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IMPROVING THE SCIENTIFIC METHODOLOGICAL APPROACH TO DETERMINING THE APPROPRIATE TYPE OF RESERVATION OF A RECONNAISSANCE FIRE SYSTEM

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The object of this study is the process of choosing the appropriate types of reservation of reconnaissance fire systems under the conditions of performing a combat mission.

The problem that was solved is the unsuitability of existing scientific and methodological apparatus to substantiate the appropriate type of reservation for reconnaissance and fire systems under specific conditions for performing a combat mission.

Possible types of reservation of reconnaissance fire systems have been analyzed. Based on the results of the analysis, appropriate types of reservation were established, in particular, active, unactive, majoritarian sliding, distributed, for subsystems, as well as general reservation.

A feature of this analysis is that it was carried out taking into account the peculiarities of the functioning of reconnaissance and fire systems. This makes it possible to eliminate existing problem associated with the complexity of the use of reconnaissance and fire systems in a combat event.

The scope of practical use of the results of the proposed analysis is the management processes associated with the creation, layout, and use of reconnaissance and fire systems in military administration bodies.

A methodology for determining the appropriate type of reservation of reconnaissance fire systems has been devised.

A feature of the proposed procedure is the choice of such a type of reservation that makes it possible to save the resource of elements, provided that the task is completed. The proposed methodology ensures an increase in the stability of the functioning of reconnaissance and fire systems by an average of 20 % for the conditions adopted within the limits of the example. The proposed methodology closes the problem part, which concerns the procedure and rules for choosing the appropriate type of reservation.

The scope and conditions for the practical use of the proposed methodology are management processes related to the planning and determination of the projected effectiveness of hostilities by military authorities

Keywords: type of reservation, reconnaissance and fire system, stability of operation, combat mission, reliability scheme

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1. Introduction

The results of the analysis of armed conflicts of recent times [1, 2] have shown the high efficiency of the use of reconnaissance and fire systems (RFS) in a combat situation. Thus, in the course of the Russian armed aggression against Ukraine, the growing role of RFS was registered [3]. And these are both regular combat units and created from existing components of the system. It should also be noted that these systems are used at different functional levels – strategic, operational, tactical.

The high efficiency of such systems is due to the relatively small detection and damage cycle, the concentration of the efforts of individual functional elements on meeting the needs of the system itself. An important factor that determines the high efficiency of the RFS is also modularity. That is, the ability to create RFS from individual functional elements for a specific task [4]. This feature makes it possible to increase the efficiency of task completion, in particular by reducing the processes associated with decision-making, obtaining and processing intelligence data.

However, with all the advantages of these systems, there are certain problems regarding their application. Thus, one of the main problems is quite frequent refusals to perform tasks. Moreover, the reasons for failures in the case of using objects under combat conditions are not only developments to the limiting state and technical malfunctions but also the influence of the enemy [5]. Moreover, while the failures associated with the internal state of individual elements of the system can be determined using technical documentation, then other types of failures will require additional research.

Moreover, the failures associated with the influence of the enemy depend not only on the conditions of use of this system but also on the intensity of application. That is, on the one hand, the more intensively the RFS is used, the more tasks will be performed, on the other hand, the probability that the system will be affected increases [6]. This greatly complicates the design process of RFS units that are capable of performing tasks without failures, or with predictable failures.

In practice, to level this problem, several elements of the system are often used to replace such elements that have a failure, that is, reservation is made. On the one hand, this makes it possible to guarantee task completion, on the other hand, this approach has several problems. One of the issues is the overspending of the functional resource, that is, it is necessary to use several identical functional elements to perform one task [6]. Another problem is the loss of efficiency of task completion because you have to spend time replacing the element that has a failure [4].

Thus, in practice, an urgent problem arose related to the design of RFS. The essence of the issue is the need to find such ways of reservation, which would minimize costs with guaranteed task completion. At the same time, given the growing role of RFS, overcoming this problem is extremely relevant.

2. Literature review and problem statement

Quite often, research into this topic is carried out in separate areas, taking into account only one type of reservation, or focusing on one of the components of RFS. Quite often, it is the means of intelligence that are chosen for such a component. There is also a certain body of research related to the definition of parameters of the characteristics of the functioning process of individual functional elements, in particular, the intensity of failures.

Paper [7] reports an analysis of an equivalent level of safety to determine the failure rate requirements for critically important unmanned aerial vehicle systems (UAVs) as one of the elements of RFS for various application conditions. This analysis is based on an object drop model derived from the methodology for assessing the safety of space transport and is confirmed by comparison with data on aircraft accidents. The analysis gives a critical criterion for the system failure rate in the range from 6.5×10^{-6} per flight hour to 1.0×10^{-7}. However, the study does not take into account the failures of other subsystems involved, in particular the control subsystem. In addition, the study does not determine how the failure rate will change if certain types of reservation of individual UAV elements are used.

Work [8] considers the assessment of the reliability of the UAV system after the choice of a specific architecture. The goal is to assess internal reliability at the design stage, to avoid any critical failure that could lead to a catastrophic impact on the UAV. At the same time, the work does not address the issues of assessing reliability with different types of reservation of individual elements.

Article [9] reports a new interpretation and statement of the problem of reliability distribution and reservation. The article proposes a new type of reservation – a «mixed» strategy, which differs from active and unactive reservation. It has been proven that the new strategy demonstrates better performance compared to existing ones. However, the article did not explore the advantages of these types of reservation in the case of several sources of failures and in the case of integrated use of several multifunctional subsystems.

Study [10] developed models for the functioning of military UAVs, which take into account both technical failures and failures associated with the influence of the enemy. In addition, the work assessed the impact of improving the reliability of the UAV on the overall effectiveness of its use under conditions of enemy influence. However, the study does not take into account the interrelatedness of the level of reliability of UAVs with the level of reliability of the control subsystem. Also, the proposed models do not make it possible to determine the most appropriate type of reservation to ensure the implementation of certain types of military tasks.

Article [11] considers this type of ensuring the reliability of the functioning of the military system, as the restoration, for example, of the generalized process of updating the aircraft engine as a component to be repaired. A methodology has been developed for determining components with a high failure rate based on availability, taking into account the dominant failures of the aircraft engine. However, the work does not take into account the possibilities of other types of reliability, in particular, reservation.

Study [12] considered the problem of reliability associated with the level of stocks of spare parts for weapons systems. A new version of the model for optimizing spare parts stocks has been developed in the work. The advantages of this model are the combination of failure rates from user field data and forecasts based on reliability guides; modification of the logic of optimization of the repair and shift unit; adding an optimization process that uses genetic algorithms. However, this model does not take into account the impact of different types of reservation in existing weapons systems on the level of readiness of these systems to perform tasks.

Article [13] reviews and investigates contextual factors from empirical research that can give an idea of the conceptual strategies that can be used to improve the efficiency of the system after failure. This article discusses sustainability and reliability studies in supply chains. The study offers four broad conceptual strategies – insurance, acceleration, strategic adaptive capabilities, and reconfiguration – each uniquely serving to reduce the likelihood and extent of failure in supply chains. The study found that the difference in utility between reservation and flexibility as a means of increasing sustainability and reliability is influenced by the interaction between the supply chain, failure characteristics, and the management subsystem. However, the article does not take into account the types of reservation that can be used to increase stability and reliability.

Thus, the systematization of local problems identified in each source allows us to formulate an unresolved problem. In general, the unresolved problem of the theoretical plan is the unsuitability of existing scientific and methodological apparatus to substantiate the appropriate type of reservation for military systems, in particular for RFS under specific conditions for performing a combat mission. Hereafter, the scientific and methodological apparatus to substantiate the expedient type of reservation is understood as a set of scientific and methodological calculations aimed at justifying the expedient type of reservation. Directly in our paper, the apparatus refers to a set of unresolved parts of an existing problem, in particular, an unproven analysis of existing types of reservation in relation to RFS and the lack of a methodology for determining the appropriate type of RFS reservation. The procedure for determining the appropriate type of reservation of RFS is understood as a sequential set of stages of actions to determine the appropriate type of RFS reservation.

3. The aim and objectives of the study

The aim of this study is to improve the scientific and methodological apparatus for determining the appropriate type of reservation of the reconnaissance and fire system for use under combat conditions. This makes it possible to minimize costs with guaranteed completion of the combat mission.

To accomplish the aim, the following tasks have been set:

– to analyze possible types of reservation of individual functional elements of the reconnaissance and fire system;

– to devise a methodology for determining the appropriate type of reservation of the reconnaissance and fire system.

4. The study materials and methods

The object of our study is the process of choosing the appropriate types of reservation of RFS under the conditions of performing a combat mission.

The main hypothesis assumes that the type of reservation of individual functional elements of RFS affects both the performance and stability of the functioning of RFS.

The main assumptions adopted in the work are: the influence of the enemy on the individual functional elements of RFS depends on the activity of these elements. Also, the introduction of backup elements instead of those that have failed requires less time than completing one task to identify and hit the target. Next, all sources of failures are grouped into three: marginal operating time, technical malfunctions, and enemy effect.

It is also necessary to note that we shall discuss the stage of RFS design. Note that the experimental part gives an example of the use of a variant of the built RFS, to check the feasibility of the proposed calculations.

The main simplifications adopted in the current work include the distribution of random failures that, according to various sources, corresponds to the exponential law of distribution of a random variable. The next simplification: individual functional elements, including backup, have the same failure rate within the same subsystem.

It should also be noted that in the current paper we propose to consider an option in which attention is focused on the gain in preserving the resource of RFS elements. Resource refers to both operation before failure and the number of workable elements. However, it should be noted that the preservation of the resource and the maximization of the indicator of the stability of RFS functioning are interrelated. That is, with a fixed stability of RFS functioning, we save the resource; with a fixed resource of RFS elements, we achieve the best possible values of the indicator of stability of functioning.

Approaches from probability theory and reliability theory are applied in the work.

The main estimation dependence for determining the probability of trouble-free operation [14–16] is proposed as follows:

$$P(t)=e^{-\lambda t}, \tag{1}$$

where λ is the failure intensity per unit of time; t – time of military (combat) operation (time of RFS operation).

To study the functioning of the system with a active (on) reserve, the method of reliability theory was applied to calculate the probability of trouble-free operation of the system with a active (on) reserve [17–20].

The formula for determining the probability of trouble-free RFS operation of with a active reserve of structural and functional elements [17–20] is:

$$P(t)_{r,ar}=1-\left(1-e^{-\lambda t}\right)^{n_e+1}, \tag{2}$$

where n_e is the number of reserve elements.

To study the functioning of the system with an unactive reserve, the method of reliability theory was applied, in particular, the method of calculating the probability of trouble-free operation of the system with an unactive reserve (passive reservation) [20–23].

The formula for determining the probability of trouble-free RFS operation o with a passive reservation of structural and functional elements [20–23] is:

$$P(t)_{r,pr}=e^{-\lambda t}\sum_{i=0}^{n_e}\frac{(\lambda t)^i}{i!}. \tag{3}$$

For the study of systems with sliding reservation [24–26], the method of calculating the probability of trouble-free functioning of the system with sliding reservation was used.

A general expression for determining the probability of trouble-free operation [24–26]:

$$P_{r,sr}(t)=\sum_{i=n_e}^{n_e+n}C^i_{n_e+n}e^{-\lambda it}\left(1-e^{-\lambda t}\right)^{n_e+n-i}, \tag{4}$$

where n is the number of individual functional elements in the subsystem (at the site).

To study systems with triple modular reservation [27–29], the method of calculating the probability of trouble-free functioning of the system with triple modular reservation was used.

A common expression for determining the probability of a system trouble-free operation with a triple modular reservation when $k=3$ [27–29]:

$$P_{mr}(t)=\left(3e^{-2n\lambda t}-2e^{-3n\lambda t}\right)e^{-\lambda_{mr}t}, \tag{5}$$

where k is the number of channels in the subsystem (at the site).

It is also necessary to note that in this paper. Microsoft Excel 2010 software was used for calculations. This is due to the fact that the calculation formulas are simple enough to program them in this software environment. At the same time, the specified software is simple and affordable to use.

5. Results of improvement of the scientific and methodological apparatus of the determining the appropriate type of reservation of the reconnaissance and fire system

5. 1. Analysis of possible types of reservation of individual functional elements of the reconnaissance and fire system

Before starting the analysis, it is advisable to define RFS. RFS is a system that combines separate functional elements of reconnaissance, control, and fire impact in order to identify enemy targets to make a decision on hitting, and hitting these targets in a single organizational circuit. A typical functional diagram of RFS is shown in Fig. 1.

The study of ways to substantiate the appropriate type of reservation of individual functional elements of RFS is proposed based on the analysis of existing approaches to reservation.

Thus, according to the degree of load, there are active, passive, and lightweight types of reservation.

Active reservation is the reservation in which one or more reserve elements are in the main element mode [17–20].

The general view of the structural scheme of RFS reliability with an active reserve of structural and functional elements is shown in Fig. 2.

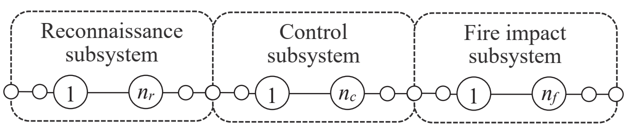

Fig. 1. Typical functional diagram of the reconnaissance and fire system

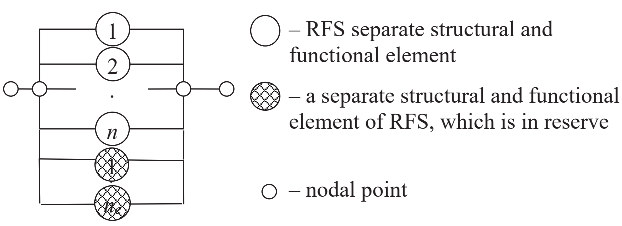

Fig. 2. Block diagram of reliability of the reconnaissance and fire system with an active reserve of structural and functional elements (active reservation)

The results of the analysis of the possibilities of using the active reserve for the needs of RFS indicate that this type of reservation can be applied both to a single element and to a specific subsystem. The advantage of this type of reservation is the lack of switching time between the main and backup elements in the case of failure. The disadvantage of the active reserve is the increased level of resource development of reserve elements because the reserve elements fully perform the functions of the main element.

Passive reservation is the reservation in which one or more reserve elements are in an unactive state before they start performing the functions of the main element [20–23].

Such backup elements are in the off state and are in good working order until they are turned on.

The general view of the structural scheme of RFS reliability with a passive reservation is shown in Fig. 3.

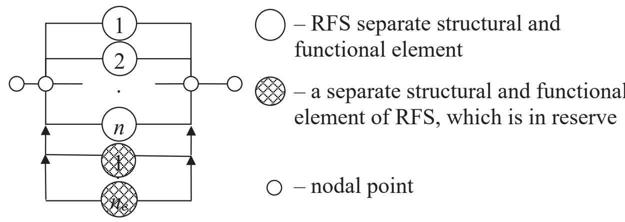

Fig. 3. Block diagram of the reliability of the reconnaissance and fire system with a passive reservation of structural and functional elements (passive reservation)

The results of the analysis of the use of passive reservation indicate that it can also be used both for a single element and for a subsystem. However, it should be noted that for the conditions of use of the passive reservation, more complex procedures for including these reserve elements are necessary.

The main advantage of this type of reservation is a longer system life relative to the active reserve because the backup elements do not have time to work. The main disadvantage of this type is lower efficiency compared to the active reserve. After all, the introduction of a backup element, with passive reservation, takes a certain time, which can be critical under combat conditions.

Lightweight type of reservation is the reservation in which one or more reserve elements are under a lower load mode compared to the main element [22].

The results of the analysis of the use of lightweight reservation indicate that this type of reserve is most appropriate in systems where partial failure is possible, or there is a complex procedure for introducing a backup element. Therefore, it is proposed within the framework of this study to consider only active and passive types of reservation. Although the analysis of the feasibility and location of the facilitated type of reservation may be a further study.

At the same time, it is advisable to consider several types of reservation that are appropriate for the conditions of RFS application. Thus, one of these types is sliding reservation [24–26]. The essence of this reservation is that a group of basic elements is reserved with one or more reserve elements, each of which can replace any of the elements of this group in the case of failure.

The general view of the structural scheme of RFS reliability with a sliding reserve is shown in Fig. 4.

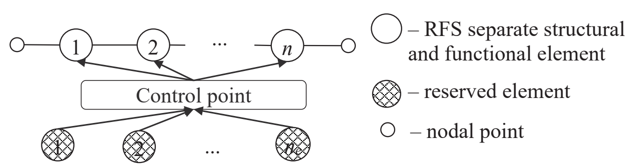

Fig. 4. Block diagram of the reliability of the reconnaissance and fire system with the use of structural and functional elements' sliding reservation

The results of the analysis of the use of this type of reserve indicate that it can be used in the case when the structural and functional elements are the same, or at least have similar functions.

The main advantage of this type of reservation is the ability to reserve a larger number of basic elements with fewer reserve elements. The main disadvantage of this type is the need to introduce a separate element of the system or additional functions existing to decide which backup element and instead of which main one will be introduced.

The next important type of reservation is the triple modular reservation [27–29]. The essence of this reservation is that instead of one element, several, usually an odd number of identical elements are included, the results of the functioning of which are received in the coordination block. In the case when all the elements of such a group are in good condition, then the same signals are sent to the approval unit. If one of the elements fails, then several identical and one different signal are sent to the approval unit. Using the majority criterion, the approval block selects the correct signal. Features of the functioning of this type of reservation determine the use of this type for the control subsystem, it is partially possible to consider the possibility of using this type for the intelligence subsystem.

The general view of the structural scheme of RFS reliability with triple modular reservation is shown in Fig. 5.

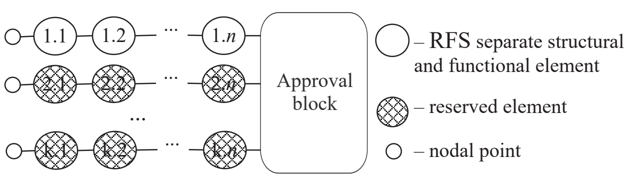

Fig. 5. Block diagram of the reliability of the reconnaissance and fire system using triple modular reservation of structural and functional elements

The results of the analysis of the use of this type of reservation indicate that the most appropriate place of application is the intelligence subsystem. The main advantage of this reservation for RFS conditions is the high probability of completing the task. The main disadvantage of this type is the need to use several elements to perform a specific task, which is the most resource-intensive of all the considered types of reservation.

Next, it is proposed to consider the types of reservation according to the level of reservation. So, for the conditions of RFS use, the most appropriate are general reservation, reservation for subsystems, reservation of individual elements.

The general view of the structural scheme of RFS reliability with the reservation of individual elements [30] is shown in Fig. 6.

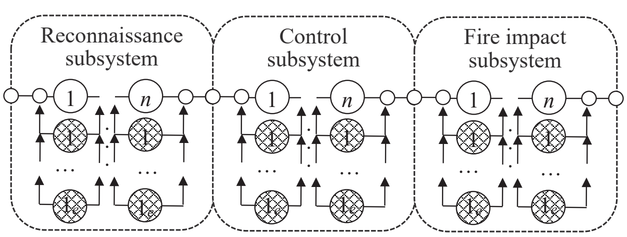

Fig. 6. Block diagram of reliability using reservation of individual elements

The results of the analysis using the reservation of individual elements indicate that this reservation can be applied to all elements of RFS. The advantage of this type of reservation is that the maximum possible saving of reserve elements is carried out because if one of the main elements fails, only one backup element is used.

The disadvantage of this approach is that it is necessary to create a more complex organizational structure and develop an additional procedure for including reserve elements. That is, this type of reservation is possible in the case when there is enough time to prepare for combat use. Also, a disadvantage of this type can be considered an increase in the possibility of failure of communication lines. Although in the study this parameter is taken as a limitation, it should be noted that a greater number of communication lines will objectively lead to more failures. That is, to perform important tasks, it is advisable to consider other types of reservation.

The next type of reservation is reservation for subsystems [31]. The essence of this reservation is to create backup chains in each RFS subsystem.

The general view of the structural scheme of RFS reliability with reservation for subsystems is shown in Fig. 7.

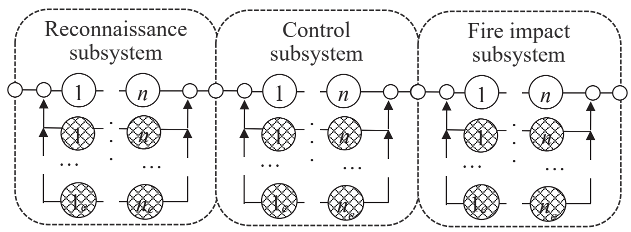

Fig. 7. Block diagram of the reliability of the reconnaissance fire system using reservation for subsystems

Regarding the use of this type of reservation, such as reservation for subsystems, it should be noted that this reservation is applicable to all RFS subsystems. The advantage of this type of reservation is that the organizational structure remains distributed by subsystems, and the inclusion procedures for reservation for individual elements are simpler. The disadvantage of this type of reservation is that there is an overrun of the resource of the reserve elements because even if only one element failed in the main chain, it is necessary to include the entire backup chain.

The essence of the general reservation is that backup RFS is created, which are included if the main RFS chain failed [32].

The general view of the structural scheme of reliability of RFS with a general reservation is shown in Fig. 8.

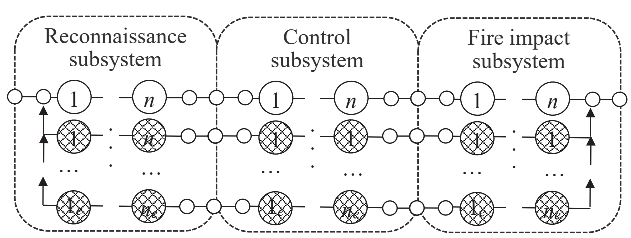

Fig. 8. Block diagram of the reliability of the reconnaissance fire system using general reservation

The application of a general reservation is a common approach to RFS reservation. Moreover, quite often the reserve elements in the backup RFS are not similar to the main RFS, but in this case there is a functional reservation. That is, such separate structural and functional elements are used that correspond to others in this RFS and make it possible to perform the task in the planned volume. This feature is the main advantage of such a reservation. At the same time, the main disadvantage of this type of reservation is the largest, compared to other types, consumption of the resource of reserve elements because the failure of at least one main element will lead to the need to include a backup RFS.

Thus, the results of the analysis of possible types of reservation of individual functional elements of RFS indicate that in relation to the active and passive reservation, it is the active that is more appropriate. In particular, because the input time of the active backup element takes less time. This can be key in a combat environment where efficiency is measured in seconds, and in some cases fractions of a second. Therefore, despite the functional suitability of the passive reservation, the study proposes to take into account this important factor.

Regarding sliding reservation, it should be noted that it is most appropriate to use it for the fire exposure subsystem. This is explained by the fact that, as a rule, this subsystem is the largest in terms of the number of individual elements and, as a rule, several elements can be involved in the implementation of one task. Moreover, different types of elements of the fire subsystem, in many cases, can perform the same tasks with a given efficiency.

Given the peculiarity of the triple modular reservation, namely the choice by the majority, the area of use of the intelligence subsystem is expedient. This is explained by the fact that it is the intelligence subsystem that determines the input data for the functioning of the entire RFS. In practice, quite often, this is exactly what happens, that is, several means of reconnaissance are assigned to reconnaissance of one target, and then it is determined whether to take this target to defeat precisely by the majority criterion.

Regarding the types of reservation level, that is, reservation of individual functional elements, reservation by subsystems, and general reservation, it should be noted that the type of reservation will be determined depending on the conditions. The main of these conditions are the time to prepare for combat use, the availability of reserve elements, and the importance of a combat mission.

5. 2. Devising a methodology for determining the appropriate type of reservation of the reconnaissance and fire system

In accordance with the proposed definition of the concept of methodology, this is a sequential set of stages of activities to determine the appropriate type of reservation of RFS. Therefore, such a sequence in the coverage of this procedure is proposed – a description of the stages followed by the algorithm elucidation.

The results of the analysis of possible types of reservation of RFS show that without assessing their feasibility for certain conditions of combat use, it is impossible to create a stable and effective RFS [33].

At the first stage (block 2), it is necessary to determine the essence of the input data. One of the main input parameters is the characterization of failures to complete the task, in particular the intensity of failures per unit of time.

Regarding these failures, it should be noted that when studying RFS, it is necessary to take into account that refusals to perform functional tasks may arise under the influence of various reasons. Thus, the main reasons for the failure of individual functional elements of RFS can be marginal operating time, technical malfunctions, and the influence of the enemy. That is, the probability of failure to function of the system can be determined by the formula:

$$P(t)=e^{-(\lambda_w+\lambda_t+\lambda_s)t}, \quad (6)$$

where λ_w is the intensity of failures per unit of time due to marginal operating time; λ_t – failure intensity per unit of time due to technical malfunctions; λ_s – the intensity of failures per unit of time due to the influence of the enemy.

It is clear that the nature of these intensities will be different and, accordingly, the approaches to their definition will also be different, but the result of these failures will be the same in nature. That is, to determine the appropriate type of reservation, it does not matter what exactly the reason was that caused the refusal, the main thing is to provide for this failure.

The next input parameter is the operating time (t). This study proposes that the time of operation be taken equal to the time of execution of a single combat mission. Although for further research, this time may be equal to the time of a military (combat) operation and even the life cycle time of RFS.

The next group of input parameters is associated with the conditions for performing a combat mission. In particular, this is the importance of the task (Y), the number of reserve elements (n_e), the time to prepare for the combat mission.

Regarding the importance of a combat mission, it is proposed, within the study, to determine it through a dimensionless value of relative importance in the range from 0 to 1. It is proposed to take the following criteria: from 1 to 0.8 – extremely important tasks, from 0.8 (exclusively) to 0.5 – important, from 0.5 (exclusively) to 0 – planned.

The time to prepare for a combat mission has two components. The first is the time required to create an RFS (t_n), and it will have several values depending on the chosen reliability scheme. The second component is the time from receiving the preparation task to the moment of the start of the combat mission (t_p).

The time to complete a task is the time it takes to complete a combat mission by the available means (t_e) and the maximum possible time allotted for the performance of this task (t_{cri}).

The specified level of probability of trouble-free operation (P_l) is set before the start of the formation of RFS to determine the suitability of this composition for the task.

The next stage of the procedure (block 3) proposes to check the condition of not exceeding 70 % of the maximum possible time allotted for the performance of a combat mission ($t_e>0.7t_{cri}$). In the case when such a condition is met, a passive reservation is selected, otherwise active (block 4), because less time is spent to enter the active reserve.

The next step (block 5) is to check the sufficiency of the reserve elements ($n_e \geq n$). This will determine the possibility of a general reservation. If this condition is met, you can proceed to checking the sufficiency of the preparation time (block 6), if not, then it is necessary to check the sufficiency of the reserve elements for subsystems ($n_{e(r,c,f)} \geq n_{(r,c,f)}$) (block 6.1). If there is a sufficient number of backup elements for certain subsystems, then they are reserved for subsystems (block 6.2), in other subsystems – reservation for elements. Moreover, it is necessary to take into account if there are not enough elements in the subsystem of fire impact ($n_{e(f)}<n_{(f)}$) (block 6.3), then sliding reservation is made (block 6.4).

An important step is to check compliance with the condition of not exceeding the time required to create RFS time allotted for training for a combat mission ($t_p \geq t_n$) (block 6). If the time required to create exceeds the allotted time, a general reservation is made (block 7.1). Otherwise, the condition of compliance with the importance of the task is checked (block 7).

To take into account the importance of the combat mission, a check is carried out if the importance of the task is higher, equal to 0.8, a reservation is selected for elements with a triple modular reservation of reconnaissance equipment (block 8). If the importance is up to 0.8, but higher, equal to 0.5 (block 8.1), the reservation for elements is selected (block 6.5), otherwise the general reservation (block 7.1).

After selecting the types of reservation, a reliability scheme (block 9) is constructed and the probability of trouble-free operation of this RFS is calculated (block 10). In the case when the calculated probability is lower than the probability of a given one (block 11), an increase in the number of reserve elements is made (block 12.1).

The general view of the flowchart of the methodology for determining the appropriate type of RFS reservation is shown in Fig. 9.

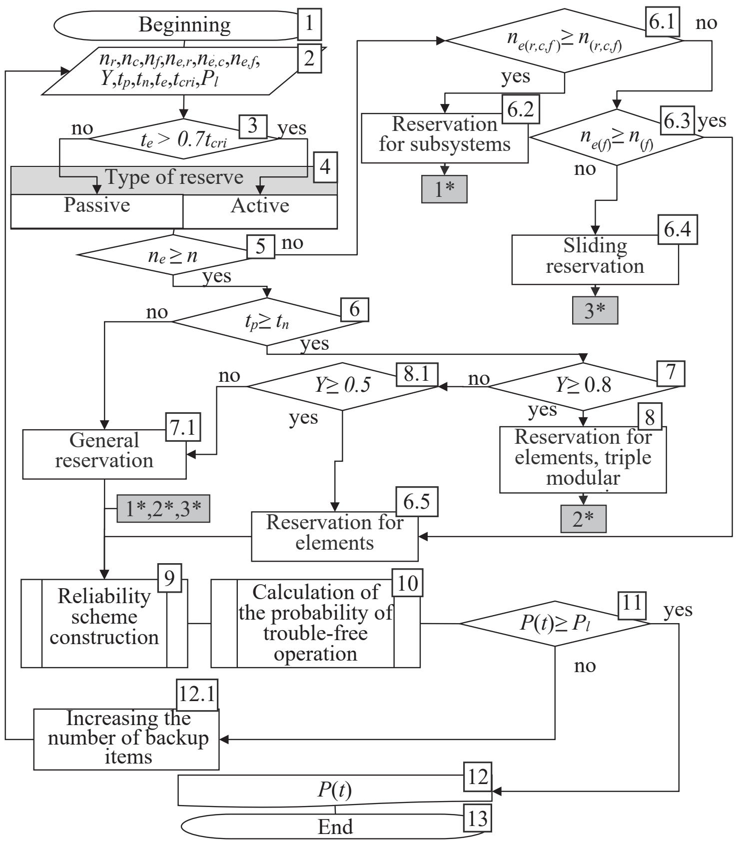

Fig. 9. General view of the flowchart of the methodology for determining the appropriate type of reservation of the reconnaissance and fire system

To verify our methodology, it is proposed to consider an example of its application.

Type of RFS proposed for modeling: tactical, single contour, single task, with adjustment function. Accordingly, such a RFS with the corresponding parameters defined as input data was subject to modeling.

Means of reconnaissance: UAV «Leleka-100» – 6 sets, 3 of which are included in the main reconnaissance module (n_r=3, $n_{e,r}$=3). These UAVs have the following failure intensities due to marginal operating time $\lambda_{w,r}$=0.01 h^{-1}, technical malfunctions $\lambda_{t,r}$=0.05 h^{-1}, enemy impact $\lambda_{s,r}$=0.1 h^{-1}.

Control means: set «Kropiva» – 2 sets, 1 of which are included in the main control module (n_c=1, $n_{e,c}$=1). These control sets have the following failure intensities due to marginal operating time $\lambda_{w,c}$=0.02 h^{-1}, technical malfunctions $\lambda_{t,c}$=0.06 h^{-1}, enemy impact $\lambda_{s,s}$=0.1 h^{-1}.

Means of fire exposure: light towed howitzers M777 – 8 units, 5 of which are included in the main module of fire exposure (n_f=5, $n_{e,f}$=3). These howitzers have the following failureal intensities due to marginal operating time $\lambda_{w,f}$=0.02 h^{-1}, technical malfunctions $\lambda_{t,f}$=0.03 h^{-1}, enemy effect $\lambda_{s,f}$=0.2 h^{-1}.

The target, which is intended for detection and destruction, is a battery of self-propelled howitzers MSTA-S (6 units). The target belongs to the category of important targets (Y=0.7). The total time allotted for preparation for the combat mission is 1 day (t_p=24 hours). The time of technical acquisition (creation) of the reconnaissance and fire circuit with these components should not exceed 20 hours (t_n=20 hours). The time required to hit this target is 3 hours (t_e=3 hours). The maximum possible time allotted for the performance of a combat mission should not exceed 5 hours (t_{cri}=5 hours).

After completing the task, the stability of the created RFS should not be lower than 25 % to perform further tasks (P_l > 0.25).

In accordance with the proposed methodology, the first step checks the sufficiency of the time to complete the task. In accordance with block 3 of the methodology, the condition corresponds to the use of a passive reservation.

In accordance with block 5 of the methodology, the number of backup elements does not correspond to the number of basic elements, so it is necessary to go to block 6.1 of the procedure. In accordance with the condition of this unit, the control and reconnaissance subsystem can be reserved for subsystems, and the fire impact subsystem can be reserved by sliding.

In accordance with block 9 of the methodology, a reliability scheme was created for the selected types of reservation (Fig. 10).

Further, in accordance with block 10 of the methodology, the probability of trouble-free operation was calculated. For this purpose, the formula for calculating the probability of trouble-free functioning of the proposed reservation scheme in accordance with (1) to (4) was derived:

$$P(t_e) = e^{-n_r \lambda_r t_e} \sum_{i=0}^{n_{e,r}} \frac{(\lambda_r t_e)^i}{i!} e^{-\lambda_c t_e} \times$$
$$\times \sum_{i=0}^{n_{e,c}} \frac{(\lambda_c t_e)^i}{i!} \sum_{i=n_{e,f}}^{n_{e,f}+n_f} C^i_{n_{e,f}+n_f} e^{-\lambda_f i t_e} \left(1-e^{-\lambda_f t_e}\right)^{n_{e,f}+n_f-i} =$$
$$= e^{-3t_e 0.16} \sum_{i=0}^{3} \frac{(0.16 t_e)^i}{i!} e^{-0.18 t_e} \times$$
$$\times \sum_{i=0}^{1} \frac{(0.18 t_e)^i}{i!} \sum_{i=3}^{8} C_8^i e^{-0.25 t_e i} \left(1-e^{-0.25 t_e}\right)^{8-i}, \qquad (7)$$

where λ_r is the total failure intensity from all sources of elements of the intelligence subsystem, $\lambda_{w,r}+\lambda_{t,r}+\lambda_{s,r}$= =0.01+0.05+0.1=0.16; λ_c – total failure intensity from all sources of control subsystem elements, $\lambda_{w,c}+\lambda_{t,c}+\lambda_{s,c}$= =0.02+0.06+0.1=0.18; λ_r – total failure intensity from all sources of elements of the fire subsystem, $\lambda_{w,f}+\lambda_{t,f}+\lambda_{s,f}$= =0.02+0.03+0.2=0.25; t_e – the time of task completion, which according to the conditions of the example is 3 hours (for modeling, a step of 0.5 hours was taken).

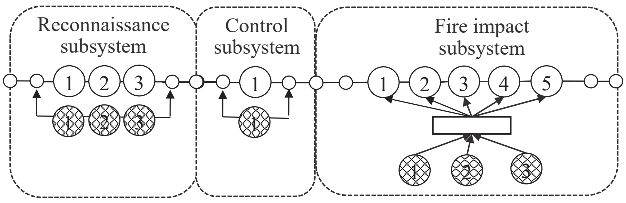

Fig. 10. The scheme of reliability of the reconnaissance and fire system with the types of reservation selected in accordance with the proposed methodology

To analyze the dynamics of changes in the probability of trouble-free functioning, it is proposed to calculate with a time step of 0.5 hours. Also, to determine the advantage of the proposed methodology, a calculation was made for RFS created according to existing approaches. That is, the use of one type of reserve (active or passive). For accepted conditions, it is advisable to use a passive reservation. Thus, the reliability scheme for such an RFS will take the following form (Fig. 11).

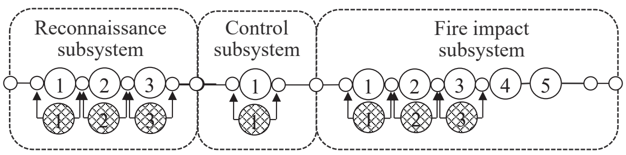

Fig. 11. The reliability scheme of the reconnaissance and fire system with the type of reservation selected in accordance with existing approaches

Accordingly, the formula for calculating the probability of trouble-free functioning in accordance with (1) and (3) will take the form:

$$P(t_e)=\left(e^{-\lambda_r t_e}\sum_{i=0}^{n_{e.r}}\frac{(\lambda_r t_e)^i}{i!}\right)^{n_r} e^{-\lambda_c t_e}\times$$
$$\times\sum_{i=0}^{n_{e.c}}\frac{(\lambda_c t_e)^i}{i!}\left(e^{-\lambda_f t_e}\sum_{i=0}^{n_{e.f}}\frac{(\lambda_f t_e)^i}{i!}\right)^{n_f} e^{-\lambda_f t_e n_f}=$$
$$=\left(e^{-0.16t_e}\sum_{i=0}^{3}\frac{(0.16t_e)^i}{i!}\right)^{3} e^{-0.18t_e}\times$$
$$\times\sum_{i=0}^{1}\frac{(0.18t_e)^i}{i!}\left(e^{-0.25t_e}\sum_{i=0}^{3}\frac{(0.25t_e)^i}{i!}\right)^{3} e^{-0.25t_e 2}. \quad (8)$$

The results of calculations according to formulas (7) and (8) with intermediate results (calculation of the probability of trouble-free functioning by subsystems) are given in Table 1.

It should be noted that Table 1 shows the results of calculations using formulas (7) and (8), carried out using Microsoft Excel 2010. At the same time, the input data for these formulas are the data specified as the input data of the example application of our methodology. The results of the analysis of our results (Table 1) are represented in the form of dependence plots of the change in the probability of trouble-free functioning of RFS created according to existing approaches and according to the proposed methodology on the time of operation (Fig. 12).

Table 1

Results of calculations of the probability of trouble-free functioning of RFS with intermediate results (calculation of the probability of trouble-free operation by subsystems)

Time	Probability of trouble-free operation							
	according to the proposed methodology				according to existing approaches			
	reconnaissance	control	fire impact	RFS	reconnaissance	control	fire impact	RFS
5	0.200	0.910	0.414	0.075	0.529	0.910	0.022	0.011
4.5	0.235	0.925	0.510	0.111	0.587	0.925	0.035	0.019
4	0.277	0.938	0.614	0.160	0.647	0.938	0.054	0.033
3.5	0.325	0.951	0.719	0.223	0.708	0.951	0.083	0.056
3	0.382	0.963	0.816	0.301	0.768	0.963	0.126	0.093
2.5	0.449	0.974	0.897	0.392	0.826	0.974	0.189	0.152
2	0.527	0.982	0.954	0.494	0.881	0.982	0.277	0.240
1.5	0.619	0.990	0.986	0.604	0.928	0.990	0.399	0.366
1	0.726	0.995	0.998	0.721	0.966	0.995	0.560	0.538
0.5	0.852	0.999	1.000	0.851	0.991	0.999	0.762	0.754
0	1	1	1	1	1	1	1	1

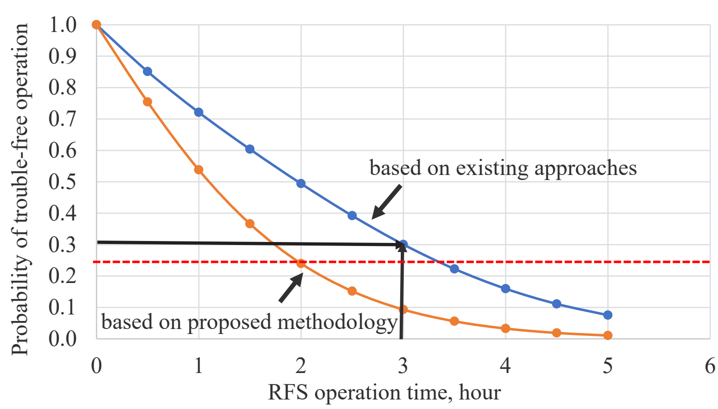

Fig. 12. Dependence plots of changes in the probability of trouble-free functioning of reconnaissance and fire systems created according to existing approaches and according to the proposed methodology on the time of operation

Analysis of our results (Fig. 12, Table 1) show that the proposed methodology makes it possible to increase the likelihood of trouble-free functioning of RFS under equal conditions relative to existing approaches. This is explained by the fact that the selection of the appropriate type of reservation in accordance with the conditions for performing a combat mission provides resource savings for both individual functional elements and subsystems. This, in turn, causes a longer time of operation.

Basic assumptions: the influence of the enemy on the elements of RFS depends on the activity of these elements; the introduction of backup elements takes less time than completing one task to identify and hit the target. Next, all sources of failures are grouped into three: marginal operating time, technical malfunctions, and enemy effect.

The limitation of this procedure is that the intensity of refusals to perform a task by individual functional elements of RFS is subject to the exponential law of distribution of random variables.

The main simplification is that individual functional elements, including backup ones, within the same subsystem have the same failure rate.

It should also be noted that during the verification of the proposed methodology, it was revealed that RFS created using this procedure makes it possible to perform a combat mission. While according to existing approaches, it is necessary to increase the number of reserve elements. For example, the increase in the probability of trouble-free functioning of RFS averages 20 %. It is clear that the specified value of the indicator increase requires more detailed research but it should be noted that the selection of the type of reservation in accordance with the conditions for performing a combat mission will provide a better result in most cases.

6. Discussion of results of the development of a scientific and methodological apparatus for determining the appropriate type of reservation of the reconnaissance and fire system

The possible types of reservation of individual functional elements of RFS are analyzed and it is established that the active reserve (Fig. 2, (2)) is more operational than the passive one (Fig. 3, (3)). This is explained by the fact that the inclusion of an active reserve (Fig. 2, (2)) takes less time because it is already functioning and performing the same operations as the main element.

Also, during the analysis, it was established that sliding reservation (Fig. 4, (4)) is most functionally suitable for the fire exposure subsystem. This is due to several factors. First, as a rule, the means of fire influence in RFS are more than the means of control and reconnaissance, and the number of reserve fire means (Fig. 4, (4)), as a rule, does not coincide with the number of basic elements. Secondly, as a rule, several fire means may be involved in the implementation of one combat mission, that is, the withdrawal of any of these means can lead to disruption of this task completion.

The next element of the analysis was triple modular reservation (Fig. 5, (5)). It has been established that the intelligence subsystem is the most appropriate subsystem for the use of this type of reserve. This is explained by the fact that the triple modular reservation (Fig. 5, (5)) makes it possible to get more reliable information than with other types of reservation. Moreover, the intelligence subsystem forms input data for the entire RFS, which causes increased attention to reliability.

In addition, during the analysis, the factors that most influence the type of reservation were identified, in particular, the time for preparation for combat use, the presence of reserve elements, and the importance of a combat mission.

The peculiarity of the proposed analysis is its comprehensive nature, that is, unlike existing studies [7, 13], where only a few types of reservation are analyzed and only for certain conditions, our analysis makes it possible to take into account the peculiarities of the types of reservation (Fig. 2–8). This becomes possible by taking into account the influence of each RFS subsystem on the functioning of RFS as a whole.

Identifying the peculiarities of the types of reservation close the problematic part of the justification of the appropriate type of RFS reservation in relation to compliance with the conditions for the application of these RFSs. This allows us to develop a methodology for determining the most appropriate type of reservation, depending on the conditions and factors of RFS functioning.

The above-mentioned makes it possible to eliminate part of the existing problem of the unsuitability of the existing scientific and methodological apparatus to substantiate the expedient type of reservation of RFS under specific conditions for performing a combat mission related to the compliance of a certain type of reserve with certain conditions.

The limitations of this analysis are that all sources of failures in the elements of RFS are grouped into three sources that have a different nature, but the same result. This is taken into account when applying the results of the analysis in practice ((7), (8)), as well as in further theoretical studies (6).

The disadvantage of the proposed analysis is the consideration of RFS subsystems as one reservation site. This somewhat narrows the scope of the results of this analysis, but the identified features and factors are appropriate and can be applied both to RFS subsystem in general and to the reservation areas.

The development of the analysis of types of RFS reservation can be continued in the direction of analysis of appropriate types of reservation in the case of partitioning RFS subsystems into reservation areas. This will significantly expand the scope of the proposed analysis and will increase the efficiency of reservation in general.

A methodology for determining the appropriate type of RFS reservation has been developed (Fig. 9). The essence of the procedure is in the selection of the type of reservation, which is most suitable for the specific conditions for the use of RFS. This procedure makes it possible to increase the stability of the functioning of RFS (Fig. 12, Table 1) on average (for accepted, within the example, conditions) by 20 %. This is explained by the fact that the use of the type of reservation that most closely meets the accepted conditions (Fig. 10, (7)) saves the resource of the elements of RFS, provided that the task is completed.

A feature of the proposed procedure is that the type of reservation is selected in accordance with the conditions of each task. That is, in contrast to existing approaches [8, 10–12] (Fig. 11, (8)), where one type of reservation is used for all subsystems, the proposed method allows minimizing the cost of performing a combat mission with its guaranteed execution.

The proposed methodology closes the problematic part of the justification of the appropriate type of RFS reservation, which concerns the procedure and rules for choosing the appropriate type of reservation. This makes it possible to save resources and ensure the implementation of the combat mission (Fig. 12).

The limitation of this procedure is that the intensity of refusals to perform a task by individual functional elements of RFS is subject to the exponential law of distribution of random variables (1).

The disadvantage of the proposed methodology is that when choosing the appropriate type of reservation, it is accepted that individual functional elements, including reserve ones, within the same subsystem have the same failure rate. However, it should be noted that it is possible to take into account the intensity of failures for each individual functional element, although the calculated formula (7) will become significantly more complicated.

Further research to improve the proposed methodology may involve determining the appropriate types of reservation in the case of reservation by area.

7. Conclusions

1. Possible types of reservation of individual functional elements of RFS have been analyzed. Based on the results of the analysis, appropriate types of reservation were established, in particular, active, passive, triple modular reservation, sliding, distributed, by subsystems, and general reservation. The peculiarity of this analysis is that it was carried out taking into account the peculiarities of the functioning of RFS as a whole. A distinctive feature of this analysis is that the analysis took into account the conditions for performing the combat mission of RFS. This makes it possible to eliminate the existing problem associated with the complexity of the use of RFS in a combat situation. The results of this analysis allow us to determine the most appropriate type of reservation, depending on the conditions for performing a combat mission. The area of application of the results of the proposed analysis are the management processes associated with the creation, layout, and application of RFS in military administration bodies.

2. A methodology for determining the appropriate type of RFS reservation has been developed. The essence of the procedure is to determine, in accordance with the conditions of combat use, the appropriate type of reservation, the creation of a reliability scheme, and the calculation of the stability indicator of this RFS. The proposed methodology ensures an increase in the stability of the functioning of RFS by an average of 20 % for the conditions accepted, within the framework of the example. A feature of the proposed methodology is the choice of the type of reservation in accordance with the conditions for the implementation of each combat mission. A distinctive feature of this procedure is the use of this type of reservation, which saves the resource of the elements of RFS, provided that the task is completed. The above makes it possible to solve part of the problem of the unsuitability of existing scientific and methodological apparatus to substantiate the appropriate type of reservation for RFS, taking into account the conditions for performing a combat mission, in particular regarding the order and procedure for creating and composing RFS. The area of application of the proposed methodology is the management processes associated with the planning and determination of the projected effectiveness of hostilities by military command bodies.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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