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ON CRITERIA OF SELECTION OF SPTA KITS

This paper discusses conceptual issues of stocking for recovery of technical systems, including issues of selecting SPTA kits and their optimization criteria, correlation of two methods of failure correction, by repairing and by replacing a faulty element by a spare part. The paper indicates disadvantiges of the approximate method of system reliability calculation taking into account SPTA and used in the industry.

Keywords: *reliability, restorable system, spare part, SPTA, sufficiency factor, strategy of replenishment.*

Introduction. Recently the attention of specialists in reliability has been increasingly focused on the problem of SPTA. It can be explained by the following reasons:

- The growing role of spares as one of the main resources to ensure reliability of modern systems, especially high-tech systems (hi-tec);
- Insufficient development of the methods of the reliability theory of restorable systems that whould take into account the peculiarities of this resource that is well known in engineering;
- Understanding of imperfection of the product reliability calcuilation methods in case of availability of spares, which are used in the industry and supported by the authority of existing regulations at the level of GOST and guidance documents;
- Accute attention to reliability in general in connection with the increasing number of serious accidents in some of safety critical systems due to equipment failures.

We can also add manifestations of competition of software offered to the industry to support the calculation and evaluation of spares, which is completely natural in the modern conditions. It is restified in particular by the article [1].

It is evident that the disadvantages of the methods of SPTA calculation and evaluation lead to errors of two types: either unjustified redundancy of spares kits or non-fulfillment of the requirements for reliability. In the end both cause direct economic losses, sometimes quite significant, and, on a number of occasions, other losses which are not less significant (prestige, loss of the position in domestic and international markets, etc.).

This article discusses the relevant issues of SPTA designing and provides a comparative analysis of different methods for calculation of spares and reliability of products using SPTA.

1. Relevant issues of SPTA designing

Currently the most relevant issues can be recognized as follows:

1.1. What is the main objective of creation of spares or SPTA system: to meet reliability requirements or improve maintenance? Depending on an answer to this question, one selects the type of indicator which is subject to standardization. If the objective is to improve the performance of maintenance, then it is necessary to standardize the sufficiency factor of a spares kit. If the objective is to improve reliability, the reliability parameter based on the requirements defined in the technical specification for a product shall be standardized.

1.2. If we recognize that the objective of spares kit is to improve reliability, is it possible to design a spares kit according to the sifficiency factor in this case? If yes, then the following question arises.

1.3. How to find the standard value of sufficiency factor that will be used to form a spares kit when external requirements (in the technical specification) for reliability are available?

1.4. If development of a spares kit and its optimization are carried out accroding to sufficiency, can the quality of this resource be estimated by the value of sufficiency? For example, if availability of a spares kit is 0.95, is it much or little? And if it is 0.2, does it mean that the kit is not sufficient and in this sense it is small (not big enough)?

1.5. Is it always that a spares kit as a resource to ensure reliability and replacement of a faulty element by an operable spare part as the procedure for recovery of a product can provide more reliability of nonredundant systems? For example, is it possible to use SPTA, if a nonredundant product operates in continuous long-term mode and the faultness factor is standardized for it?

1.6. If while answering to questions 1 – 3 we agree that the objective of spares kit creation is to improve reliability but in order to form a spares kit, the sufficiency factor should be used, and if we somehow manage to find the standard value of sufficiency corresponding to the standard value of reliability, then the following question arises. Is it possible to optimize SPTA according to the criterion of minimum aggregate costs while fulfilling the requirements for sufficiency (direct problem of optimization) or criterion of maximum sifficiency with constraints on the aggregate costs (inverse problem)? If so, is there any confidence that the kit which is optimal according to sufficiency will be optimal with constraints on reliability (according to the reliability criterion)? And if it is not so, then the following question arises.

1.7. If to admit that optimization using sufficiency is not appropriate, then why should we standardize sufficiency and calculate it at all?

1.8. Now the question of spares kit estimation and optimization is treated in practical terms. There are at least three software packages which implement the analytical methods of spares kit estimation and optimization: ROKZERSIZ [2], ASONIKA-K-ZIP [3], INTELLEKT-ZIP [4]. In addition, there is another ASONIKA-K-RES software package which is used to calculate a spares kit by the statistical simulation method [1]. They are developing in the environment of healthy competition. In the work [1] there is some criticism of one of the software packages in favor of another one. The criticism is quite useful and aimed at finding the best applications of the proposed industrial facilities. But some question arises in this regard. What methods and means of software support should be recommended to the industry for practical application in view of the whole complex of the stated questions?

The reader will not find ready answers to the questions, but there will be an open discussion, and the author's position on all these aspects of the problem will be set forth.

2. The main objective of creation of spares kit or system

As for the objective of spares kit creation, normative documents use unclear wordings which allow of various interpretations. In GOST V 15.705-86 it is stated that the objective of development, production and application of spares kits is to support permamently product availability by conducting (specified) maintenance services, scheduled and unscheduled repairs. In GOST RV 27.3.03-2005 it is indicated that single and (or) group sets of spare parts, tools and accessories (SPTA) or two-level systems of SPTA are provided to ensure reliability (maintainability) of a product. In RD V 319.01.19-98 guidance document it is indicated that this document is applied to restorable and servicable apparatuses, devices, equipment and other products in operating conditions, whose requirements for reliability, including requirements for sufficiency and volume of spares kits, are specified in the regulations.

Hence it ensues that, on the one hand, SPTA is created to ensure reliability, to support operability (faultness, availability) and to meet the requirements for reliability. On the other hand, it is necessary to ensure maintainability, to conduct maintenance for the benefit of operability. And the guidance document allows that reliability requirements include requirements for sufficiency and volume of spares kits.

If we should single out the main objective within this variety, there are still grounds to believe that the main objective of the regulations is to ensure reliability. This is consistent with the logic of designing and and operational tasks.

3. Criteria of SPTA sufficiency

When selecting a spares kit, the criterion function should be specifed. Currently there are, essentially, only two proposals: to use sufficiency (stock availability (of SPTA) or the average delay in request fulfilment) or reliability (faultness, availability) as the criterion.

If we use sufficiency parameters, two questions arise. Since the type of the pattern of internal redundancy of a product does not affect sufficiency, and the total intensity of requests for spare parts is only important, then the parameter of stock availability (of a spares kit) becomes the sole and universal sufficiency parameter. Therefore, to select or optimize a spares kit it is necessary to know the standard value of sufficiency. It is subject to computation using the standard value of the given reliability parameter. The first question is how to do it. The link formula given in [2, p.16]

$$K^{тр}_{г,ЗИП} = K^{тр}_{г} \,/\, K_{г\infty} \tag{1}$$

can be used only if two conditions are satisfied as follows: product availability is standardized and there is no redundancy in the product. When standardizing another parameter of reliability (e.g. mean time to failure, probability of failure-free operation) or with internal redundancy in the product, the formula (1) cannot be used. With respect to complexity the task of finding the link of standard values of sufficiency and reliability is comparable to the problem of direct calculation of reliability of a product with finite stock in SPTA.

Of course, it is possible to standardize sufficiency without linking its value with the standard value of reliability, but then the second question arises: how with the known spares kit to estimate the actual value of reliability. The formula [2, p.16]:

$$K_{г} = K_{г,ЗИП} K_{г\infty} \tag{2}$$

is true only for calculation of product availability in the absence of internal redundancy. For other cases the model of reliability of a restorable item with an unlimited spares kit is used in which the correction of the mean to time to recovery is carried out according to the formula:

$$\overline{T}_{в} = \overline{T}_{в\infty} + \Delta t_{ЗИП-О}. \tag{3}$$

This methodological approach gives an approximate value of reliability with an unexplored error. Without evaluation and control of the error the selection of a spares kit may turn out to be faulse.

Discrepances occur in different methods of $K_{г,ЗИП}$ calculation too. So, [8] suggests that in order to avoid the situation when a spares kit includs items with zero initial stock we should stick to the principle of spares kit integrity. This suggestion is beneath cricisim. First, a product can include expensive modules and devices. Their compulsory inclusion in a spares kit without justification according to the accepted criterion will lead to a significant increase in the cost of initial stock. Second, this suggestion does not take into account possible redundancy in a product. And though the selection of SPTA is conducted in accordance with sufficiency, the purpose of SPTA is still to meet reliability requirements. But then it is possible to consider the case of degeneracy as acceptable when a spares kit is zero, i.e. it contains no spare parts. With periodic replenishment, spare parts coming out of an inexhaustible source will only be used to restore a baseline structure. And with this procedure the reliability requirements will be met.

Thus, we get a very paradoxical situation. Except for rather simple cases not often faced in practice, the sufficiency and reliability parameters are linked by correlations which we are not able to establish. However, recognizing the main objective of ensuring reliability, we select spares kits according to sufficiency.

But there is more to come. Standardizing sufficiency without knowledge of the link between sufficiency and reliability, we do not take into account an important degree of freedom, namely the type and depth of structural or functional redundancy. As a result, trying to insure some level of sufficiency, we can say nothing about the value of reliability. It can be low with high sufficiency and it can be high with a low sufficiency value. When the factor of stock availability is 0.95, the probability of failure-free operation can be equil to 0.1, even 0.001 or less. On the contrary, with the factor of stock availability of 0.3 the probability of failure-free operation can be equal to 0.95 or higher. But if it is so (further the examples will be given that it is possible), and it is impossible to predict in advance whether it is good or bad, then it is natural to ask what the role of sufficiency parameters is and whether they are necessary at all. And if they are necessary, then what their purpose is. It is clear that their calculation in many cases does not bring us to the solution of reliability problem. The selection of SPTA according to sufficiency does not guarantee that the reliability requirements will be met.

4. Criteria of SPTA optimization

While optimizing SPTA, the same dilemma occurs as in the case of spares kit selection: to carry it out according to reliability or sufficiency criterion. Since the conversion of reliability requirements into sufficiency ones is not practically possible, except for the case referred to in Section 3, optimization by sufficiency criterion can be conducted only if sufficiency standardization is carried out independently of reliability requirements. The certified software packages [1, 2] offered for application in the industry conduct optimization according to sufficiency criterion. Optimization should be performed by minimum cost of spares kit creation. The idea of not taking into account the cost of spare parts [8] in optimization can not be considered seriously. One should expect that replacement of reliability parameter by sufficiency one shall bring consequences similar to those observed in the formation of spares kit. In terms of quantity these consequences can be defined by the comparative analysis of optimization results by practical examples.

Let us consider the example of some fragment of a real project performed by the author on request of the industry and discussed in detail in [4]. The control system of nuclear power plant technological means is a complex set of software and hardware tools designed for reliable and safe automated control of technical equipment in normal and emergency modes. One branch of this seven-level hierarchy system contains 41 items of 18 types. The mean time to failure of the system without taking into account structural redundancy is 89550 hours. The reliability requirements are stated as follows: the probability of failure-free operation of the system for a year (8760 hours) should be at least 0.95 (option 1) or not less than 0.9 (option 2). Optimization should be performed by the criterion of minimum aggregate costs of a single spares kit with periodical stock replenishment of T=1 year. While optimizing according to sufficiency, the factor of SPTA availability should be ensured at the level of not less than 0.95 (option 1) or not less than 0.9 (option 2).

Without SPTA the probability of failure-free operation for a year taking into account structural redundancy is equal to 0.151. The factor of SPTA availability with zero stock is 0.23. The optimization results are shown in Table 1.

Table 1.

№	Criterion	Standard	L	Cost, thousand rubles	Relative cost, %	$P(t)$	K_{aSPTA}
1	$K_{\text{aSPTA}} \geq K_0$	0.95	19	839	47.4	0.9512	0.953
2	$K_{\text{aSPTA}} \geq K_0$	0.90	15	655	34.7	0.825	0.910
3	$P(t) \geq P_0$	0.95	12	411	21.8	0.9524	0.67
4	$P(t) \geq P_0$	0.90	10	368	19.5	0.902	0.613

Comparing the results of the optimization by two criteria, one can see that the calculation of a spares kit according to sufficiency gives an overrated stock level compared to the level required to ensure reliability. In option 1 (standard 0.95) the cost of a spares kit has increased from 411 thousand rubles to 839 thousand rubles, i.e. more than twice. With that the probability of failure-free operation has not increased but decreased a little: from 0.9524 down to 0.9512.

In option 2 (standard 0.90) the cost of a spares kit has increased from 368 thousand rubles up to 655 thousand rubles, i.e. 1.78 times. In addition, the probability of failure-free operation has not increased but declined significantly: from 0.902 down to 0.825.

Option 1 in Table 1 is the only option for spares kit composition that provides K_{aSPTA} and P(t) value of not less than 0.95. With that the single spares kit selected by sufficiency turns out to be the most expensive. In option 3 in Table 1 the reliability requirements are also satisfied, but a single spares kit is more than half the price than in Option 1 and the availability factor is at the level of 0.67. It is hardly possible to justify such a high price for a higher level of sufficiency, if the reliability requirements are satisfied by a more cost-efficient kit.

With the standard level of 0.90, the results are even more significant. Achieving the required value of К_{aSPTA}, we can not provide the level of P(t) as not less than 0.9, though with half the cost of the kit, $P(t) \geq 0{,}9$ can be reached. In this case К_{aSPTA} is only equil to 0.613. The result is paradoxical: with twice the costs it is not possible to satisfy the requirements for reliability, although the requirements for sufficiency are ok.

5. Application of SPTA in nonredundant systems

Comparing repair and replacement of a faulty module by a spare part from SPTA it is legitimate to ask about the probability and equivalence of these ways to restore operability. It is clear that the opportunity to repair does not allow us to increase the probability of failure-free operation, but allows us to increase the availability factor of a product. If the time to replace a faulty module, when a spare part is available, is comparable to the time of recovery by repairing, then both ways to recover are equivalent. If, in accordance with the purpose of a product and functioning features in which the product may be used, some interruption in operation for recovery by repair or replacement is acceptable, then we can speak about time reserve. According to [5], the probability of failure-free operation of homogeneous subsystems with elements of the *i*-th type should be calculated using the formula:

$$P_i(t, t_{\text{доп}i}, \infty) = \exp(-k_i \lambda_i \max(0, t - t_{\text{доп}i})(1 - F_{\text{в}i}(t_{\text{доп}i}))), \tag{4}$$

where $t_{\text{доп}i}$ is the accepatable interruption, $F_{\text{в}i}(t_{\text{доп}i})$ is the probability of recovery before the expiration of time $t_{\text{доп}i}$. It can be a recovery by repair or replacement.

If the repair time on average is much longer than the replacement time, repair and replacement of the module by a spare part are not equivalent. For example, if

$$t_{\text{зам}} << t_{\text{доп}} << \overline{T}_{\text{в}\infty}, \tag{5}$$

then, according to (4), the probability of failure-free operation will be close to one with recovery by replacement and close to zero with recovery by repairing. Satisfaction of conditions (5) requires careful inspection. And if time reserve is actually available, there is the Renyi type pattern of failure flow sifting, with which reliability calculation is performed with the equivalent failure rate $\Lambda_{\text{э}} = k\lambda(1 - F_{\text{в}i}(t_{\text{доп}i}))$.

If time reserve is not available, the spares kit does not improve reliability. And then for the relevant components of a product the structural redundancy which allows using spare parts to improve faultness is required.

The importance of time reserve is not just a matter of its measurement. It can be a problem of designing [5]. To determine the value $t_{\text{доп}}$, it is necessary to simulate the functioniong process in the condition of temporary performance loss of a device which contains a faulty element. In some cases new design solutions may be required, such as a temporary change in the functioning mode to slow down adverse processes and increase $t_{\text{доп}}$ up to the value sufficient to satisfy conditions (5). In systems of different purposes, it is possible to create special conditions that will lead to time reserve used to replace a faulty module by a spare part. It means that it is accepatable to use spares kits to improve faultness in a nonredundant system.

6. Comparison of methods and methodologies of sufficiency and reliability calculation

The methodology specified in the documents [2, 6] is designed for evaluation and calculation of spares kits on the basis of sufficiency. The methodology is implemented in two software packages of ROKZERSIZ and ASONIKA-K-ZIP. As an alternative to the methodology [2,6], it is possible to consider the analytical method of direct registration of spares kit composition in the reliability models and a relevant methdology described in [4], as well as the statistical method of Monte Carlo simulation. On the basis of these methods and methodologies, ASONIKA-K-ZIP and INTELLEKT-ZIP software packages are developed. The comparative analysis of various proposals to estimate their actual opportunities, advantages, disadvantages and identification of areas of their appropriate applications are of practical interest.

As the opinion of universality of the methodology [2,6] is quite common, the real opportunities within the framework of a certain product classification should be considered in detail. As characteristics of the classification it is possible to use the following:

- Type of the structure,
- Application mode and standardized value of reliability,
- Number of executed functions,
- Strategy of stock replenishment in a spares kit.

According to the type of structure it is possible to distinguish:

- Nonredundant (sequential) systems,
- Systems with series connection of homogeneous redundant subsystems,
- Systems with series connection of homogeneous partially redundant subsystems,
- Systems with series connection of heterogeneous redundant subsystems,
- Structurally complex systems.

For systems of class 1 and 3, the methodology [2,6] allows finding the availability factor of a product using the formula (2), but does not provide guidance for the definition of faultness parameters. In class 3 the problem of spares kit application and reliability calculation occurs due to the fact that a part of the elements of homogeneous subsystems is not redundant. For systems of class 2, the availability and faultness parameters can be found with the help of formula (3). In fact, it is the only class of systems for which the methodology [2, 6] and the reliability theory of restorable systems can offer known formulas for calculation of faultness and availability parameters. For the other classes a general idea based on correction of mean time to recovery using the formula (3) is suggested. Since in terms of complexity the problem of finding the reliability parameters in the condition of unlimited spares kits is comparable to the task of evaluation of reliability with direct inclusion of SPTA into the model of reliability, the use of the approximate methodology [2, 6] is hardly reasonable when the accurate one is available.

According to the third characteristic (number of executed functions), the methodology [2, 6] is also limited. It considers only single function systems in which stock consumers are only those components included in the model of reliability. In multifunction systems reliability is calculated for individual functionally independent operations. In this case stocks are consumed not only by the components which are involved in the performance of the functionally independent operation but by the other ones. The methodology [2, 6] does not consider multifunction systems as an object of the analysis.

When taking into account replenishment policies in the model of reliability, it is required to define, first, the time of request generation to replenish the stock, and second, the amount of stock that should be supplied on request. In the methodology [2, 6] using the periodic replenishment strategy with urgent delivery, the option of request generation upon actual failure of a spares kit is considered. But there are other options. For example, reqest generation is carried out upon redundant subsystem failure, at a certain level of degradation of redundant subsystems, etc. According to the request volume, the option of full restoration of the initial stock of that type whose exhaustion has been the reason for the request generation is only considered. However, there are many other options for request generation. For example, delivery of only one spare part, when replenishment strategy with urgent delivery is used, replenishment of the initial stock of several or all types, when replenishment strategy with urgent delivery is used, and replenishment according to the level. The methodology does not foresee any correction of the request upon generation but before the moment of delivery either.

Outside the framework of the methodology there is also such tool as reconfiguration of the system during which operable elements of faulty components can be used as spare parts.

Thus, comparison of the methodology [2, 6] with alternative ones is only possible within the existing framework of a quite narrow area of its application.

As for the method of statistical simulation, its advantages and disadvantages are well known and fully observed when estimating the reliability of systems with a limited spares kit. The advantages include universality of the method and weak dependence of calculation labour intensity on a structure type of a product, replenishment strategy and structure of a spares kit system. The disadvantages of the method are increasing errors and labour intensity of calculations in the evaluation of small probabilities and complexity of optimization procedure of a spare kit.

It is convenient to show quantitative comparison of different methodologies and software packages with the help of a general case. In this case for the comparative analysis the radioelectronic device Pamir-1 is selected which is considered in Example 1 of Appendix A of the normative document [2].

7. Comparative quantitative analysis of methods and methodologies using the example of radopelectronic product of Pamir-1 type [5]

General characteristics of the product

The example of spares kit calculation according to the sufficiency criterion is taken from the normative document **[2]**. Pamir-1 contains 1422 elements (radioelectronic devices and components) of 30 items. In the structural and reliable pattern the product is presented as a serial connection of 30 homogeneous subsystems divided into 4 groups according to the type of replenishment strategy. Continuous replenishment with average delivery time 1 week = 150 hours is used for six subsystems. Continuous replenishment with average delivery time 2 weeks = 300 hours is used for 12 subsystems. Periodic replenishment with the period of restocking of 1 year = 8000 hours is used for seven subsystems. Periodic replenishment at the interval of 8000 hours and the mean time of urgent delivery of 3 days = 65 hours are used for five subsystems. The total flow of failures is equal to 0.02772, the mean time to failure is 36.1 hours. The reliability requirements are not stated. The internal structure of the product is not known and there is no information on structural or functional redundancy in it. However, the sufficiency requirements for a single spares kit are given as follows: the availability factor of a spares kit is $K_{\text{aSPTA-S}} \geq 0.95$ with the solution of direct problem of optimization according to the sufficiency criterion.

Table 2 and 3 shows the results of calculations of the availability factor of a single spares kit and the probability of failure-free operation. The single spares kit composition with the total amount of spare parts $L = 245$ is taken from [2]. Calculations of the probability of failure-free operation of the product and the single spares kit composition were performed using INTELLEKT-ZIP softeware package [4] or taken from [1]. The parameter m expresses the total number of redundant elements in homogeneous subsystems that use moving redundancy. With m = 0 there is no redundancy. With m = 25 modules 19, 20, 22 and 23 have two backup elements, and 17 ones have one backup element each. With m = 26, in group 19 (relay RES-49) there are three backup elements.

Table 2. Direct and inverse problems

№	**ROKZERSIZ, direct problem**			**ASONIKA-К-ZIP, direct problem**				**ASONIKA-К-ZIP, inverse problem**		
	L	$P(t)$		**L**	$P(t)$			L	$P(t)$	
		$m=0$	$m=26$		$m=0$	$m=25$	$m=26$		$m=0$	$m=26$
1	1	0.99814	0.999996	1	0.99814	0.999996	0.999996	2	1.000000	1.000000
2	1	0.91813	0.998422	2	0.99651	0.999978	0.999978	2	0.999976	0.999978
3	1	0.64895	0.976906	2	0.96008	0.999224	0.999224	2	0.999699	0.999224
4	1	0.98375	0.985370	1	0.98375	0.983751	0.983751	2	0.999998	0.983751
5	1	0.72095	0.991816	2	0.97364	0.999766	0.999766	2	0.999806	0.999766
6	1	0.95646	0.999728	1	0.95646	0.956460	0.956460	2	0.999991	0.956460
7	0	0.82531	0.998973	1	0.99869	0.999996	0.999996	1	0.998688	0.999996
8	1	0.98002	0.999708	1	0.98002	0.999708	0.999708	2	0.999992	0.999997
9	1	0.99301	0.999945	1	0.99301	0.999945	0.999945	1	0.993005	0.999945
10	1	0.99796	0.999992	1	0.99796	0.999992	0.999992	1	0.997958	0.999992
11	1	0.99869	0.999997	1	0.99869	0.999997	0.999997	1	0.998688	0.999997
12	1	0.99483	0.999970	1	0.99483	0.999970	0.999970	1	0.994834	0.999970
13	1	0.99707	0.999992	1	0.99707	0.999992	0.999992	1	0.997071	0.999992
14	1	0.95667	0.999016	1	0.95667	0.999016	0.999016	2	0.999974	0.999986
15	1	0.94409	0.998533	2	0.99729	0.999976	0.999976	2	0.999961	0.999976
16	1	0.99349	0.999962	1	0.99349	0.999962	0.999962	1	0.993487	0.999962
17	1	0.90834	0.996690	2	0.99412	0.999928	0.999928	2	0.999913	0.999928
18	1	0.99483	0.999980	1	0.99483	0.999980	0.999980	1	0.994834	0.999980
19	**112**	0.52510	0.999990	**40**	4.0E-15	0.964811	0.999343	**58**	1.40E-08	0.999875
20	14	0.52812	0.999778	9	0.09177	0.999526	0.999526	19	0.528121	0.999993
21	2	0.45060	0.991640	4	0.83501	0.998682	0.998682	6	0.450605	0.999701
22	25	0.48016	0.999499	14	0.00792	0.998140	0.998140	31	0.480164	0.999972
23	25	0.48016	0.999499	14	0.00792	0.998140	0.998140	31	0.480164	0.999972
24	18	0.99281	0.992813	21	0.99930	0.999300	0.999300	23	0.999880	0.999300
25	3	0.99997	0.999968	3	0.99997	0.999968	0.999968	4	0.999999	0.999968
26	13	0.99684	0.996843	16	0.99985	0.999855	0.999855	17	0.999953	0.999855
27	4	0.99977	0.999771	5	0.99998	0.999980	0.999980	6	0.999998	0.999980
28	6	0.99976	0.999764	7	0.99997	0.999966	0.999966	8	0.999996	0.999966
29	3	0.99993	0.999935	4	1.00000	0.999997	0.999997	4	0.999997	0.999997
30	3	0.99995	0.999953	4	1.00000	0.999998	0.999998	4	0.999998	0.999998
	245	**0.00740**	**0.926783**	**164**	1.5E-20	**0.899650**	**0.931849**	**239**	**7.53E-10**	**0.93835**

Table 3.

№	Problem	Software	L	Cost, thousand rubles	*m*	K_{aSPTA}	*P*(*t*)
1	direct	ROKZERSIZ	**245**	**3395.65**	0	**0.95719**	0.0074
2	inverse	ASONIKA-K-ZIP	239	3391.1	0	0.98504	7.53E-10
3	direct	ASONIKA-K-ZIP	**164**	**1942.15**	0	**0.95312**	1.51E-20
4	direct	ROKZERSIZ	245	3395.65	26	0.95719	0.9268
5	inverse	ASONIKA-K-ZIP	239	3391.1	26	0.98504	0.9384
6	direct	ASONIKA-K-ZIP	164	1942.15	25	0.95312	0.8997
7	direct	ASONIKA-K-ZIP	164	1942.15	26	0,95312	0,9319

The analysis of the calculation results allows us to make the following conclusions:

1. We can't doubt the claim made in [1] that with the solution of the direct problem of optimization according to the sufficiency criterion, the kit of 164 spare parts should be preferred to the kit of 245 parts, as both provide the required availability factor, but one is substantially smaller and more cost-efficient than the other.

2. The same conclusion can be made by the results of the inverse problem, according to which two single spares kits of an approximate equal value provide different values of availability: in one case it is 0.957 and in the other case it is 0.985. It is clear that the preference should be given to the kit with higher sufficiency.

3. However, good results of the analysis in one case and bad ones in the other case lose value and become pointless, if we return to the problem of reliability. If we assume that there is no structural redundancy in the product, then all the options of a single spares kit are not acceptable, as in one case the probability of failure-free operation for a year is equal to 0.0074, and in the other one it is practically equil to zero: 1.51 E-20. Even the least cost-efficient option is not sufficient because it does not provide the required reliability.

4. If we assume that there is structural redundancy in the product, the comparison makes sense. The options with structural redundancy shown in the Table differ in the number of backup elements. Calculations according to formula [4] are carried out for the structural patterns in which loaded redundancy of fractional multiplicity is used for a number of subsystems. For subsystems with numbers 1-3, 5, 7-18, 21 (according to the numbering in [2]), one backup element is introduced, for the subsystems number 20, 22 and 23 two backup element are introduced. In the subsystem with numbers 19 for options 4, 5 and 7 in Table 2 three backup elements are introduced, and for option 6 two elements are introduced. Table 2 shows that with such redundancy multiplicity the probability of failure-free operation for a year has increased from the value close to zero up to the values of 0.9 – 0.94. Moreover, such significant increase in the probality of failure-free operation is achieved with the total number of backup elements 6 – 9 times less than the number of spare parts.

5. With the increased multiplicity of structural redundancy, the reliability requirements are met at lower sufficiency (as in the example shown in Section 5). If you choose a single spares kit by reliability, K_{aSPTA} values of 0.9 and 0.5, and 0.1, and even lower may, in fact, become acceptable. It means that during product designing, including Pamir-1, the sufficiency parameters are of no interest. They may be of interest only in the designinig of maintenance systems. Rational allocation of common resources between two types (structural redundancy and spares kit) is possible with the help of additional criteria (constraints on the volume, dimension, power consumption, etc.). Therefore, spares kit designing and selection of redundancy patterns should be carried out jointly within the framework of common problem of reliability.

9. Comparison of analytical methods and statistical simulation methods

The analytical methods have a methodological error [7] or require very large efforts to obtain calculating formulas or computational procedures. However, they can be used to estimate the probability values that are close to zero and one, to optimize spares kits, to establish some general patterns in the analysis. The statistical simulation methods (SSM) are highly universal, cost-effective enough with manual preparation of initial data to evaluate reliability and sufficiency of spares kit products. However, they require large and sometimes unacceptable amount of time to estimate small probabilities and provide a significant and uncontrollable error of estimation. The example of the difficulty of SSM application may be the data of Table 2. The probability of failure-free operation of a product without structural redundancy is impossible to estimate by SSM, as the value of 1.5 E-20 is estimated. There are certain difficulties in solving optimization problems. ASONIKA-K-RES is currently not adapted to solve optimization problems. INTELLEKT-ZIP can solve optimization problems by SSM. However, its possibilities when using SSM is not yet sufficiently investigated. Nevertheless, it is interesting to evaluate the accuracy and labour intensity of SSM in some specific examples to compare analytical methods and methods of statistical simulation.

Let us return to the example taken from [4] and discussed in Section 4 for the control systems of nuclear power plant technological means. The optimization results of a spares kit by means of the analytical methods and the method of statistical simulation are shown in Tables 4-6. With the standard value P^0= 0.95 and the sampling volume N = 1000 in 10 trials obtained with SSM, the optimal kit coincided with the kit obtained by means of the analytical methods, 50% of the trials. With P^0 = 0.99 and the sampling volume N = 1000 in 10 trials obtained with SSM the optimal kit never coincided with the kit obtained by the analytical methods. Table 4 shows the results of two trials for P^0= 0.95. With 12 spare parts the evaluation of the probability of failure-free operation *P(t)* = **0.9559** turned out higher than the required value and the actual one obtained by the analytical method. With 13 spare parts the probability is *P(t)* = 0.9631. The relative cost of a spares kit increased by 0.29%. With the same standard value and the sampling volume N = 10000, the optimization using SSM definitely gives a kit whose values coincide with the result of the optimization using the analytical methods.

If P^0 = 0.99, then with the sampling volume N = 10000 and even for N = 10^6, the statistical simulation method gives unstable results (Table 5 and 6). When N = 10^7 only, it gives the result coincided with the results of the analytical optimization (Table 6). Actual values of *P(t)* obtained by two methods are close to each other (the difference is in the fifth decimal place).

Table 4. *N*=1000. P^0=0.95, the probability of failure-free operation (SSM)=0.9559

№	Module	*k*	*kλT* *10^6, 1/h	*L*, AM	K_{aSPTA}, AM	*P*(*t*), AM	*L*, SSM	*L*, SSM
1	P III	2	0.3590	1	0.98199	0.993835	1	1
2	Mon	4	1.4016	1	0.82942	0.9961981	1	1
3	CPU-434	2	0.0727	0	0.96451	0.9950821	0	0
4	TBL	2	0.1752	1	0.99531	0.9991964	1	1
5	XBP-010	3	0.0045	0	0.99777	0.9970172	0	0
6	DDO	1	0.0365	1	0.99978	0.9986981	1	1
7	CHS	2	0.0235	0	0.98835	0.9994616	0	0
8	CPS-114	1	0.0159	1	0.99996	0.9997513	1	1
9	CPS-124	4	0.0634	0	0.96895	0.9999991	0	0

№	**Module**	***k***	**$k\lambda T$ $*10^6$, 1/h**	**L, AM**	**K_{aSPTA}, AM**	**$P(t)$, AM**	**L, SSM**	**L, SSM**
10	CRP	2	0.0280	0	0.98611	0.9992359	0	0
11	CRA	1	0.0142	1	0.99997	0.9998005	1	1
12	NOE	2	0.0293	0	0.98551	0.9991686	0	0
13	TSX	1	0.0394	1	0.99975	0.9984869	1	1
14	UPS	5	0.6570	3	0.99899	0.9907869	3	3
15	RPS-60	4	0.1577	0	0.92515	0.988538	1	0
16	RS2	2	0.0282	1	0.99987	0.9992193	1	1
17	NRP	2	0.0477	1	0.99963	0.9978011	1	1
18	RXN	1	0.0004	0	0.99978	0.9991244	0	0
19	Total	41	3.1541	12	0.67020	0.95241	13	12
20	Cost %			21.77			22.06	21.77

Table 5. N=10000. P^0=0.99

№	**Module**	***k***	**$k\lambda T$ $*10^6$, 1/h**	**L, AM**	**K_{aSPTA}, AM**	**$P(t)$, AM**	**L, SSM**	**L, SSM**	**L, SSM**
1	P III	2	0.3590	2	0.9984419	0.9994609	2	2	2
2	Mon	4	1.4016	2	0.9484916	0.9991841	2	2	2
3	CPU-434	2	0.0727	0	0.9645113	0.9950821	0	1	0
4	TBL	2	0.1752	2	0.9997982	0.9999653	1	1	1
5	XBP-010	3	0.0045	1	0.9999967	0.9999934	1	1	1
6	DDO	1	0.0365	2	0.9999980	0.9999842	1	1	2
7	CHS	2	0.0235	0	0.9883529	0.9994616	0	0	0
8	CPS-114	1	0.0159	1	0.9999584	0.9997513	1	1	1
9	CPS-124	4	0.0634	0	0.9689487	0.9999991	0	0	0
10	CRP	2	0.0280	0	0.9861141	0.9992359	0	0	0
11	CRA	1	0.0142	1	0.9999667	0.9998005	1	1	1
12	NOE	2	0.0293	0	0.9855124	0.9991686	0	0	0
13	TSX	1	0.0394	2	0.9999975	0.9999802	2	1	2
14	UPS	5	0.6570	5	0.9999902	0.9998724	4	4	4
15	RPS-60	4	0.1577	2	0.9998513	0.9999882	2	1	1
16	RS2	2	0.0282	1	0.9998692	0.9992193	1	1	1
17	NRP	2	0.0477	2	0.9999956	0.9999652	2	2	2
18	RXN	1	0.0004	1	1.0000000	0.9999998	1	0	1
19	Total	41	3.1541	24	0.84960	0.990147	21	19	21
20	Cost %			36.74			33.85	40.98	34.37
21	$P(t)$, AM			0.9901			0.987	0.989	0.988

AM – analytical method

Table 6. $P^0=0.99$

№	**Module**	**$L, N=10^5$**	**$L, N=10^5$**	**$L, N=10^5$**	**$L, N=10^6$**	**$L, N=10^7$**	**$P(t), N=10^7$**
1	P III	2	2	2	2	2	0.999482
2	Mon	2	2	2	2	2	0.999190
3	CPU-434	1	0	0	0	0	0.995075
4	TBL	1	2	2	2	2	0.999977
5	XBP-010	1	1	1	1	1	0.999993
6	DDO	2	2	2	2	2	0.999984
7	CHS	0	0	0	0	0	0.999459
8	CPS-114	1	1	1	1	1	0.999752
9	CPS-124	0	0	0	0	0	1.000000
10	CRP	0	0	0	0	0	0.999233
11	CRA	1	1	1	1	1	0.999802
12	NOE	0	0	0	0	0	0.999167
13	TSX	1	2	2	2	2	0.999979
14	UPS	4	5	5	5	5	0.999871
15	RPS-60	1	1	2	2	2	0.999987
16	RS2	1	1	1	1	1	0.999214
17	NRP	2	2	2	2	2	0.999964
18	RXN	0	1	1	1	1	1.000000
19	Total	20	23	24	24	24	0.990163
20	Cost %	41.79	36.45	36.74	36.74	36.74	
21	$P(t)$, AM	0.9905	0.9899	0.9901	0.9901	0.99015	

Summary table 7 shows that with the insufficient sampling volume the calculation results in different trials behave erratically. The optimal kits do not coincide for different trials and differ from the kit obtained by the analytical methods. It is then possible to observe deviations in either direction: greater and lesser cost. The estimation of the probability of failure-free operation differs from the calculations using the analytical methods. In most cases the estimation is too high, and the actual value of the $P(t)$ is sometimes less than the standard value. The results are sustainable for very large sampling volumes. In this example this is achieved with N = 10000 for $P^0 = 0.95$, and with N = 1000000 for $P^0 = 0.99$.

Table 7. Summary table of statistical optimization of SPTA

Method	**N**	**P^0**	**L**	**$P(t)$,AM**	**$P(t)$, SSM**	**C**	**Share**
AM	-	0.95	**12**	**0.952412**		**411.24**	**21.77**
SSM	1000	0.95	13	0.963161	0.954943	416.71	22.06
SSM	1000	0.95	**12**	**0.952412**	**0.955884**	**411.24**	**21.77**
SSM	1000	0.95	13	0.963161	0.961660	416.71	22.06

Method	N	P^0	L	$P(t)$,AM	$P(t)$, SSM	C	Share
SSM	10000	0.95	12	**0.952412**	0.952637	**411.24**	**21.77**
SSM	10000	0.99	21	0.987069	0.990035	639.412	33.85
SSM	10000	0.99	19	0.989248	0.991136	774.138	40.98
SSM	10000	0.99	21	0.988050	0.990238	649.276	34.37
SSM	100000	0.99	23	0.989857	0.990236	688.548	36.45
SSM	100000	0.99	20	0.990522	0.991097	789.475	41.79
SSM	100000	0.99	**24**	**0.990147**	0.990254	**694.021**	**36.74**
SSM	1000000	0.99	**24**	0.990147	0.990268	694.021	**36.74**
SSM	1000000	0.99	**24**	0.990147	0.990219	694.021	**36.74**

For Pamir-1 the methods can only be compared with the evaluation of suffucuency, since the requirements for reliability and structural redundancy patterns are not known. With $N = 10^6$ the estimations for the least reliable element of RES-49 obtained by INTELLEKT-ZIP are given in Table 8.

Table 8. RES-49

Optimization problem	L	K_{aSPTA}, SSM, $N=10^6$	K_{aSPTA}, AM
direct	40	0.9782	0.98175
inverse	58	0.9847	0.98950
direct	112	0.9920	0.99541

The statistical simulation method gives consistently reduced values of sufficiency.

10. Conclusion

1. The analysis of the results of the methodologies for SPTA formation and optimization according to sufficiency gives disappointing conclusions. In some cases the recommended composition of a spares kit with high sufficiency can not provide the acceptable level of reliability of a product. Even in the example given in the guidance document and considered as a benchmark, the calculated spares kit provides the probability of failure-free operation of 0.0074 only. An attempt to improve the composition of a single spares kit in [1] leads to a significant reduction of SPTA composition without reducing the availability factor, but the probability of failure-free operation drops to 10^{-20}. The question arises why one should reduce stock and achieve high values of sufficiency, if the reliability of products due to that drops practically to zero. The reason of the absurdity of this situation is a misconception of stock purpose in SPTA.

2. Selection of SPTA should be carried out according to the criterion of the required reliability parameter. Stock sufficiency parameter is not of particular interest and can be calculated for information only. The methodologies currently used in the industry for spares kit selection based on sufficiency should be replaced by methodologis based on reliability. This will allow us to eliminate the apparent contradiction between the purpose of spares kits and the criterion of their composition selection.

3. Optimization of spares kits should also be conducted according to reliability. Usage of one of the sufficiency parameters as a criterion for optimization may provide decisions which are worse than the optimal one according to the reliability criterion in terms of stock cost and achievable reliability value (with a more expensive kit, a lower reliability).

4. Valid regulations prescribing to conduct selection and optimization of a spares kit according sufficiency should be revised in favour of the change in the selection criteria or supplemented by new sections reflecting the selection and optimization of SPTA according to the reliability criterion.

5. The method of statistical simulation should be recognized as quite competitive in comparison with the analytical methods, as it has a high degree of universatility. However, it is not investigated enough in terms of estimations and accuracy control of the obtained statistical values of reliability and sufficiency. Therefore, while solving the direct problem, the method should be used with extreme caution. With an insufficient sampling volume, it is possible to observe significant deviations of estimates from their true values. For optimization of spares kits, the method is less adapted, as the selection of the following spare part for the next step of optimization has to be carried out according to the probabilities which are very close to one. For the right selection, the high accuracy of probability estimation, and thus, large sampling volumes are required.

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