UDC: 621.38.004.15:621.3.019.3:519.718(047)=20
COSATI: 09-03, 14-04, 15-05

Optimization of sudden failures elimination during design and development of electronic systems - basics of methodology

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The results of original optimization methodology for the elimination of sudden failures (ESF) of electronic systems (ES) during design and development have been presented in this paper. The optimization of ESF treats all ESF elements: reliability, repairability, corrective maintenance and spare parts supply. From the standpoint of quality of service, operational availability has been taken as a criterion and the ES life-cycle costs depending on ESF from the standpoint of expenditure. The basis of this methodology is finding the optimal ESF alternative among the generated relevant ones. The whole process of elimination has been explained here. On one of the ESs, a part of the ESF optimization has been presented.

Key words: **electronic system, sudden failure, reliability, maintainability, repairability, corrective maintenance, optimization, optimal type of sudden failure elimination.**

Introduction

MOST of electronic systems (ES) during their service life encounter failures followed by high costs, lost time, undesirable psychological effects and, in some particular cases, serious threats to personal and national security. Therefore, in a complete ES life cycle, activities are undertaken in order to eliminate ES failures. During ES research, development and production these activities are 'built in' ES construction characteristics - reliability and maintainability. During ES service, in the field of logistic support, these activities are maintenance and spare parts supply. By 'building in' higher reliability, the number of ES failures is reduced, and by 'building in' higher-quality maintainability, the rate of ES returning from the 'in-failure' state into the 'in-service' state is increased with reduced demands concerning time, finance and human work. Maintenance prevents failures (preventive maintenance) and returns ES from the 'in-failure' state into the state of readiness for work (corrective maintenance). Activities such as spare parts supply during maintenance provide necessary parts for replacement in ES and their repairable parts. Thus reliability, maintainability, maintenance and spare parts supply can be treated as the elements of ES failure elimination. Each particular element of ES failure elimination can be realized in a number of different ways and alternatives. Quality of service and ES life-cycle costs, as basic validity criteria of a system, depend highly on a chosen alternative of each failure elimination element. Bearing these criteria in mind, it is therefore necessary to choose an optimum alternative of each failure elimination element. Failure elimination elements are highly mutually dependent. Reliability, on the one hand, and other elimination elements, on the other hand, are mutually complementary. Namely, failures not prevented by building in higher reliability are prevented during service life by preventive maintenance or eliminated by corrective maintenance. There is also complementarity between maintainability and maintenance itself. Spare parts supply depends both on maintainability and maintenance. Due to such mutual dependence between these elements, optimization of particular elements undertaken separately cannot lead to an optimum alternative of complete failure elimination. This alternative can be reached only by total, simultaneous optimization of all failure elimination elements during design as well as development of ES.

Total optimization of ES failure elimination elements forms part of logistic engineering (logistic of systems). In the US Army the approach to arms and military equipment supply is called 'integral logistic support-ILS'. The ILS basic objective is to create systems suitable for support, systems which will give requested effects with minimum costs. All procedures oriented to achieve this are called 'logistic support analysis-LSA'. Numerous LSA models have been developed throughout the world, a number of them being intended for solving problems of failure elimination optimization. Since they were being developed by different services, these models for a long while were used for solving only separate optimization of ES failure elimination elements (models: level-of-repair, spares provisioning, relability prediction/allocation, maintainability predition/allocation, life-cycle costs, etc.). Only in the mid-eighties did the first attempts to unite optimizations of ES failure elimination elements appear - by joining the spares provisioning model and the level-of-repair model [1]. Very soon there appeared models carrying out both optimizations simultaneously (e.g. the OATMEAL model for the US Army). The analysis of possibilities of current models and computer programs concerning LSA and being offered by the leading software producers in this field does not point out any program for united optimization of all elements of failure elimination in electronic systems [2-5]. In the US Armed

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forces, which are a way ahead in ILS element optimization procedures, this problem is solved by a number of programs and a complex procedure of iterative choice, defined by the standards (MIL-STD-1388, MIL-HDBK-502, MIL-PRF-49506, etc.) of the best construction alternative and system logistic support. In our country the problem of the united optimization of ES failure elimination elements was being only partially solved (for military purposes in particular), so our experts of logistic engineering do not dispose of the methodology and computer tools for solving this problem.

In non-professional ES, an interruption of service will not usually cause objective costs to the user, only subjective damage which cannot be easily expressed in material terms. In a part of professional systems, the application of which is connected with safety and security, loss of user costs cannot be expressed either. In a part of professional profit-creating systems (e.g. mobile communications ES), loss of user costs (C_{lu}) can be measured because system delay causes direct financial damage. These costs depend on appearance frequency (reliability) as well as on corrective maintenance duration (repairability, logistic support), so they show validity of ESF alternatives. Therefore, from the aspect of costs, the criterion for estimating ESF alternatives in these systems will include the following costs

$$C_{esflu} = C_{esf} + C_{\ell u} \tag{4}$$

Limiting factors in ESF are demands and assumptions which are to be met and fulfilled while defining the elements of this elimination. Demands can be given in words or in quantitative values of ESF parameters. Limitations reduce the scope of ESF optimization due to the reduction of the number of logical alternatives. An alternative which does not satisfy certain limitations is not tolerated so there is no point in estimating it. When the moment of limitation conceiving is concerned, it is useful to divide limitations into primary and secondary ones [24]. Both types of limitations are defined in the beginning of the ESF optimization procedure. Primary limitations are conceived during the generation of ESF alternatives and, depending on their demands, certain alternatives are eliminated. Secondary limitations are conceived after the calculation of the criteria for ESF alternative estimation. Primary limitations, because of their nature, concern most frequently technical performances of ES and their components as well as possibilities of level of maintenance resources, some of them being as follows:

- volume and weight of ES and their components,
- standard size of modular ES units,
- personnel qualifications for a particular maintenance level,
- performances of standard support equipment at a particular maintenance level,
- working space conditions at a particular maintenance level, etc.

Secondary limitations are most frequently tactical and economic in character, some of them being as follows:

- minimally tolerated operational availability,
- maximally tolerated down time due to corrective maintenance,
- maximally tolerated ESF costs during system development and production, etc.

Relevant alternatives of elements of the elimination of sudden failures

Each ESF element can be realized in many different ways - mutually different alternatives. From the ESF optimization point of view all these ESF element alternatives are not relevant for this optimization. Namely, relevant are only those which, when applied, give different values of, at least, one of ESF criteria and for which it cannot be determined without ESF optimization whether they should be applied in ES or not. All possible combinations of ESF element alternatives make relevant ESF alternatives. The survey of relevant ESF element alternatives is given onwards, with the explanation of their relevancy.

Certain level of ES reliability can be achieved by applying the methods for reliability increase: application of more reliable components, unloading of components, application of redundance and application of electronic components and module of new technologies. Each of these methods can be applied in a number of alternatives for one ES. In ES, related to reliability, there are sets of possible alternatives: component reliability $\{ACR\}$, component unloading $\{ACUR\}$, redundance $\{ARDR\}$ and component technology $\{ACTR\}$. Both defined ESF criteria differ for different alternatives from these sets, so all possible combinations of alternatives of these sets make a set of relevant ES reliability alternatives

$$\{AR\} = \{ACR, ACUR, ARDR, ACTR\} \tag{5}$$

Some of the alternatives from the $\{AR\}$ set can have the same or approximately the same relability value (the same ES MTBF), and therefore, on the basis of expression (2), the same operational availability. But, since they all differ among themselves on life-cycle costs, they all represent relevant ES reliability alternatives.

In order to achieve suitable repairability of ES and their repairable modular units, the following methods for repairability increase are used: a) securing access to system components, b) securing easy replacement of system elements, c) clear and understandable designation of system elements, d) usage of modular construction, e) building in of test equipment and f) building in of automatic adjustment of parameters during replacement of components (when adjustment is needed). Each of these methods can be applied in a number of alternatives, giving thus different values of ESF criteria. In order to build in the first three methods (from a) to c)) of repairability increase into a system, no significant financial means are needed for system research, development and production. During service, all these methods have a positive influence on ESF criteria - it is therefore useful to apply them in every ES in full. As a consequence, they are not a basis for forming relevant repairability alternatives. Unlike them, the last three methods (from d) to f)) of repairability increase cannot lead to a decision on their application without ESF optimization. In ES, when repairability is concerned, there are sets of relevant alternatives: modularity $\{AMRP\}$, built-in test equipment $\{ABITERP\}$, and automatic adjustment $\{AAARP\}$. All possible combinations of alternatives from these sets make a set of relevant ES repairability alternatives

$$\{ARP\} = \{AMRP, ABITERP, AAARP\} \tag{6}$$

The main phases of ES corrective maintenance are: transport to repair, handing in for repair, waiting for repair, waiting for spare parts, repair, handing in after repair and transport to the site of use [13]. The most complex phase of all is the repair phase defined by the repair technology of ES and their repairable modular units. Duration of the waiting phase for spare parts is determined by another ESF element - spare parts supply. Duration of other phases primarily depend on the organization of ES corrective maintenance. Therefore, relevant alternatives of corrective maintenance should be looked for in the technology of repair of systems and their repairable units as well as in the organization of corrective maintenance. Relevant alternatives of technology of repair $\{ATRCM\}$ can be formed as regards: defectation procedure, used equipment and tools, number of personne[redacted] operation[redacted] Technol[redacted] various [redacted] resent a[redacted] i.e. lev[redacted] combin[redacted] o[redacted] ES [redacted]rective maintenance

$$\{ACM\} = \{ATRCM, ALRCM\} \tag{7}$$

In t[redacted] spare parts supply system all complets of spare parts s[redacted]d have, from the beginning to the end of ES service, [redacted] spare parts assortment and quantity - stocks of spare[redacted]th criteria for ESF estimation highly depend on th[redacted]The stocks of nonrepairable spare parts of a syste[redacted]est level of supply should be 'inexhaustible'. [redacted]red in the beginning of service according [redacted]d quantities for a complete ES life-cycl[redacted]red periodically during service. The alte[redacted] of these stocks do not have effec[redacted]nal availability or ES life--cycle or [redacted]ificance for ESF optimization. Us[redacted]ervice is included into used sp[redacted]t of other spare parts in a co[redacted]nance level is determined by[redacted] the competences of pa[redacted]rticular alternati[redacted] re[redacted] spare parts d[redacted] several[redacted]nds o[redacted] a par t[redacted]

[redacted]

zation of stocks of spare parts which can be carried out only after the prediction of reliability and repairability. The sign' indicates that a part of alternatives from the {*AESF**} set is generated. The alternative from the {*AESF**} set is obtAES73.66 Tm95

$ABITERP_2$ - BITE only indicates ES failure, $ABITERP_3$ - - BITE carries out defectation to level II of MUs and $ABITERP_4$ - BITE carries out defectation to level I of MUs. This implies that in $ABITERP_3$, BITE also indicates ES failure and that in $ABITERP_4$, BITE also indicates ES failure and carries out defectation up to level II of MUs. A particular ABITERP is generated for a particular AMRP so that after this generation modularity alternative and BITE - - AMRP, ABITERP are created. In ABITERP where BITE is applied, in ES construction - besides the basic set of components $\{CESF\} = \{K_1, K_2, ...K_q\}$ which ensure its function - a set of new components $\{CMBITE\}$ appears. The number of these components is increased with defectation depth. After generating ABITERP, these components are to be 'built in' the ES modular construction. Therefore, the rework of previously generated AMRP, for which ABITERP is generated, is carried out if necessary.

In the beginning of generating automatic adjustment alternatives - AAARP, it is necessary to identify components during the replacement of which the adjustment of certain parameters (voltage, frequency, power level, etc.) is needed for the generated modularity alternative and BITE - AMRP, ABITERP. The basis for generating AAARP is that necessary adjustments are performed manually or automatically. Two extreme alternatives of one kind are the AAARP where all necessary adjustments are done automatically and the AAARP where all necessary adjustments are done manually. This generation gives the alternative of modularity, BITE and automatic adjustment - AMRP, ABITERP, AAARP, i.e. the alternative of repairability - ARP. As in generating ABITERP, in this generation, with automatic adjustment, also appears a set of new components $\{CMAA\}$ in ES construction. Therefore, in the end of AAARP generation, the rework of previously generated AMRP, ABITERP for which AAARP is generated, is carried out if necessary.

After the generation of the repairability alternative, the redundance alternative - ARDR is generated. The generation of this alternative is performed for the obtained ARP as follows: one or more spare elements are added to the elements of an ES (MUs and components) in different ways. After this generation, the alternative of repairability, redundance - ARP, ARDR is created. This generation also gives a set of new components $\{CMRD\}$ in ES construction. Therefore, in the end of ARDR generation as well - if spare parts are added to this generation - the rework of previously generated ARP is carried out.

Other reliability alternatives are related to ES components: ACR - component reliability, ACTR - component technology and ACUR - component unloading. These alternatives are generated by the choice of different reliability, different technological generations and different unloading of components. They are generated for all sets of components created by the previous definition of the ES functional model and by generating ARP, ARDR: $\{CESF\}, \{CMBITE\}, \{CMAA\}$ and $\{CMRD\}$. This generation gives the alternative of repairability, reliability - ARP, AR, i.e. an alternative of ES construction from the standpoint of ESF.

The ES repair technology represents a set of methods which gets ES and their repairable components to operating condition after sudden failure. It depends considerably on the alternative ARP, ARDR without depending at all on other reliability alternatives - ACR, ACTR and ACUR. In order to generate the alternative of technology of repair - ATRCM, it is useful to apply systematization of ES technology of repair through the technology program of repair - TPR [24, 25]. In this systematization, all repair operations (dismantling ES, defectation of defective MU, replacement of components, adjustment of particular ES parameters, etc.) are gathered in the TPR sequence. The basic criterion for defining these programs is the depth of engagement of repair operations. Table 1 gives, as an example, a possible maximum set of these programs for ES repair with two levels of MUs (the ES shown in Fig.5).

The MU repair/discard alternative, as a subalternative ATRCM, after MU failure - ATRCMR/D is generated before defining the TPR program because the TPR number and the structure of particular TPR depend on this alternative. The ATRCMR/D is generated for the generated ARP, ARDR in such a way that every ES MU can be repaired or discarded after a failure on it. This generation creates the alternative of repairability, redundance and repair/discard - ARP, ARDR and ATRCMR/D. After this generation of MUs, it can happen that MUs are discarded on a particular level and that ABITERP supposes their defectation. In such case, after the generation of ATRCMR/D, the defectation of such MUs by using BITE is canceled and the generated ARP and ARDR are reworked.

After the generation of ATRCMR/D, on the basis of the maximum set of technological programs of ES repair, TPR is defined for the generated ARP, ARDR and ATRCMR/D.

Table 1. Maximum set of technology programs of ES repair with two-level MUs

PROGRAM	PROGRAM CONTENTS
TPR-1	ES repair by simple replacement of accessories or independent components
TPR-2	ES repair by replacement of higher modular units (HMUs) and/or lower modular units (LMUs) without adjustment
TPR-3	ES repair by replacing HMUs and/or LMUs with adjustment
TPR-4	Repair of accessories
TPR-5	HMUs repair by replacing LMUs and/or a component without adjustment
TPR-6	HMUs repair by replacing LMUs and/or a component with adjustment
TPR-7	LMUs repair by replacing a component without adjustment
TPR-8	LMUs repair by replacing a component with adjustment
TPR-9	ESs repair by replacing HMUs, LMUs and a component with adjustment (most complex repairs)

In order to perform generated TPR, different equipment and tools can be used as well as different number of executing staff, different defectation procedure, etc. All this makes a basis for generating the alternative of technology of repair – $ATRCM^{-}$ (the sign^{-} signifies an alternative of technology of repair without ATRCMR/D). This generation does not give new TPR, it only defines precisely the method of their realization. One of the chosen methods is $ATRCM^{-}$. This gives the alternative of repairability, redundance, repair/discard and technology of repair^{-} - ARP, ARDR, ATRCMR/D, $ATRCM^{-}$.

The generation of the repair level alternative - ALRCM is performed by different distribution of TPR on maintenance levels. This generation gives the alternative of repairability, redundance, repair/discard, technology of repair and level of repair - ARP, ARDR, ATRCMR/D, $ATRCM^{-}$, ALRCM.

The generation of other reliability alternatives gives the alternative ARP, AR and the generation of the level of repair alternative gives, ARP, ARDR, ATRCMR/D, ATRCM‾, ALRCM. Based on these alternatives, ARP, AR, ARDR, ATRCMR/D, ATRCM‾, ALRCM are defined, i.e. the relevant alternative of elimination of sudden failures without the alternative of stock of spare parts - AESF*.

In case of the modification of an already existing AESF*, the modification algorithm depends on which alternative type is modified. If the repairability alternative - ARP, redundance alternative - ARDR and repair discard alternative - ATRCMR/D are modified, it will be necessary to modify a number of other alternatives because reliability alternatives - AR and corrective maintenance alternatives - ACM depend on them. If AR modified, it will not be necessary to modify of other alternatives. The same refers to ALRCM modification, while after the modification of ATRCM‾ it is sometimes necessary to modify only ALRCM.

The first generation of the set of alternatives {*AESF**}' is performed when the first functional model of ES is defined, i.e. when all functional units of the system (modulator, memory, output amplifier, etc.) are determined, namely, components of these units (integrated circuits, resistors, coils, etc. - set of components $(\{ESF\})$. During this generation, the largest number of AESF* is generated. Namely, during this generation, for a defined functional model of ES, all possible ARP, ACR, ACTR, ATRCMR/D, ATRCM‾ and ALRCM are generated. Due to a relatively large number of ARDR and ACUR, only a part of AESF* is generated during the first generation. Further generations will generate a part of these alternatives which have positive effects (proven by analysis) on costs $C_{esf}(v, m_{op}) / C_{esflu}(v, m)$ and which, therefore, potentially belong to the optimum alternative of ESF.

If a functional model of ES is changed, it will be necessary to modify *AESF**-{*AESF**}$^+$ generated up to that moment and/or to generate new *AESF**.

4. In order to determine optimum alternatives of stocks of spare parts of all generated {*AESF**}' and then to predict ESF criteria, it is necessary to carry out a quantitative prediction of validity of generated alternatives of ESF construction elements: reliability and repairability from the standpoint of functioning certainty. When reliability is concerned it is the prediction of indices of frequency of sudden failure occurrence in all ES components. When repairability is concerned, it is mean time of sudden failure removal in ESs and each of their MUs. As these times in ESs and their MUs depend on relative frequency of failures of their components, the results of reliability prediction are used to predict repairability, i.e. reliability prediction should precede repairability prediction. Fig.6 shows a model of reliability and repairability prediction with respective input and output sets.

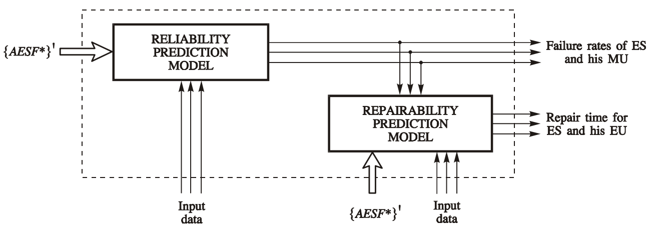


Figure 6. Reliability and repairability prediction model

At the entrance of this model there are {*AESF**}', namely, their reliability and repairability alternatives- $\{AR, ARP\}$ which are significant for this prediction, and input data. The input data for reliability prediction concern the conditions of ESs and each of their components. The input data for repairability prediction concern the mean times of repair of ESs and their MUs in case of failures of each of their components.

5. During the generation of the {*AESF**}' set of alternatives, the alternatives of stocks of spare parts - $\{ASSP\}$ are not generated because of a countless number of these alternatives. In order to perform the prediction of ESF criteria, it is necessary, before this prediction, to generate a reduced relevant set of alternatives of stocks of spare parts for each alternative belonging to the set {*AESF**}'. This set is obtained by the optimization of stocks of spare parts (Fig.7). At the entrance of the model for optimization of stock of spare parts there are {*AESF**}', the results of reliability and repairability prediction and other input data. These data refer to the MU technology of repair, the organization of corrective maintenance of ESs and their MUs, the system of spare parts supply and the cost of spare parts.

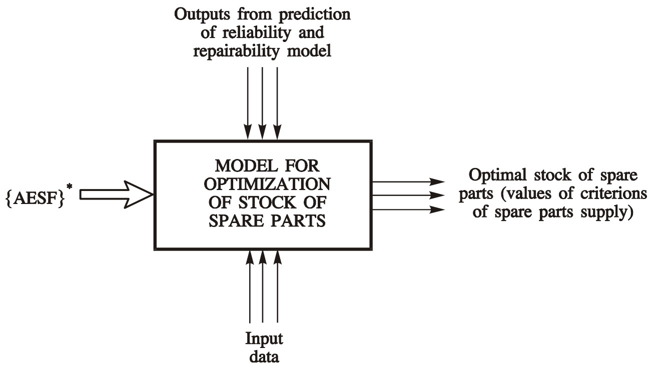


Figure 7. Determination of optimum alternatives of spare parts stock for {*AESF**}' alternatives

The criteria of this optimization are: ES down time due to shortage of spare parts (T_{ssp}) and overall costs of stocks of spare parts for ES corrective maintenance (C_{ssp}). This optimization for one $AESF^*$ is performed as follows: starting from empty sets of spare parts a spare part (MU or component), for which the ratio of the increment of funds for spare parts (ΔC_{ssp}) and the increment of system down time due to shortage of spare parts (ΔT_{ssp}) has the minimum value

$$D = \frac{\Delta C_{ssp}}{\Delta T_{ssp}}, \quad (9)$$

is introduced into the sets. The procedure finishes when the corresponding $C_{ssp\max}$ or $T_{ssp\min}$ is achieved. Each introduction of one spare part gives a new optimum alternative of stocks of spare parts, from the standpoint of supply-ASSP, and an overall optimization procedure creates a set of optimum alternatives of stocks of spare parts - $\{ASSP\}$, where $ASSP_o$ is the alternative with empty sets of spare parts, $ASSP_1$ is the alternative with one part, $ASSP_2$ is the alternative with two parts, etc. After a complete optimization of stocks of spare parts for the whole set {*AESF**}', a set of relevant alternatives of ESF - {*AESF*}' is obtained. For each *m* optimum alternative of spare parts of *v AESF**, the values of criteria of spare parts supply: $C_{ssp}(v,m)$ and $T_{ssp}(v,m)$ are obtained.

6. The prediction of ESF criteria is carried out for all {*AESF*}' (Fig.8). Besides {*AESF*}', the input data at the entrance of the model of ESF criteria prediction are: results of reliability and repairability prediction, values of spare parts supply criteria (obtained by stocks of spare parts optimization) and other input data. These data refer to: research, development and production of ES reliability; research, development and production of ES repairability; technology of repair of ESs and their MUs; organization of performing corrective maintenance of ESs and their MUs, and spare parts supply system.

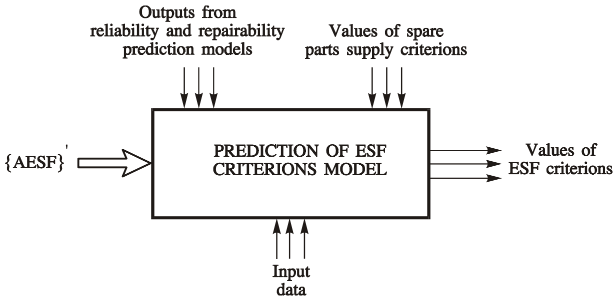


Figure 8. Prediction of ESF criteria

The following vectors are obtained by the prediction of ESF criteria: vector of system operational availability - $A_{oc}(v,m)$, vector of total costs of ESF - $C_{esf}(v,m)$ and vector of total costs of ESF and loss of users $C_{esflu}(v,m)$, where: *v* is the ordinal number of *AESF** and *m* is the ordinal number of the optimum alternative of spare parts of the *AESF** in question. If the lowest necessary operational availability - A_{ocn} is defined for an ES, then all *AESF** with $A_{oc}(v,m) < A_{ocn}$ are eliminated from the rest of the optimization procedure.

7. In ranking ESF alternatives, the ranks of all ESF alternatives generated up to that moment $\{AESF\}^+$ (alternatives obtained by the last generation - {*AESF*}' and all alternatives obtained by previous generations and not being eliminated from the optimization procedure) are determined. The ranking is performed on the basis of obtained vector values: $A_{oc}(v,m)$, $C_{esf}(v,m)$ and $C_{esflu}(v,m)$ of all alternatives from the $\{AESF\}^+$ set, and the very ranking procedure depends on the optimization goal, determined by ES purpose. The following procedure refers to two groups of ESs:

- group I - ESs intended for security and safety purposes where dependability comes before costs,
- group II - ESs taking part in making profit, where costs are of highest importance.

In group I systems, the ESF optimization goal is to attain requested operational availability with as low elimination costs as possible. The procedure of raking ESF alternatives consists of two phases:

- In the first phase, for each *AESF** from the $\{AESF\}^+$ set, we seek for an optimum alternative of stock of spare parts from the standpoint of ESF optimization, namely, bearing in mind the optimization goal in this group, the alternative of stock of spare parts which gives

$$A_{oc}(m) \geq A_{ocn} \text{ and } C_{esf}(m)_{\min} \qquad (10)$$

where $A_{oc}(m)$ stands for the system operational availability for the *m* optimum alternative of stock of spare parts, and $C_{esf}(m)$ are the costs of ESF for the *m* optimum alternative of stock of spare parts. Fig.9 shows the procedure of choosing the optimum alternative of stock of spare parts of an *AESF**. The figure gives general dependence of costs- $C_{esf}(m)$ and operative availability- $A_{oc}(m)$ of ESs on the alternatives of stock of spare parts for one of its *AESF**. Based on research results in [13-15], the function of these costs can have the form *X* or *Y*, depending on the level of influence of spare parts stocks on the costs of transportation of spare parts and defective repairable MUs. When the function $C_{esf}(m)$ has the form *X*, the optimum alternative of spare parts m_{opt} is determined by A_{ocn}. If the function $C_{esf}(m)$ has the form *Y* and if it is the solution of the first condition in its declining part, then m_{opt} is determined by the minimum of the function $C_{esf}(m)$.

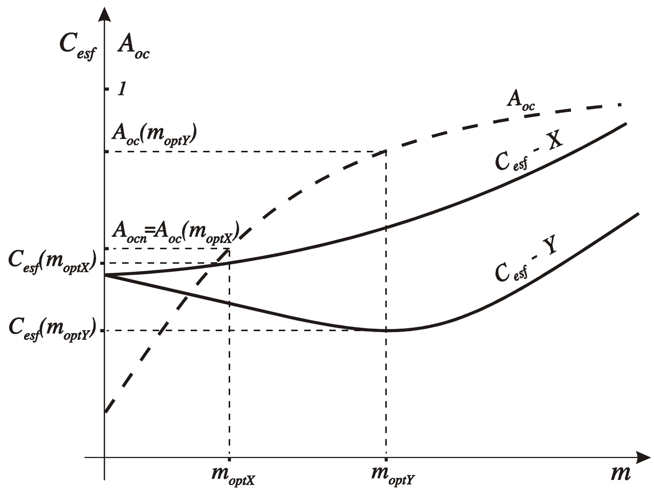


Figure 9. Determination of the optimum alternative of spare parts stock for one *AESF** and the value of ESF criteria for this alternative

- In the second phase, *AESF** are ranked on the basis of the ESF criterion value, for the optimum alternative of stock of spare parts, of each *AESF**: $A_{oc}(v,m_{opt})$ and $C_{esf}(v,m_{opt})$. When all the elements of the vector $A_{oc}(v,m_{opt})$ fulfill the condition (10), this problem is, in principle, reduced to arranging the elements of the vector $C_{est}(v,m_{opt})$ from the minimum value to the maximum one. The *AESF** with the minimum $C_{esf}(v,m_{opt})$ is the best, and such an alternative with the maximum $C_{esf}(v,m_{opt})$ is the worst. Only in case when there are the *AESF** sets with approximately the same costs $C_{esf}(v,m_{opt})$, the rank of these alternatives in the sets can be changed. Namely, alternatives with greater $A_{oc}(v,m_{opt})$ will be ranked better in these sets.

In group II systems, the ESF optimization goal is that the sum of total ESF costs and financial losses caused by these failures in ES life cycles is kept to the minimum. It means that the problem of *AESF** ranking is reduced to arranging the elements of the vector $C_{esflu}(v,m)$ from the minimum

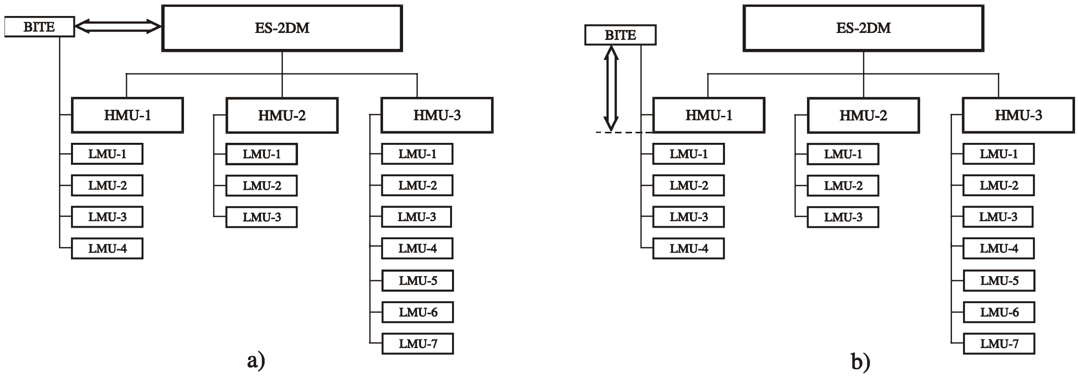


Figure 12. Alternatives of BITE at ES-2DM for AMRP-A: a) ABITERP-A b) ABITERP-B

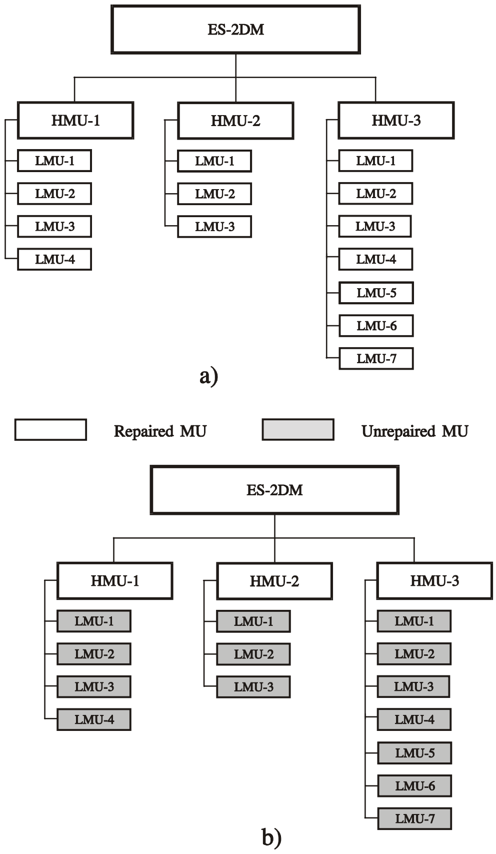


Figure 13 Repair/discard alternative at ES-2DM: a) ATRCMR/D-A b) ATRCMR/D-B

Table 2. Technology program of repair in ES-2DM and its MUs

TPR	PROGRAM CONTENTS
TPR-2	System repair by the replacement of HMUs without adjustment
TPR-5	Repair of HMUs by the replacement of LMUs without adjustment
TPR-7	Repair of LMUs by the replacement of components without adjustment

Technological programs of repair of ES-2DM are distributed in two ways on maintenance levels, which generates two alternatives of the level of repair: ALRCM-A and ALRCM-B. Table 3 shows these two alternatives of the level of repair.

All possible combinations of the generated alternatives represent $\{AESF^*\}^+$. There can be no repair of ES-2DM by ABITERP-A on the first level of repair (level I is not equipped and prepared for system defectation up to the level of HMUs without BITE), and because of this limitation, *AESF** which include both ABITERP-A and ALRCM-B are not logical and they are, therefore, eliminated from the rest of optimization. Table 4 shows generated $\{AESF^*\}^+$.

Table 3. Level of repair alternatives in ES-2DM

LEVEL OF MAINTENANCE	TECHNOLOGY PROGRAM OF REPAIR		
	TPR-3	TPR-5	TPR-7
ALRCM-A			
I			
II	*		
III		*	
IV			*
ALRCM-B			
I	*		
II			
III		*	
IV			*

Table 4. Presents the generated $\{AESF^*\}^+$

	A L T E R N A T I V E				
*AESF**	*AMRP*	*ABITERP*	*ATRCMR/D*	*ACR*	*ALRCM*
1	*A*	*A*	*A*	*A*	*A*
2	*A*	*A*	*A*	*B*	*A*
3	*A*	*A*	*B*	*A*	*A*
4	*A*	*A*	*B*	*B*	*A*
5	*A*	*B*	A	*A*	*A*
6	*A*	*B*	*A*	*A*	*B*
7	*A*	*B*	*A*	*B*	*A*
8	*A*	*B*	*A*	*B*	*B*
9	*A*	*B*	*B*	*A*	*A*
10	*A*	*B*	*B*	*A*	*B*
11	*A*	*B*	*B*	*B*	*A*
12	*A*	*B*	*B*	*B*	*B*
13	*B*	*A*	*A*	*A*	*A*
14	*B*	*A*	*A*	*B*	*A*
15	*B*	*A*	*B*	*A*	*A*
16	*B*	*A*	*B*	*B*	*A*
17	*B*	*B*	*A*	*A*	*A*
18	*B*	*B*	*A*	*A*	*B*
19	*B*	*B*	*A*	*B*	*A*
20	*B*	*B*	*A*	*B*	*B*
21	*B*	*B*	*B*	*A*	*A*
22	*B*	*B*	*B*	*A*	*B*
23	*B*	*B*	*B*	*B*	*A*
24	*B*	*B*	*B*	*B*	*B*

The prediction of reliability and repairability of ES-2DM and its components results in obtaining the rate of failure and time to repair of the ES and its components. Only a part of these results is presented here. Table 5 gives failure rates of ES-2DM and its MUs for the reliability alternatives A and B for AMRP-A. Mean times to repair of ES-2DM by replacing HMUs (TPR-2) for the B modularity alternative are given in Table 6.

Table 5. Failure rates of ES-2DM and its MUs for ACR-A and ACR-B

UNIT	ACR-A	ACR-B
	Failure rates (x10^{-6})	Failure rates (x10^{-6})
SYSTEM	1.150	230
HMU-1	380	76
LMU-11	120	24
LMU-12	180	36
LMU-13	50	10
LMU-14	30	6
HMU-2	350	70
LMU-21	20	4
LMU-22	250	50
LMU-23	80	16
HMU-3	420	84
LMU-31	70	14
LMU-32	30	6
LMU-33	40	8
LMU-34	50	10
LMU-35	45	9
LMU-36	75	15
LMU-37	110	22

Table 6. Mean time to repair of ES-2DM with the replacement of HMUs (for AMRP)

HMU which is failed	ABITERP-A			ABITERP-B		
	Mean time to defecta-tion ES (h)	Mean time to resolve failure of ES (h)	Mean time to repair of ES (h)	Mean time to defecta-tion of ES (h)	Mean time to resolve failure of ES (h)	Mean time to repair of ES (h)
HMU-1	2.0	0.1	2.1	0.006	0.1	0.106
HMU-2	1.9	0.1	2.0	0.006	0.1	0.106
HMU-3	1.5	0.1	1.6	0.006	0.1	0.106
HMU-4	2.3	0.1	2.4	0.006	0.1	0.106
HMU-5	2.3	0.1	2.4	0.006	0.1	0.106

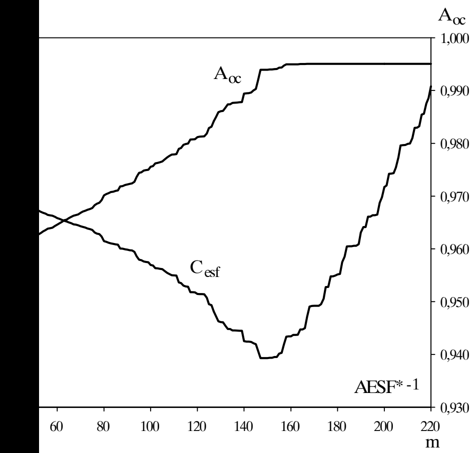
Six characteristic optimum alternatives of stock of spare parts of ES-2DM for its *AESF*-*1 are given in Table 7. as an example of results of stock of spare parts optimization. The first alternative is with completely empty sets of spare parts. From alternative 1 to alternative 25 there are optimum alternatives with LMUs which are only on level IV. In case of optimum alternatives from 26 to 113, LMUs are on level IV and on level III. When optimum alternatives ranking from 114 to 141 are concerned, besides LMUs on levels IV and III, there are also HMUs on level III, and from optimum alternative 142 onwards, there are HMUs on level II as well. In optimum alternatives 26, 114 and 142, spare units appear on lower levels of supply as well, thus reducing time of waiting for spare parts in these alternatives more quickly but, on the other hand, increasing the growth of spare components costs. The table shows that two adjacent alternatives 141 and 142 differ only in one unit but they significantly differ in system down time due to spare parts as well as in spare parts costs. In optimum alternative 170 system down time due to shortage of spare parts is practically reduced to zero, but stock of spare parts costs are enormously increased.

Table 7. Optimum stock of spare parts in ES-2DM for *AESF**-1

UNIT	ORDINAL NUMBER OF OPTIMAL STOCK OF SPARE PARTS					
	1	26	114	141	142	170
	Quantity of HMUs in set on level II					
HMU-1	0	0	0	0	0	3
HMU-2	0	0	0	0	1	3
HMU-3	0	0	0	0	0	3
	Quantity of HMUs in set on level III					
HMU-1	0	0	0	3	3	6
HMU-2	0	0	1	4	4	5
HMU-3	0	0	0	3	3	6
	Quantity of LMUs in set on level III					
LMU-11	0	0	1	2	2	3
LMU-12	0	0	4	5	5	5
LMU-13	0	0	1	1	1	2
LMU-14	0	0	1	1	1	1
LMU-21	0	0	1	1	1	1
LMU-22	0	0	5	5	5	6
LMU-23	0	0	1	2	2	2
LMU-31	0	0	2	3	3	3
LMU-32	0	0	1	1	1	2
LMU-33	0	0	1	2	2	2
LMU-34	0	1	2	3	3	3
LMU-35	0	0	1	2	2	2
LMU-36	0	0	1	2	2	2
LMU-37	0	0	2	3	3	3
	Quantity of LMUs in set on level IV					
LMU-11	0	0	8	10	10	10
LMU-12	0	5	13	14	14	15
LMU-13	0	0	3	5	5	5
LMU-14	0	0	3	3	3	4
LMU-21	0	0	2	2	2	3
LMU-22	0	9	17	18	18	19
LMU-23	0	0	6	6	6	7
LMU-31	0	2	6	7	7	7
LMU-32	0	0	3	3	3	4
LMU-33	0	2	4	4	4	5
LMU-34	0	4	5	6	6	6
LMU-35	0	2	5	5	5	5
LMU-36	0	0	6	6	6	7
LMU-37	0	0	7	8	8	9
Values of criteria for	Stock of spare parts costs-C_{ssp} (MU)					
stock of	0	34.200	426.050	987.800	1.223.800	5.035.800
spare parts	Mean down time of ES due to spare parts – T_{ssp}					
optimization	46.06	39.52	14.39	6.42	5.01	0.005

The values of system operational availability - A_{oc} (v,m) and total costs of ESF - C_{esf} (v,m) are obtained by elimination criteria prediction for each *AESF** and each of its optimum stock of spare parts. The result of calculation of ESF criteria for *AESF*-1* of ES-2DM is given graphically in Fig.14.

The generated ESF alternatives are ranked on the basis of obtained results of the prediction of ESF criteria for ES-2MD. Table 8 shows the results of the first phase of this ranking. The optimum alternative of stock of spare parts m_{opt} is determined for each *AESF** at three values of requested operative availability (A_{ocn}=0.980; 0.995 and 0.999). The ESF criteria values C_{esf} and A_{oc} are determined for each m_{opt}.



[redacted] availability-A_{oc} and ESF costs-C_{esf} dependence on [redacted] are parts for *AESF*-1*

[redacted] C_{esf} (v,m_{opt}) from Table 8 are given in the [redacted] am in Fig.15 (A_{ocn}=0.980) and Fig.16 [redacted] e requested operational availability [redacted] e *AESF** cannot be achieved so these [redacted] inated from the rest of optimization.
[redacted] d $\{AESF^*\}^+$, i.e. $\{AESF\}^+$ can be ranked on [redacted] F costs values - C_{esf} (v,m) given in Table 8, [redacted] 6. When the case A_{ocn}=0.980 is concerned, [redacted] C_{esf} (v,m_{opt}) are in *AESF*-2*, so this alterna- [redacted] ptimum alternative of spare parts 48, is the [redacted] *AESF*-20*, etc. come after it. The worst [redacted] ve is *AESF*-15* due to its maximum costs

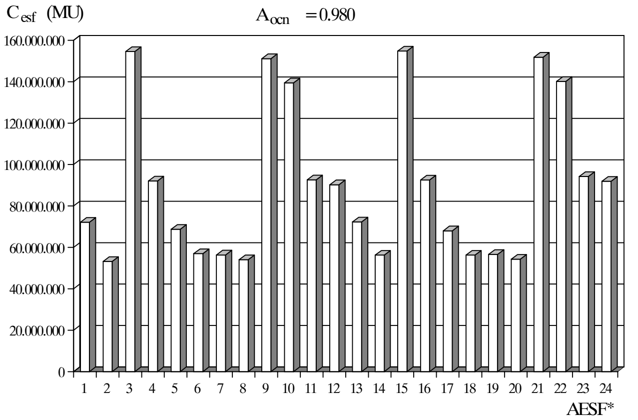


Figure 15. ESF costs of *AESF** in the optimum alternative of spare parts (for A_{ocn}=0.980)

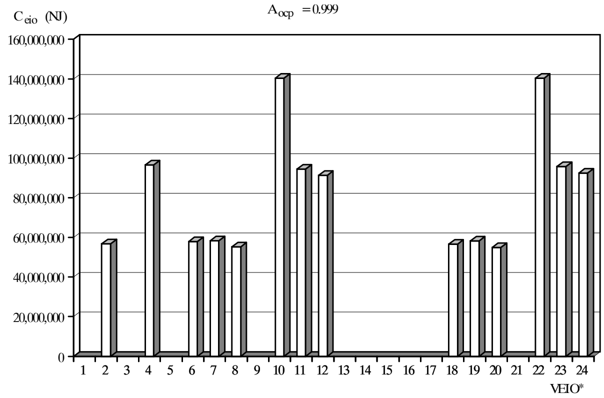


Figure 16. ESF costs of *AESF** in the optimum alternative of spare parts (for A_{ocn}=0.999)

[redacted] lts of the first phase of ranking of $\{AESF^*\}^+$, in ES-2DM

	A_{ocp} = 0.980			A_{ocp} = 0.995			A_{ocp} = 0.999		
[redacted] DF*	m_{opt}	$C_{esf}(MU)$	A_{oc}	m_{opt}	$C_{esf}(MU)$	A_{oc}	m_{opt}	$C_{esf}(MU)$	A_{oc}
[redacted]	148	72.126.700	0.994	168	73.918.000	0.995	-	-	-
[redacted]	**48**	**52.055.500**	**0.997**	**48**	**52.055.500**	**0.997**	72	56.708.700	0.999
[redacted]	44	154.526.000	0.994	58	156.171.000	0.995	-	-	-
[redacted]	14	92.075.300	0.997	14	92.075.300	0.997	31	96.561.700	0.999
[redacted]	147	68.711.900	0.996	147	68.711.900	0.996	-	-	-
[redacted]	146	56.978.800	0.998	146	56.978.800	0.998	158	57.905.700	0.999
[redacted]	48	56.334.400	0.997	48	56.334.400	0.997	59	58.336.700	0.999
[redacted]	47	54.001.000	0.998	47	54.001.000	0.998	57	55.170.100	0.999
[redacted]	44	151.142.000	0.996	44	151.142.000	0.996	-	-	-
[redacted]	44	139.419.000	0.998	44	139.419.000	0.998	55	140.309.000	0.999
[redacted]	14	92.569.100	0.997	14	92.569.100	0.997	23	94.506.100	0.999
[redacted]	14	90.254.100	0.998	14	90.254.100	0.998	22	91.397.700	0.999
[redacted]	146	72.285.300	0.994	-	-	-	-	-	-
[redacted]	47	56.231.500	0.997	47	56.231.500	0.997	-	-	-
[redacted]	47	154.775.000	0.994	-	-	-	-	-	-
[redacted]	16	92.524.700	0.997	16	92.524.700	0.997	-	-	-
[redacted]	146	67.961.200	0.996	146	67.961.200	0.996	-	-	-
[redacted]	146	56.231.000	0.998	146	56.231.000	0.998	156	56.587.900	0.999
[redacted]	47	56.581.300	0.998	47	56.581.300	0.998	63	58.141.60040	0.999

The analysis of the results of ranking generated ESF* alternatives leads to the conclusion that the alternatives comprising ATRCMR/D-B are not satisfactory (LMUs are non-repairable and are discarded at repair) because in all these alternatives the costs C_{esf} (v,m_{opt}) go beyond the sum of 80,000 MUs. The worst of them are those which, besides ATRCMR/D-B, comprise the alternative ACR-A. It is clearly seen that in their case C_{esf} (v,m_{opt}) > 120,000 MUs. The reason for this is that in this *AESF** LMUs with frequent failures are discarded during service. It can be also concluded from the ranking results that the costs C_{esf} (v,m_{opt}) differ slightly according to the generated alternatives AMRP-A and AMRP-B.

Conclusion

The standard of national defense - SNO 1096 [26] has been in power in our armed forces since 1985. It defines a part of operational-technical requirements for development of technical systems which determine, directly or indirectly, parameters on which system logistic support depends. This standard has considerably contributed to the integration of integral logistic support elements into the already developed technical systems for satisfying the needs of our armed forces. However, it has significant disadvantages from the standpoint of combined optimization of failure elimination. Namely, this standard stipulates fixed requirements for reliability (value of mean time between failures) and maintainability (the longest mean maintenance time) on the basis of only one criterion - system complexity. The requirements concerning maintenance levels are fixed as well. Solutions for reliability, maintainability and maintenance, which are not optimal in most cases from the standpoint of dependability and system life cycle costs, are thus imposed to a team developing ES. Furthermore, a development team is "prevented" by standards from carrying out combined optimization of elements of ES failure elimination even in case it has adequate methodology and program support.

A developed methodology, i.e. a professional computer program developed on the basis of this methodology, would enable, during ES design and development, making optimum decisions on:

- reliability level to be built in ESs,
- method of reaching a particular reliability level in ESs,
- number of modular construction levels of ESs,
- number of MUs on a particular level of ES modular construction,
- building in test equipment and its depth of defectation,
- repair or discard of ES MUs after their failure,
- maintenance level competency in elimination of failures in ESs and their repairable MUs,
- quantity of stocks of spare parts for repair of ESs and their repairable MUs according to maintenance levels, etc.

Besides sudden failures, gradual failures also occur in ESs. The elements of their elimination can also be defined - - they are reliability (concerning gradual failures), preventive maintainability, preventive maintenance and spare parts supply (for preventive maintenance). As all these elements can be realized in a number of different ways and they are mutually dependent, combined optimization of gradual failures should be carried out during design and development ESF elements and elements of elimination of gradual failures are not mutually independent. Thus it often happens that building in preventive maintainability improves corrective maintainability as well, enables corrective and preventive maintenance at a particular maintenance level to be performed by the same personnel, often with the same maintenance equipment, a particular spare part for corrective maintenance can also be used for preventive maintenance, etc. Because of such a connection between elements of these two eliminations, ESF optimization should be combined with optimization of elimination of gradual failures.

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Received: 17.12.2001

Osnovi metodologije optimizacije eliminacije iznenadnih otkaza pri projektovanju i razvoju elektronskog sistema

Prikazani su rezultati razvoja originalne metodologije optimizacije eliminacije iznenadnih otkaza (EIO) elektronskog sistema (ES), koja se izvodi u fazi njegovog projektovanja i razvoja. Optimizacijom EIO su obuhvaćeni svi elementi EIO: pouzdanost, pogodnost opravke, korektivno održavanje i snabdevanje rezervnim delovima. Sa stanovišta upotrebnog kvaliteta za kriterijum optimizacije je uzeta operativna gotovost, a sa stanovišta troškova kriterijum su troškovi životnog veka ES koji su zavisni od EIO. Osnova razvijene metodologije optimizacije EIO je traženje najbolje varijante EIO među generisanim relevantnim varijantama EIO, koje predstavljaju sve moguće kombinacije relevantnih varijanti elemenata EIO. Objašnjen je kompletan postupak optimizacije EIO. Na jednom ES prikazan je deo postupka optimizacije EIO.

Ključne reči: **elektronski sistem, iznenadni otkazi, pouzdanost, pogodnost održavanja, pogodnost opravke, korektivno održavanje, optimizacija, optimalna varijanta eliminacije iznenadnih otkaza.**

Elimination des défaillances soudaines pendant la conception et le développement des systèmes électroniques-fondements de la méthodologie de son optimisation

L'élimination des défaillances soudaines (EDS) des systèmes électroniques (SE) est optimisée à l'aide d'une méthodologie originale au cours des phases de la conception et du développement de tels systèmes. L'optimisation de l'EDS comprend tous les élements de l'EDS: fiabilité, facilité de l'entretien correctif, entretien correctif et fourniture des pièces de rechange. Les critères de l'optimisation sont la disponibilité opérationnelle du point de vue de la qualité d'usage et les frais de longévité des SE du point de vue des frais. La méthodologie de cette optimisation est basée sur la recherche de la meilleure EDS parmi toutes les EDS pertinentes générées. Le procédé complet de l'optimisation de l'EDS est expliqué et une de ses phases et démontrée sur un système électronique.

Mots-clés: **système électronique, défaillances soudaines, fiabilité, facilité de maintenance, entretien correctif, optimisation, version optimale de l'élimination des défaillances soudaines.**