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Institute of Logistics
Faculty of Security, Logistics and Management
Military University of Technology
in Warsaw

Reliability issues of combat means

Piotr Kasprzak
Piotr.Kasprzak@witpis.eu; ORCID: 0000-0002-8911-4682
Research Division, Military Institute of Armored and Automotive Technology, Poland

Jan Figurski
figurskij@witu.mil.pl; ORCID: 0000-0002-6389-5759
Center for explosives and warfare agents, Military Armament Technical Institute, Poland

Tomasz Chmura
chmurat@witu.mil.pl; ORCID: 0009-0004-4978-2856
Center for Small Arms and Ballistic Shields, Military Armament Technical Institute, Poland

Abstract. The article addresses the fundamental functional prerequisites necessary to ensure the reliability of combat assets during their operational use. It outlines and characterizes the functional components of reliability within systems exhibiting both series and parallel configurations. The quantifiable aspect of reliability encompasses the critical conditions required for these structural configurations to function effectively. Based on the analyzed reliability components, key availability indicators were defined, along with exemplary values that these indicators may assume for various categories of combat assets. These indicators constitute the basis for determining prognostic parameters, which are capable of characterizing the reliability behavior of a combat asset throughout its operational life cycle. The research contribution of the article lies in demonstrating the practical applicability of reliability theory to the domain of combat assets. The primary objective of the research was to identify and describe the correlations between reliability issues and combat systems, whose operational condition requires ongoing monitoring. As demonstrated, the principles of reliability theory provide an accurate framework for describing failure mechanisms and operational degradation processes in such assets. The article includes illustrative calculations of reliability indicators for a notional combat system, based on practical research experience with real-world military assets. It is shown that weapon systems may be analyzed within the framework of reliability engineering, similarly to other types of technical equipment whose performance and failures can be described using mathematical models. The scheduling and scope of maintenance and repair activities are generally defined in applicable technical documentation (where available). However, the detailed procedures and workflows are usually developed at the initiation of operational deployment and are subsequently refined and expanded in response to service experience and feedback. Given the ongoing modernization of armaments within the

Polish Armed Forces, there is a critical need for the continuous enhancement of test methodologies and diagnostic tools used in the evaluation of emerging combat systems. This underscores the importance of adapting research infrastructure and instrumentation to meet current and future technical requirements
Keywords: combat means, reliability, reliability structures, life cycle of combat means, exploitation

Introduction

All companies (organizations, enterprises) are composed of individual units (employees), each of whom differs in their understanding and execution of assigned tasks. When such a group is left unsupervised, it tends to operate in a disorganized manner, even if each member is genuinely striving to perform at their best. This results from two primary factors: a lack of coordinated actions and a natural tendency to simplify tasks. The method of task execution should not be left to the discretion of rank-and-file employees, as this leads to arbitrary behavior. Such a system stands in stark contrast to a structured and organized approach, which can be broadly defined as a “management system.”

A similar situation occurs when ensuring the reliability of combat assets. In this context, order and structure are achieved by clearly defining who issues commands, who executes them, and who is responsible for recording what, when, where, and how. Within such a system, particular attention must also be given to identifying special-case issues and formulating predictable preventive or corrective measures. This knowledge is fundamental to the effective operation of any organization or process.

Another key aspect concerns process logistics and economic principles. These allow for a comprehensive understanding of employee motivation and the natural variability of elements within a process. According to the *Polish Language Dictionary* (PWN, 2002), a process is defined as a sequence of causally linked changes occurring over time. In process-based thinking, it is crucial to recognize that every activity requires a certain amount of time and the appropriate resources for its completion.

The effective functioning of combat assets is essential for the operational performance of weapons systems. Their design and components should exhibit high functional reliability, extended service life, and a simple, modular construction. Technical reliability is also a key element of the comprehensive assessment of a combat asset’s effectiveness (Olsson, 2020, pp. 93–107)

This implies conformity of their functional components with normative requirements as well as user expectations**.** It should be emphasized that reliability refers to the probability that a system or component will perform its intended function without failure under specified conditions for a given period of time. In order to provide a universal and comprehensive description, it is necessary to present certain functions of combat asset components. In this context, the durability of combat assets—defined as the time during which the system retains its operational properties—is also of great importance.

Characteristics of structures

One of the essential elements in the characterization of the reliability and proper functioning of combat assets is the reliability structure, which is designed according to the system's intended function. Reliability structures of combat assets are developed based on their functional applications. The blocks or components of the structure are interconnected according to functional dependencies. It is assumed that the reliability of a technical system is understood as the probability of the system fulfilling its intended function without failure over a given period of time, or as the probability that changes in specific system properties will not exceed certain predefined limits under specified operating conditions (Szelmanowski, Pazur, et al., 2024, p. 69).

Various types of structures can be identified in a functional process. These include the main types—series and parallel structures—as well as hybrid configurations such as series-parallel and parallel-series structures. There are also other structural types, such as threshold, complex, bridge, and sequential linear *k-out-of-n* systems (where $k < n$).

The series reliability structure, represented in the block diagram in Figure 1, is based on the assumption that the failure of any component within the system is independent of the failures of the other components. This assumption is made to simplify the modeling process.

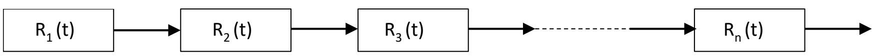

Fig. 1. Diagram of the series reliability structure
Source: own study

To calculate the analytical reliability of a series structure, the reliability function R(t) is determined under the assumption that nnn represents the number of components in the combat asset. The reliability function for a series system is expressed as follows:

$$R_s(t)=R_1(t) \cdot R_2(t) \cdot R_3(t) \cdot \ldots\ldots \cdot R_n(t) \tag{1}$$

or more generally:

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \tag{2}$$

Since the reliability function is based on an exponential distribution, the failure rate λ\\lambdaλ (lambda), representing the failure intensity, is constant over time. Consequently, the reliability function in its analytical form is expressed as:

$$R_s(t) = e^{-\lambda 1t} \cdot e^{-\lambda 2t} \cdot e^{-\lambda 3t} \cdot \ldots \cdot e^{-\lambda nt} \tag{3}$$

therefore:

$$R_s(t)=exp[-\lambda(t) \cdot t] \tag{4}$$

where:

$$\lambda=\lambda_1+\lambda_2+\lambda_3+ \ldots +\lambda_n =1/\theta \tag{5}$$

In this case, the failure rate λ is the sum of the failure rates of all components within the given system (combat asset). Therefore, the mean time to failure (MTTF) of the system can be expressed as:

$$\theta = \frac{1}{\lambda} \tag{6}$$

The correct operation of a combat asset under this structure implies that if any component fails, the entire system is considered to have failed. Consequently, the reliability of the entire system cannot exceed the reliability of its weakest component.

When applying a parallel reliability structure, it is assumed that the system continues to function until all its components have failed. The block diagram (Figure 2) of such a structure is relatively simple, and importantly, it assumes no interdependence between system components in this configuration.

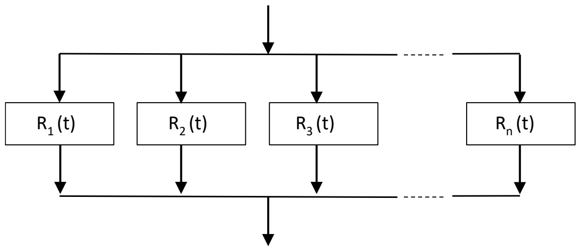

Fig. 2. Diagram of the parallel reliability structure
Source: own study

In a parallel structure, the reliability function R(t) is replaced by the failure (unreliability) function *Q* (t). In this case, the probability of failure for each individual system component can be approximated by the following expression:

$$Q_i\,(t) = 1 - R_i\ (t) = 1 - e^{-\lambda it} = 1 - exp(-\lambda(t))\cdot t \tag{7}$$

Accordingly, the failure probability of the entire system can be expressed as:

$$Q_s\,(t) = Q_1(t)\cdot Q_2(t)\cdot Q_3(t)\cdot\ldots\ldots\cdot Q_n(t) \tag{8}$$

or more generally:

$$Q_s = \prod_{i=1}^{n} Q_i(\mathrm{t}) \tag{9}$$

Hence, the system reliability can be derived as:

$$R_s = 1 - Q_s \tag{10}$$

Parallel structures are significantly more reliable than series configurations. Such designs are often referred to as redundant systems, meaning they include more components than strictly necessary to fulfill minimum requirements. Redundancy may be perceived both positively and negatively: it can lead to unnecessary consumption of resources and potential inefficiencies, or be highly desirable as a safeguard against component failure.

Typically, complex system architectures involve combinations of series and parallel structures (Figurski, 2021, p. 129-134). One such example is the series-parallel reliability structure, schematically illustrated in Figure 3.

To calculate the reliability of a combat asset configured in a series-parallel structure, the following relation is applied:

$$Rrs(t) = 1 - \prod_{i=1}^{z}\cdot\left(1 - \prod_{j=1}^{m}\cdot exp(-\lambda ij\ (t)\cdot t)\right) \tag{11}$$

where: z – number of subsystems connected in series,

m – number of elements within each subsystem connected in parallel.

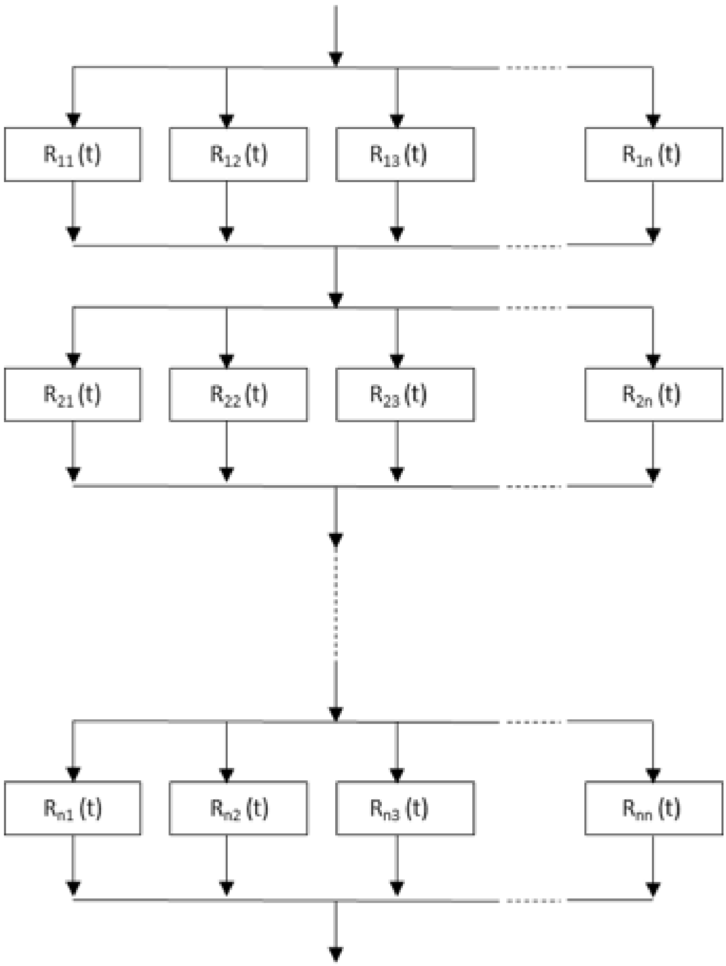

Fig 3. Schematic Representation of the Series-Parallel Reliability Structure
Source: own study

The reliability structures described above, which underpin the functioning of combat assets, are essential for estimating the readiness level of such systems. These estimations are associated with various readiness indicators. Maintaining these indicators at the required levels necessitates the replacement of components or subsystems of combat assets. Consequently, this generates a need for adequate research and maintenance infrastructure, spare parts, and consumable materials, all of which contribute to increased operational costs. Therefore, accurate estimation of readiness for parallel functional subsystems in combat assets is of great importance.

Technical readiness indicators

The forecasting of combat asset readiness is characterized by two primary indicators:

Readiness function

$$Wg(t)=exp(-\lambda(t)\cdot t) \tag{12}$$

Failure-related readiness function

$$Wz(t)=1- exp(-\lambda(t)\cdot t) \tag{13}$$

The readiness indicator Wg(t) can be described as the system's capability to meet operational requirements within a specified time frame, assuming the availability of necessary external resources. These indicators are defined through functional probability distributions, and their analytical forms are expressed as follows:

$$\lambda(t) = \frac{n(t)}{t} \tag{14}$$

where: n(t) – the number of failed components at time t,

t – the duration of component operation up to the moment of analysis.

Forecasting is based on determining the value that ensures the specified readiness level Wg(t) during the planned operational periods. At a given point in time ttt, both the failure intensity values λ(t) and the corresponding readiness indicators are analyzed. To illustrate an example of the readiness indicator determination process and readiness-related dependencies, a munition depot was considered, in which combat assets are stored over a period of 10 years. Combat assets fall under the category of hazardous materials. Their technical condition directly affects decision-making and operational activities across various domains of resource management, including the organization of transportation and delivery planning (Kalbarczyk, Kler, 2023, pp. 111–128). As a representative of the combat asset population, a specific combat asset was selected, whose construction schematic is presented in Figure 4.

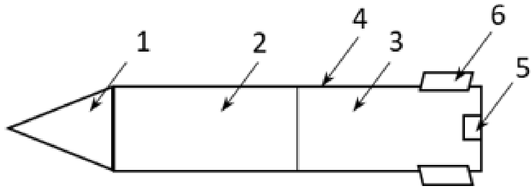

Fig. 4. Schematic representation of a combat asset:1 – fuze, 2 – explosive charge, 3 – propellant charge, 4 – casing of the device, 5 – ignition element, 6 – control element

Source: own study

During the operational lifecycle of a combat asset—including inspection, transport, maintenance, and other processes—its components may become damaged. Sample data regarding the number and intensity of such failures are presented in Table 1.

Table 1. Assumed Number of Failures, Calculated Failure Intensities, and Indicator Values for the Combat Asset

Lp.	damaged element	n(t)	λ(t)	Wg (t)	Wz (t)
1	Fuze	1	1.1416E-05	0.9048	0.0952
2	Explosive Charge	3	3.4247E-05	0.7408	0.2592
3	Propellant Charge	5	5.7078E-05	0.6065	0.3935
4	Casing of the Device	2	2.2831E-05	0.8187	0.1813
5	Ignition Element	6	6.8493E-05	0.5488	0.4512
6	Control Element	4	4.5662E-05	0.6703	0.3297

Source: own study

Based on the data presented in Table 1, the values of *n(t)*—the number of failures over time - were assumed. Subsequent columns of the table include values calculated in accordance with the previously defined formulas for failure intensity *λ(t)*, readiness coefficient *Wg(t)*, and unavailability coefficient *Wz(t)*. The failure intensity *λ(t)* was determined based on the operational time *t* of the combat asset. Below is a sample calculation procedure for the fuze component. The time span for operation and data collection is 10 years, which approximates to *t ≈ 87 600 hours* (total hours over 10 years):

$$\lambda(t) = \frac{1}{87600} = 1.1416 \cdot 10^{-5}$$

This approach was used to calculate the time-dependent failure intensity *λ(t)* for each component block. The values of the readiness coefficient *Wg(t)* and the unavailability coefficient *Wz(t)* were calculated using Equation (12). The prediction time for readiness was set to one year (*t = 8 760 h*).

Accordingly, the sample calculation for the fuze is as follows:

$$Wg(t)= \exp(-1.1416\ 10^{-5} \cdot 8760)=0.9048$$

$$Wz(t)= 1 - 0.9048=0.0952$$

Using this scheme, the values of *Wg(t)* and *Wz(t)* were calculated for each of the remaining component blocks. Analysis of the computed values summarized in

Table 1 reveals a direct correlation between the failure intensity *λ(t)* and the readiness coefficient *Wg(t)*—as the number of failures increases, the projected readiness decreases. The operational period of the combat asset also significantly affects this indicator. Since *Wg(t)* follows an exponential structure, it allows for analyzing the operational readiness of a combat asset over successive years of use. Based on the above computations, a forecast of the readiness of each component of the combat asset as a function of time can be determined for an operational lifespan of 0–10 years. To accomplish this, the base time coefficient $t = 8\,760\ h$ (1 year) is multiplied by the number corresponding to each respective year. The calculation results are presented in Table 2.

Table 2. Readiness Indicator Values for Combat Asset Component

t	$Wg_1(t)$	$Wg_2(t)$	$Wg_3(t)$	$Wg_4(t)$	$Wg_5(t)$	$Wg_6(t)$
0	1	1	1	1	1	1
1	0.9048	0.7408	0.6065	0.8187	0.5488	0.6703
2	0.8187	0.5488	0.3679	0.6703	0.3012	0.4493
3	0.7408	0.4066	0.2231	0.5488	0.1653	0.3012
4	0.6703	0.3012	0.1353	0.4493	0.0907	0.2019
5	0.6065	0.2231	0.0821	0.3679	0.0498	0.1353
6	0.5488	0.1653	0.0498	0.3012	0.0273	0.0907
7	0.4966	0.1225	0.0302	0.2466	0.0150	0.0608
8	0.4493	0.0907	0.0183	0.2019	0.0082	0.0408
9	0.4066	0.0672	0.0111	0.1653	0.0045	0.0273
10	0.3679	0.0498	0.0067	0.1353	0.0025	0.0183

Source: own study

An analysis of the results presented in Table 2 assumes that at time $t = 0$, the readiness coefficient *Wg(t)* is equal to 1. This is because, at that moment, all system components are considered new. In every idealized system used to describe failure intensity—particularly those concerning combat assets—three distinct phases can typically be identified:

- Initial phase, during which manufacturing defects, incomplete assembly, labeling deficiencies, and other faults are identified, usually at the acceptance or inspection stage;
- Guaranteed operational phase, characterized by a low rate of failures and rare occurrences of nonconforming performance;
- System aging phase, during which the number of failures increases, requiring regular diagnostics and the systematic exclusion of hazardous or noncompliant combat assets from operational use.

Based on Table 2, readiness function plots *Wg(t)* were generated for each component of the combat asset.

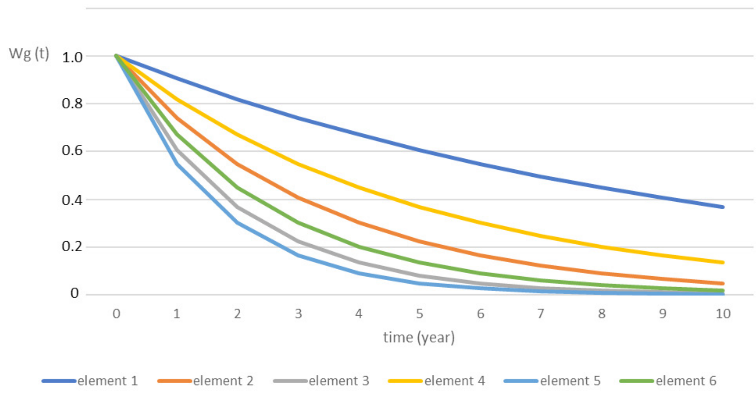

Fig. 5. Readiness Function Wg(t) Plot for the investigated combat asset components over time
Source: own study

To avoid overlapping data series, it was initially assumed that each component experienced a different number of failures. Preparing this type of data processing arrangement for combat assets is particularly beneficial within logistical systems, especially when there is a need for early requisitioning of components likely to require replacement.

Combat asset reliability index

To enhance the performance of systems responsible for maintaining a combat asset in a state of technical readiness for use, its reliability distribution is presented in order to determine its reliability index. For this purpose, a reliability threshold (β) that satisfies the user is defined for the entire system. This threshold determines whether the system requires intervention in the form of maintenance, repair, component replacement, etc. These conditions are analyzed for a system with a series-parallel structure described using the technical readiness index expressed by Equation (11). Assuming the reliability function value for the analyzed system is at the level of $\beta(t) = 0.7$, a system with the structure shown in Figure 6 is examined. The diagram utilizes data obtained during previous calculations (rounded to two decimal places)

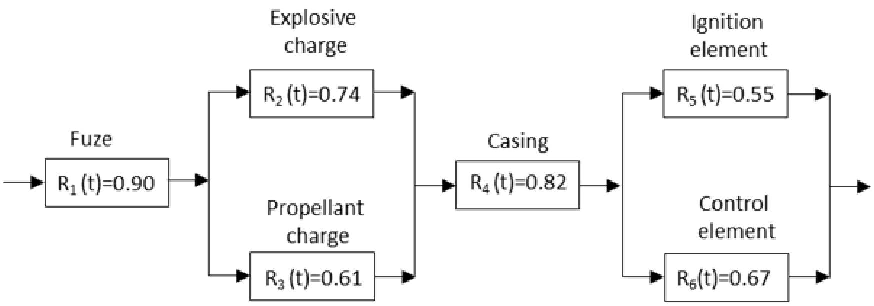

Fig. 6. Example structure of a combat asset
Source: own study

To calculate the reliability of the above structure, it must first be decomposed into its basic components. It can be observed that the system consists of two series structures and two parallel structures. Parallel structures are calculated using the failure function Q(t); therefore, they should be evaluated first, and then expressed in the form of the reliability function R(t)=1 – Q(t). This configuration is then calculated as a series structure as follows:

$Q_2(t)= 1-0.74=0.26$

$Q_3(t)= 1- 0.61= 0.39$

$Q_{23}(t)= 0.26 \cdot 0.39= 0.1014$

$R_{23}(t)= 1 - Q_{23}(t) =0.8986$

Analogous calculations are carried out for the remaining subsystems and their associated functions:

$Q_5(t)=1-0.55= 0.45$

$Q_6(t)=1-0.67=0.33$

$Q_{56}(t)=0.45 \cdot 0.33= 0.1485$

$R_{56}(t)= 1 - Q_{56}(t) = 0.8515$

The next step is to present the simplified reliability structure of the warfare agent as presented in Figure 7.

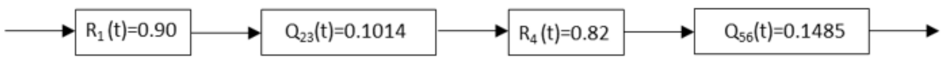

Fig. 7. Simplified reliability diagram of the combat system structure
Source: own study

The simplified diagram of the combat system consists of both parallel and series structures; therefore, the failure functions $Q_{34}(t)$ and $Q_{56}(t)$ must be converted into reliability functions $R_{34}(t)$ and $R_{56}(t)$ respectively. The calculation procedure is as follows:

$R_{ŚB}(t)= R_1(t) \cdot (1 - Q_{23}(t)) \cdot R_4(t) \cdot (1 - Q_{56}(t))$

$R_{\acute{S}B}(t) = 0.90 \cdot (1 - 0.1014) \cdot 0.82 \cdot (1 - 0.1485) = 0.56$

After completing the calculations, the assumed reliability function value of $\beta(t) = 0.7$ is not met, as the result obtained from the equation is:

$R_{\acute{S}B}(t) = 0.56$

which is below the expected threshold.

The structural configuration of the combat system does not fulfill the specified reliability requirements. To meet these criteria, it is necessary to consider the critical points of the system—those with the lowest reliability (i.e., the highest failure rates over time). To improve reliability, multiple approaches can be undertaken, such as modifying or upgrading the element, or replacing it with a new one. Once elements are replaced with new units, their reliability becomes equal to one, thereby ensuring the system's overall reliability function meets the assumed requirements. Based on the aforementioned relationships, one can determine the replacement schedules of system components to ensure the reliability of the entire system remains within acceptable limits.

A significant challenge in forecasting the reliability functions of combat system components is the determination of the reliability or failure function of the analyzed elements. Typically, previously calculated readiness indicators are used. However, when historical data on the examined elements is unavailable, it is recommended to construct a dedicated testing platform for reliability assessments. This platform should take into account the functional parameters, operating conditions of the structural components, as well as the total operational time of the combat system.

As a result of such reliability testing, a dataset $Z(t)$ is obtained, comprising n elements of the combat system, described by the following relation:

$$Z(t) = [\{ B_j(t), E_j(t) \}]^n \tag{15}$$

where: Bj(t) – number of assemblies within the combat system,
Ej(t) – number of individual components in the combat system.

This dataset serves as the foundation for planning and executing maintenance and repair processes, and should be continuously updated with new information. It is important to emphasize that the validity of all such analyses is contingent on the consistent and accurate integration of data into the system.

Conclusions

This article presents the fundamental conditions for assessing the functional reliability of combat systems. The analytical process considered two primary types of structural configurations: series and parallel, as well as a mixed structure. These structures are most commonly found in the design of combat systems. The reliability level of the combat system in each structural configuration was determined, along with predictive values based on performance indicators.

From the conducted analysis, the following conclusions can be drawn:

– The results allow for the assessment of the readiness of combat systems to perform designated operational tasks.
– They support the preparation of maintenance and repair infrastructure to ensure the functional integrity of the process.
– The results also facilitate the preparation of storage and research facilities necessary for evaluating combat system reliability and ensuring appropriate maintenance procedures.

To ensure the effectiveness of both analytical and maintenance processes, a dedicated management system should be implemented. The models of such a system should be integrated with both operational and reporting activities, including any anomalies encountered during system usage. The most effective approach involves the continuous improvement of the system through the real-time incorporation of updated data

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