specified modes and conditions of operation, maintenance, storage and transportation" should be associated with the term "dependability of object", but not "dependability", as it implies a wider notion. Additionally, the article suggests a number of new terms, such as dependability of object, reliability of object, maintainability of object, etc. that are directly related to the dependability indicators of a specific facility a user is concerned with. In the conclusion examples are given of construction of terms and definitions for such technical objects as control systems. The distinctive feature of such objects is that they are usually multifunctional and it is not correct to set dependability requirements for the system as a whole, as that is impossible. In such cases it is believed that the system's dependability has been identified when the dependability indicators of all the functions it performs are known.*

Keywords: *aspect, safety, time, reliability, time, longevity, survivability, quality, operation time, science, object, definition, limit state, mode, maintainability, property, storageability, term, operational application.*

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In today's world, dependability is one of the primary characteristics that define the quality of any product. Therefore, the matters of dependability have been and still are the focus of attention, especially in the high-technology industry, as well as in the context of regulatory documentation development, specifically when it comes to the terminology that covers practically all required technical aspects of products that ensure their normal operation over the specified period of time.

This article questions the current dependability-related terminology, as it has significant shortcomings that will be identified below.

We will begin with a list of notions that are criticized in this article and that are taken from [1].

Dependability is the property of an object to maintain in time and within the set limits the values of all parameters that characterize the ability to perform the required functions in specified modes and conditions of operation, maintenance...

Reliability is the property of an object to continuously maintain its operability over a certain time of operation.

Maintainability is the property of an object that consists in its ability to maintain and recover operability through maintenance and repair.

Longevity is the property of an object to continuously maintain its operability from the beginning of operation to the onset of the limit state, i.e. a condition at which the object is removed from operation.

Storageability is the property of an object to maintain its operability over the period of storage and transportation.

Survivability is the property of an object to maintain its operability after the failure of individual functional units.

Time to failure is the value (time or volume of work) used for measurement of equipment operation time.

Service life total time from the beginning of operation to the onset of the limit state.

Let us begin with the term "dependability" that is used in many documents, for example in [1, 2], where it has a similar definition:

Dependability is the property of an object to maintain in time and within the set limits the values of all parameters that characterize the ability to perform the required functions in specified modes and conditions of operation, maintenance, storage and transportation.

As we see from those examples, the generic term for "dependability" is "property of object".

According to another opinion, e.g. in [3], "it is only since very recently that the dependability theory is a stand-alone science. It happened at the beginning of the technological revolution, i.e. in the middle of the XX century. That period was marked with a new qualitative leap in the technological development, widespread deployment of large and small-scale automated control systems (ACS) of various purposes. The development and application of such technology without the use of special measures to ensure its dependability is meaningless. The problem of dependability of automated control systems was first encountered by the scientists of the Nazi Germany who created the first of its kind unmanned airplane, the V-1 cruise missile."

Besides that, in [4] it is also noted that "the dependability theory is a science that deals with the failure patterns of technical systems and possesses the methods that allow using the analysis of statistical data on populations of identical objects to identify the probability of failures of objects in operation."

Therefore, as shown above, according to an opinion the word "science" can be used as the generic term for "dependability", and the former, in my opinion, is preferable due to the following reasons:

First, like any science, dependability has a subject matter, i.e. the failure patterns of technical objects;

Second, like any science, dependability has its methods, i.e. deterministic, stochastic and physical;

Third, like any science, dependability has its pragmatic goals, i.e. development of regulatory documents that set forth the methods and ways of identifying such special properties of technical systems as reliability, maintainability, storageability, longevity, survivability, service life, etc.

The above allows defining "dependability" as follows:

Dependability is a science that deals with failure patterns of technical systems for the purpose of identifying the causes of failures, their prediction, as well as preparation of regulatory documents that set forth the definitions, requirements, rules, assumptions and exceptions of which the observance enables the development of products with required time and quality of operation.

This definition of dependability allows for different definitions of its indicators, i.e. reliability, maintainability, storageability, survivability, longevity, etc. that are different from those given in regulatory documents.

For example:

Reliability is a dependability indicator that characterizes the time from the start of object operation to its expected failure.

Maintainability is a dependability indicator that characterizes the time required for object recovery after failure.

Storageability is a dependability indicator that characterizes the time during which an object can be stored under certain storage conditions with no loss of required quality.

Longevity is a dependability indicator that characterizes the time during which an object can maintain its operability.

Now let us go back to the existing dependability-related definitions with the generic term "property of object" that are widely used today. In my opinion, the error is that the definition in those notions is incorrectly associated with the term it refers to. For example, when defining the term "dependability", if the definition is referred to the term "dependability of object" everything falls into place:

"Dependability of object" is the property of an object to maintain in time and within the set limits the values of all parameters that characterize the ability to perform the required functions in specified modes and conditions of operation, maintenance, storage and transportation.

As we see, the term is easily associated with the definition.

In the same manner, the term "maintainability" from [1] should be replaced with a term associated with the object:

Maintainability of object is the property of an object that consists in the adaptation to prevent and detect the causes of failures, defects and eliminate their consequences by means of maintenance and repair.

Similarly, it is suggested to replace the remaining terms for dependability indicators from [1] with object-related terms:

Reliability of object is the property of an object to continuously retain operability with a specified operation time.

"Operation time" should also be understood as a term related to the object of which the operating time we deal with:

Operation time of object is the duration or amount of work.

Longevity of object is the property of an object to maintain operability until the limit state.

Here the term "limit state" should also be associated with the object:

Limit state of object is the condition of object under which its further operation is inacceptable or impractical, or recovery of operability is impossible or impractical.

In this case the equipment is not repairable and is removed from operation.

Storageability of object is the property of an object to maintain operability during the whole storage and transportation period.

Survivability of object is the property of an object to maintain operability after failure of individual functional units.

Service life of object is the object's operation time from the beginning of operation till the onset of the limit state.

Lifetime of object is the total time from the beginning of operation till the onset of the limit state.

Thus, the existing definitions of dependability indicators fit in well with the above proposals. In order to maintain the conformity of terms and definitions if referring to a product or equipment rather than an object, it is recommended to replace the word “object” in the term and definition accordingly. For example:

Reliability of product (equipment) is the property of a product (equipment) to continuously maintain operability with the specified operation time.

For further considerations let us note that currently calculations of dependability indicators are predominantly associated with only artificial objects with known structure, components and their connections. This is especially the case with control systems that perform a number of functions in operation. For example, protection function, information display function, information registration function, diagnostics function, etc. In such cases there is no reason to talk about the dependability of a control system that implements several functions, as each of the implemented functions has its own set of dependability indicators. In other words, the dependability of a control system is known if the dependability indicators of each implemented function have been identified.

As is well known, a function is the sum of actions of a control system aimed at the implementation of a specific control objective. As the control systems actions are performed by means of automation facilities each of which has its own dependability indicators, in [5] functional groups were introduced as elements for dependability evaluation and safety classification.

As defined in [5]: “Functional group is a designed part of a control system representing the sum of automation facilities that perform the specified function of the control system”.

Thus, it is recommended to use the following terms when dealing with control systems dependability.

Dependability of functional group of control system power level protection is the sum of dependability indicators of the functional group of control system power level protection that are specified in the respective regulatory document or control system performance specification. For example [6].

Reliability of functional group of control system power level protection is the property of the functional group of control system power level protection to continuously maintain operability within a specified operation time.

Maintainability of functional group of control system power level protection is the property of the functional group of control system power level protection that consists in the adaptation to prevent and detect the causes of failures, defects and eliminate their consequences by means of maintenance and repair.

Longevity of functional group of control system power level protection is the property of the functional group of control system power level protection to maintain operability until the onset of the limit state.

Similarly, we can continue defining terms for various functional groups of control systems, but it is not required for the purpose of this article, as the method is clear and simple.

In conclusion, we should note the systemic nature of the proposals in respect to the whole dependability terminology that fits in well with all the previous research in this area. The author hopes that the proposals above will find wide application both in regulatory and design documentation.

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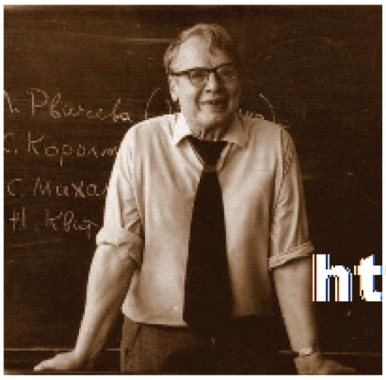

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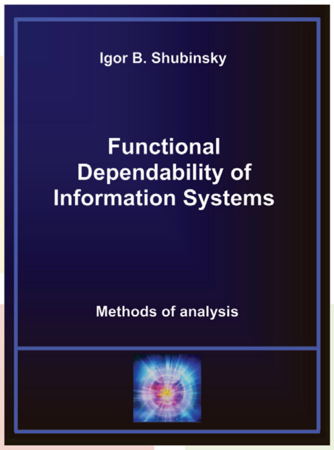

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Methods of analysis

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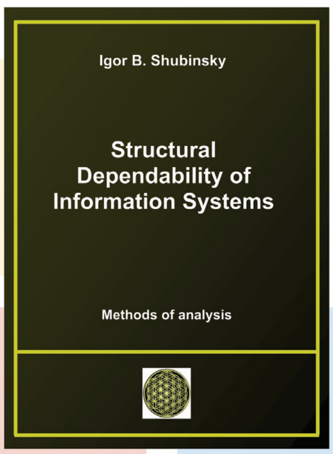

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2012

The book presents the basic concepts and parameters of the structural dependability of information systems. It discusses general and specific differences in dependability indices used in domestic and international standards, along with recent developments in approaches to dependability modeling. Markov reliability models together with graph semi-Markov methods for calculating reliability are described in detail and illustrated by numerous examples. Considerable attention is paid to the engineering methods of calculation and the approximate prediction of structural dependability and error estimation of information systems as well as to the statistical assessment of dependability parameters. At the end of each chapter there are checklists of the most complex and significant subjects of the chapter.

The book is intended primarily for professionals involved in practical work on the development, production, operation and modification of information systems. It is designed for scientists in the field of structural dependability of various discrete systems, academic staff and graduates (students) specializing in information systems as well as in the field of automated control systems.

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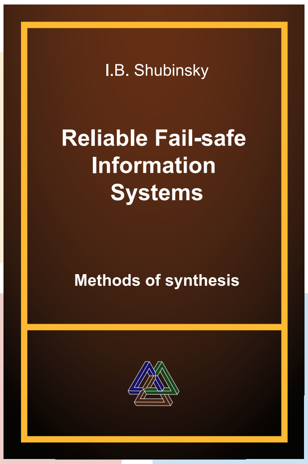

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I.B.Shubinsky
Reliable Fail–safe Information Systems
2016

The book describes conceptual provisions to ensure structural and functional reliability of information systems at all stages of a life-cycle. It represents different types of redundancy taking into account limited efficiency of the failure detection system. Under these conditions a broad-based assessment of their efficiency is performed, with determination of capabilities of structural redundancy with an endless number of standby facilities. Ways to ensure functional reliability of software are represented, including the recommendations for the development of software programs requirement specification, with the description of the process of a reliable program architecture development and well proven rules and recommendations used for design and implementation of software, as well as for integration with system hardware.

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You can find the description of the principles to ensure functional safety of information systems, with a substantiation of the possibility to restart independent channels in two-channel safe systems. The rules of determination of the allowed time for a guaranteed detection of single and double hazardous failures are developed, including the method of synthesis of a combined two-level information system developed with higher functional safety requirements.

To prove the conformance of reliability with functional safety the method of accelerated field testing of the information system has been developed. The book contains the description of this method, including the example of its practical implementation. You will also find the information about the procedures of certification tests based on the requirements of information safety and software certification conformance.

A checklist of the most complex and significant subjects is provided at the end of each chapter. The book is primarily intended for experts who are engaged in practical development, manufacture, operation and updating of information. It is intended for researchers in the field of structural reliability of different discrete systems, academic staff, post-graduate students and students specializing in the field of information systems and as well as those working in the field of automated control systems.

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