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# Analysis and evaluation of the technical equipment maintenance system in the Polish Army

# Analiza i ocena systemu obsługiwania sprzętu technicznego w Wojsku Polskim

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**Abstract.** Maintaining the high level of operational readiness of the army requires ensuring constant high technical readiness of its technical equipment. The reliability of a technical device results from its design and operational features, and in the operation phase it depends solely on the efficiency of the logistics supply system, service, and diagnosis. The principles of implementing these processes and the functioning of the systems are determined by the adopted equipment exploitation strategy. The study presents the results of the assessment of the technical equipment maintenance system in the Polish Army. Methods, procedures and tools for obtaining data to achieve the set goal, methods of data processing, and analysis of the obtained information were characterized. Information and data characterizing the functioning of the maintenance system were obtained as a result of the use of interview techniques with experts with theoretical and practical knowledge about the functioning of the system in the armed forces, using observation techniques, analysis of operational documentation in paper form as well as collected in IT systems. The method of surveying of two groups of experts, participants of the logistics course involved in the implementation and managing the operation of the equipment was of fundamental importance in the research process. IT tools such as MS Excel, MatLab and Statistica were used to develop the obtained numerical and linguistic results. The study determined the parameters of descriptive statistics, histograms and probability distributions and used fuzzy logic. As a result of the study, the reasons for the currently not fully satisfactory level of operation of the equipment maintenance system were revealed and possible solutions were identified to increase the efficiency and effectiveness of the system, and thus the technical readiness of the equipment.

**Keywords:** maintenance system, surveying, fuzzy logic, operation of military technology, readiness of technical facilities

**Abstrakt.** Utrzymanie wysokiego poziomu gotowości operacyjnej wojska wymaga zapewnienia stałej wysokiej gotowości technicznej sprzętu stanowiącego jego wyposażenie. Niezawodność urządzenia technicznego wynika z jego cech konstrukcyjnych i eksploatacyjnych, a w fazie eksploatacji jest zależna wyłącznie od sprawności działania systemu zaopatrzenia logistycznego, obsługiwania, w tym diagnozowania. Zasady realizacji tych procesów i funkcjonowania systemów determinuje przyjęta strategia eksploatacji sprzętu. W opracowaniu przedstawiono wyniki oceny funkcjonowania systemu obsługiwania sprzętu technicznego w wojsku polskim. Scharakteryzowano metody, procedury i narzędzia pozyskiwania danych dla realizacji postawionego celu, metody przetwarzania i opracowania danych oraz analizy uzyskanej informacji. Informacje i dane charakteryzujące funkcjonowanie systemu obsługiwania uzyskano w wyniku zastosowania techniki wywiadu z ekspertami dysponującymi wiedzą teoretyczną jak i praktyczną o funkcjonowaniu systemu w siłach zbrojnych, za pomocą techniki obserwacji, analizy dokumentacji eksploatacyjnej w formie papierowej, jak również zgromadzonej w systemach informatycznych. Podstawowe znaczenie w procesie badawczym miała metoda ankietowania dwóch grup ekspertów, uczestników kursu logistycznego związanych z realizacją i zarządzających eksploatacją sprzętu. Do opracowania uzyskanych wyników liczbowych i lingwistycznych wykorzystano narzędzia informatyczne w postaci MS Excel, MatLab i Statistica. W opracowaniu wyznaczono parametry statystyki opisowej, histogramy i rozkłady prawdopodobieństwa oraz wykorzystano logikę rozmytą. W wyniku przeprowadzonego badania ujawniono przyczyny aktualnie nie w pełni zadowalającego poziomu funkcjonowania systemu utrzymania stanu technicznego sprzętu oraz wskazano możliwe do zastosowania rozwiązania pozwalające na podniesienie sprawności i efektywności systemu, a tym samym gotowości technicznej sprzętu.
**Słowa kluczowe:** system obsługiwania, ankietowanie, logika rozmyta, eksploatacja techniki wojskowej, gotowość obiektów technicznych

## Introduction

The concept of exploitation of military equipment is understood as a set of purposeful organizational, technical and economic activities undertaken towards it by personnel and the relations between them, from the moment of introduction to use until its withdrawal. Equipment exploitation in the Armed Forces is carried out in a specific system resulting from the adopted optimal exploitation strategy for it, taking into account the basic, most important criteria of the functioning of the armed forces, i.e.:

- operational readiness, including technical readiness of equipment,
- operational safety,
- economics of exploitation.

The basic strategies used in the exploitation of military equipment are:

1. strategy according to equipment resource wear,
2. strategy according to equipment technical condition.

In organizationally and economically justified cases, other operating strategies can be adopted, taking into account aspects of reliability and technical and technological progress. The name of the system in which the exploitation processes are carried out is associated with a specific exploitation strategy. In view of the above, the basic systems for the exploitation of military equipment in the Armed Forces, resulting from the adopted exploitation strategies, are (Doktryna Logistyczna, 2019):

1. planned and preventive exploitation system,
2. planned and preventive exploitation system with diagnosis,
3. exploitation system according to technical condition,
4. mixed system – one of the above systems with selected elements of other exploitation systems.

The assignment of a given type of equipment to the appropriate exploitation system results from established operating standards, defined by a normative or planning numerical value. The choice of the exploitation system is the domain of the Central Logistics Authority, which may be agreed with the equipment manager and result from the specificity of its use, including the assessment of the risk of unsuitability, the time of its removal and operating costs (Wsparcie i zabezpieczenie, 2017). It is also allowed to change the exploitation strategy (system) during the operational phase, in accordance with the principles of life cycle management of military equipment (STANAG 4728, 2015).

The implemented network and IT systems in the Armed Forces provide the basis for using the RCM – Reliability Centered Maintenance (Rausand, 1998) strategy in the exploitation of weapon systems. This is one of the strategies increasingly implemented in many important equipment operation systems (Legutko, 2009). The Integrated Multilevel IT System of the Ministry of National Defense (ZWSI-RON) has been implemented and developed in the Armed Forces for many years, and its ultimate task is to replace the field IT systems used (Borucka, 2013). There is a Renovation Management Module within this system, but it is not available at lower levels of management (Zintegrowany Wieloszczeblowy, 2020). In the context of implementing the RCM strategy, it is important to study the reliability features of military equipment, as well as to develop diagnostic systems using IT systems for collecting and processing diagnostic information (Żółtowski, Simiński 2022). It is reasonable to aggregate information resulting from operational experience in military units and use it to determine the distribution of damage to complete objects, their systems or individual spare parts, and to use the information to make exploitation decisions. The need for constant improvement of military technical equipment and their exploitation systems implies the need to research, analyze and control the processes of using equipment and security systems: supply and service.

These processes became the subject of knowledge during extensive research on the military equipment exploitation system presented in this publication. The research hypothesis was adopted that the study of the processes and system of exploitation military equipment is an area of uncertain and imprecise knowledge, and hence social research methods will also be useful in the research process (Babbie, 2012), and in the phase of processing results and inferences, statistical methods of reliability and fuzzy logic (Zadeh, 1965). It was also assumed that the parallel use of many research methods and tools will allow for a full, exhaustive and orderly description of processes and, at the same time, the use of formal, mathematical tools for describing exploitation processes. The aim of the research was to gather knowledge about the exploitation system, taking into account the knowledge of the participants of the exploitation processes – the staff managing the exploitation, mainly using the interview and survey methods, in order to identify the state of the exploitation economy, reveal the reasons for its possibly unsatisfactory state and determine the ways of improving it.

## The system of exploitation of military technique and its research

The exploitation of military equipment takes place in accordance with the rules known and commonly used in the civilian economy (Duffua, Raouff, et al., 1999; Legutko, 2007; Pszczółkowski, 2020; Słowiński 2011). The processes of exploitation of military equipment are the subject of many doctoral dissertations (Kończak, 2016; Kuźma, 2019; Sweklej, 2020). They are also the subject of monographic studies (Ziółkowski, 2019). The cognitive tools here are the principles of reliability theory, fuzzy logic and Markov processes. The procedures used in research and exploitation processes of military technology are also available in domestic and world literature on equipment maintenance issues.

An important, if not fundamental, problem in terms of maintenance and equipment suitability is the planning of preventive actions. Planning procedures should use the following data: system structure, reliability, potential and limitations of the service system. Maintenance planning based on fuzzy logic was proposed in (Fouad, Samhouri, 2011). The combination of knowledge in the field of system reliability based on the RCM strategy and fuzzy logic allows you to adapt the maintenance strategy to the current and future condition of devices (Felecia, 2014). A model based on fuzzy set theory was proposed to assess the risk of operational damage to devices (Gallab, Bouloiz at. al., 2019). The risk assessment takes into account: the probability of failure (frequency), the probability of detection and its consequences. Markov models are often used and popular, especially in reliability research and maintenance planning (Gámiz, Limnioz et al., 2023). The Markov model is based on and allows for determining the probability of systems being in a specific operating state, but the problem here is the selection of the model and the selection of the appropriate number of states. Selecting too many considered states may limit the accuracy of the model used. From the point of view of logistic security of exploitation systems, especially the maintenance and repair system, an important task is to forecast the consumption of materials and replaceable parts (Młyńczak, 2008).

Undoubtedly, the processes of operation of exploitation systems, in which decisions made by humans are an important factor, constitute a difficult area of knowledge and formal description. The principles of functioning of systems are difficult to describe using mathematical functions (Owczarek, Brzeziński et al. 2022). There is no simple dependence of the evaluation parameters on the extracted forces for the studied processes.

Hence, multi-valued, fuzzy logic methods are widely and justifiably used. Research methods, also in the case of military technology support systems, may be qualitative (e.g. interviews, observations) or quantitative, when the results obtained can be expressed numerically (e.g. surveys). Wherever possible, empirical research should also be used and statistical methods, including reliability, should be used to process them. Analogous research techniques are recommended by the authors (Niziński, Żółtowski, 2001) in the process of identifying the operation system for the purposes of designing IT systems for managing the operation of technical facilities.

An unstructured interview belongs to the group of qualitative methods – it is conducted according to a specific plan in the form of instructions for the interview. There are a number of criteria for classifying an interview: the nature of the interview, standardization, structure, freedom to ask and answer questions, and the place of its performance (Lutyński, 2001).

## Planning and stages of a survey

The subject of a survey may be processes, their nature, type and essence. Quantitative and qualitative research can be conducted using a survey – they are not alternatives to each other, but are usually complementary (Babbie, 2004; Read, Marsh, 2006). Survey research provides essential information for decision-making processes (Ścibiorek, Borucka, 2022) not only in the social area, but also in the economic, technical and even security areas (Poliak, Čulík, et al., 2023). In the context of the above, an important issue is the selection of the appropriate method, technique and research tool (Pilch, Wujek, 1974). Research technique means an activity, e.g. observing, conducting an interview, and a research tool is an instrument used for technical data collection – the research tool is a survey or interview questionnaire. A survey is an «information collection technique that involves filling out, most often by the respondent himself, special questionnaires, usually with a high degree of standardization.» (Bauman, Pilch, 2019). The starting point is a set of questions that the researcher wants to get answers to. The scope of the study and the general population should be determined, which constitutes the basis for selecting the research sample, i.e. the population subject to the study – the result can be generalized to the general population. The most popular sampling methods include: simple random sample, quantum sample, stratified sample, group (team) sample, two-stage sampling, random quota sample, systematic sample or expert sample (purposive sampling) (Szreder, 2010).

After developing an appropriate research tool, i.e. a survey questionnaire to obtain empirical data (Krok, 2015), a pilot study is carried out to check and verify the tool and, if necessary, it is corrected. Presenting the results of the actual survey includes, among others: statistical analysis of the results, it is possible to verify the initial hypotheses or evaluate the verified phenomena.

Survey research can be classified according to various criteria:

– confidentiality: public and anonymous research is distinguished,
– questionnaire filling technique,
– method of distributing the questionnaire,
– how to fill out the questionnaire,
– scope of the study.

The basis for preparing the survey was the authors› own knowledge and experience in the exploitation of military equipment, conversations and informal interviews with personnel operating military equipment, planning operation and managing technical subsystems. The problems of rationalizing service, and repair time and the accompanying processes, i.e. repair planning, defining the level of spare parts inventories, circulation of accounting documents, and optimizing the circulation of information in the area of public procurement law were analyzed and assessed. In order to describe the impact of important factors on the above processes in the maintenance and repair subsystem of military equipment at various organizational levels, an Ishikawa diagram was constructed. Its essence is a graphical presentation of the causes causing a specific problem, which allows for the analysis of cause-and-effect relationships (Gołaś, Mazur, 2010). In the case of exploitation decisions, the method is also called 5M, because the basic groups of reasons are: manpower, machine, methods, materials, and management. Therefore, the following factors were taken into account in the analysis (Fig. 1):

– method of performing maintenance and repairs,
– maintenance and repair staff,
– machines and devices supporting processes,
– system management,
– availability of materials and spare parts and information.

Based on the presented Ishikawa diagram, a survey for experts was developed. The causes and effects contained in the diagram became the subject of survey questions. The diagram contains the number of the survey question corresponding to a given reason, and the background color indicates the median value (its range) for the obtained answers. The study was conducted among two groups of students of the logistics course conducted at the Military University of Technology – a total of 95 participants, officers in the logistics security department, therefore having extensive experience in the researched area. The soldiers came from various military units in the country, thanks to which the sample selection was extensive and random. The necessary permits resulting from legal regulations were obtained for the survey.

Fig. 2 presents a description of the structure of the survey participants and the equipment used at their place of business activity (Fig. 3).

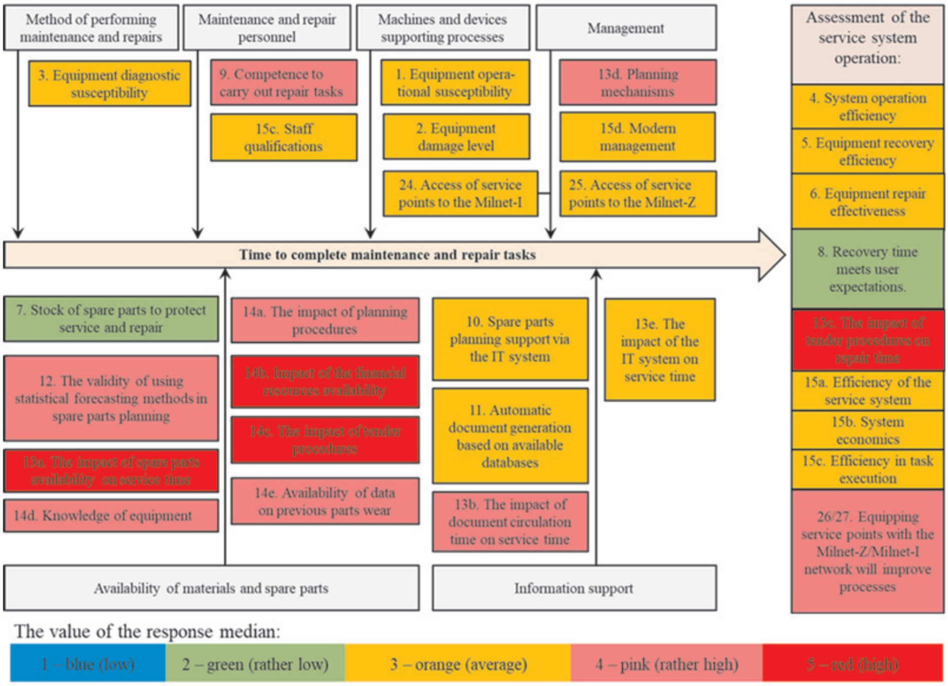


Fig. 1. Ishikawa chart – dependencies in the maintenance system
Source: Own study

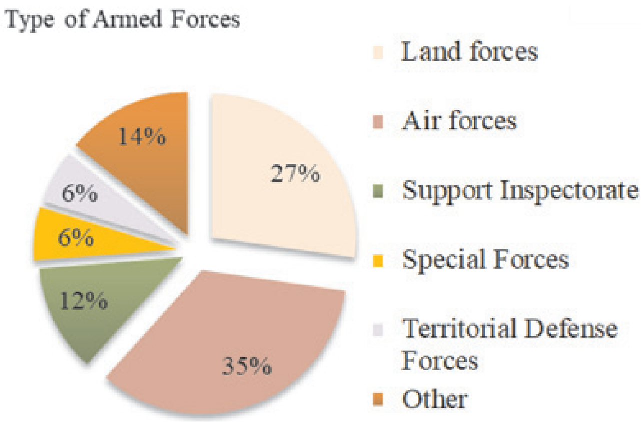


Fig. 2. Affiliation of respondents to the Branches of the Armed Forces
Source: Own study

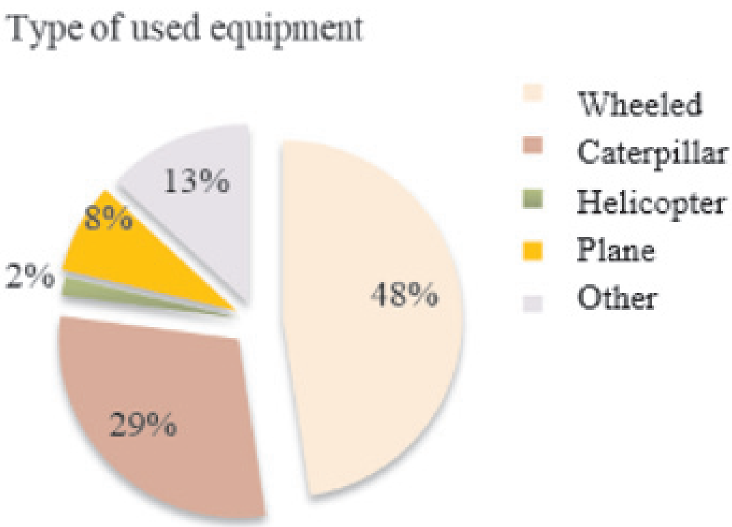


Fig. 3. Type of equipment used by respondents' military units
Source: Own study

Respondents' responses were obtained in two categories, numerical and linguistic. Linguistic answers were assigned a five-point numerical scale, i.e.: Low – 1, Rather low – 2, Average – 3, Rather high – 4, High – 5. The obtained results were checked for any differences from the others using Grubbs' criterion (Słowiński, 2002). The Grubbs test allows you to reject questionable data – it detects outliers of normal distributions, indicating the probability that a given sample belongs to the basic population. The value of Grubbs' parameter $\eta$ is expressed by the relationship (1):

$$\eta = \frac{\left| x_i - \overline{X} \right|}{S}, \tag{1}$$

where:
- $\overline{X}$ – average value of the studied population,
- $x_i$ – extreme sample value,
- $S$ – standard deviation.

It is necessary to check the condition for outliers:

$$\eta \geq \eta_g, \tag{2}$$

where: $\eta_g$ = Grubbs criterion read from the table of critical values.

A broad analysis of the participants' answers to the questions was made. The values of selected descriptive statistics parameters of the study results are presented in Table 1. They are:

- simple, arithmetic average value,
- median – middle value,
- mode, dominant value – the most common occurring value,
- standard deviation, which is the square root of the variance,
- coefficient of variation, expressed as the ratio of the standard deviation to the mean value,
- skewness coefficient (left-sided skewness – positive value, right-sided skewness – negative value),
- kurtosis – determines the degree of dispersion of a random variable (positive – more dispersed than a normal distribution, negative – less dispersed (more clustered) than a normal distribution).

Table. 1. Selected descriptive statistics of survey questions

| Variable | Average | Median | Dominant | Std. Dev. | Coef. of variation | Skewness coefficient | Kurtosis |
|---|---|---|---|---|---|---|---|
| Question 1 | 3.32 | 3.00 | 3.0 | 0.62 | 0.19 | 0.47 | 0.36 |
| Question 2 | 3.01 | 3.00 | 3.0 | 0.76 | 0.25 | -0.02 | -0.48 |
| Question 3 | 3.29 | 3.00 | 3.0 | 0.73 | 0.22 | 0.33 | 0.05 |
| Question 4 | 2.85 | 3.00 | 3.0 | 0.82 | 0.29 | 0.28 | -0.30 |
| Question 5 | 2.92 | 3.00 | 3.0 | 0.77 | 0.26 | 0.15 | -0.49 |
| Question 6 | 3.03 | 3.00 | 3.0 | 0.74 | 0.24 | 0.28 | -0.26 |
| Question 7 | 2.57 | 2.00 | 2.0 | 0.91 | 0.35 | 0.27 | -0.46 |
| Question 8 | 2.73 | 3.00 | 2.0 | 1.05 | 0.38 | 0.40 | -0.58 |
| Question 9 | 3.35 | 3.00 | 4.0 | 1.05 | 0.31 | -0.40 | -0.39 |
| Question 10 | 2.87 | 3.00 | 3.0 | 0.95 | 0.33 | -0.28 | -0.31 |
| Question 11 | 2.91 | 3.00 | 3.0 | 1.05 | 0.36 | -0.31 | -0.63 |
| Question 12 | 3.89 | 4.00 | 4.0 | 1.02 | 0.26 | -0.97 | 0.66 |
| Question 13a | 4.48 | 4.00 | 5.0 | 0.92 | 0.21 | -2.29 | 6.22 |
| Question 13b | 3.73 | 4.00 | 4.0 | 1.11 | 0.30 | -0.83 | 0.67 |
| Question 13c | 4.49 | 4.00 | 5.0 | 0.85 | 0.19 | -2.43 | 8.28 |
| Question 13d | 3.83 | 4.00 | 4.0 | 0.95 | 0.25 | -1.01 | 2.12 |
| Question 13e | 3.41 | 3.00 | 3.0 | 1.09 | 0.32 | -0.27 | -0.23 |
| Question 14a | 4.09 | 4.00 | 4.0 | 0.96 | 0.23 | -1.31 | 2.60 |
| Question 14b | 4.39 | 4.00 | 5.0 | 0.97 | 0.22 | -1.93 | 4.21 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Question 14c | 4.37 | 4.00 | 5.0 | 0.95 | 0.22 | -2.19 | 6.28 |
| Question 14d | 4.13 | 4.00 | 5.0 | 0.97 | 0.24 | -1.33 | 2.51 |
| Question 14e | 4.07 | 4.00 | 5.0 | 0.97 | 0.24 | -1.15 | 2.05 |
| Question 15a | 3.34 | 3.00 | 3.0 | 0.83 | 0.25 | -0.71 | 2.20 |
| Question 15b | 3.22 | 3.00 | 3.0 | 0.88 | 0.27 | -0.93 | 1.47 |
| Question 15c | 3.34 | 3.00 | 3.0 | 0.83 | 0.25 | -0.71 | 2.20 |
| Question 15d | 3.34 | 3.00 | 3.0 | 0.83 | 0.25 | -0.71 | 2.20 |
| Question 15e | 3.34 | 3.00 | 3.0 | 0.83 | 0.25 | -0.71 | 2.20 |
| Question 24 | 3.12 | 3.00 | 5.0 | 1.43 | 0.46 | 0.01 | -1.33 |
| Question 25 | 3.23 | 3.00 | 3.0 | 1.32 | 0.41 | -0.13 | -1.06 |
| Question 26 | 3.85 | 4.00 | 5.0 | 1.14 | 0.30 | -0.75 | -0.31 |
| Question 27 | 3.84 | 4.00 | 5.0 | 1.04 | 0.27 | -0.56 | -0.45 |

Source: Own study

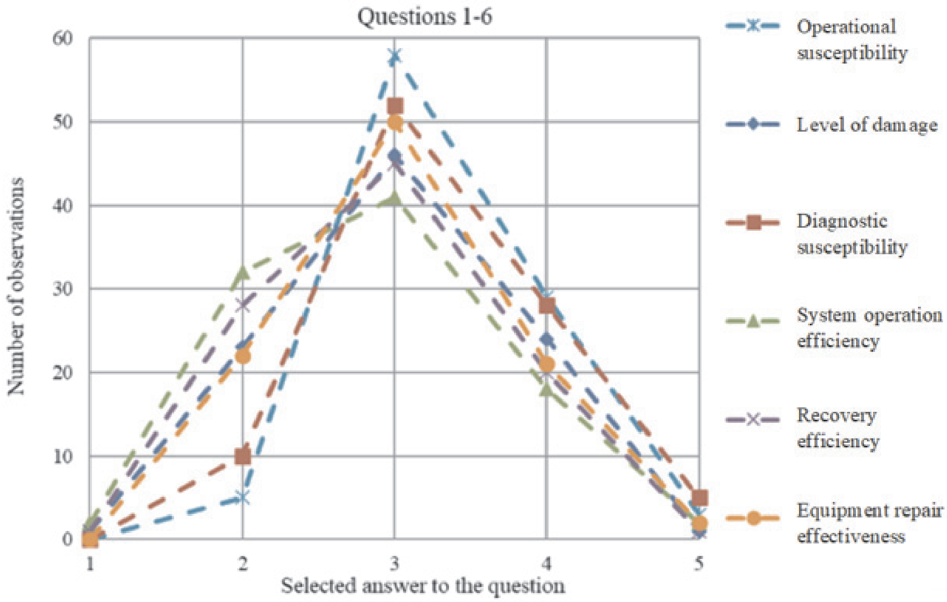


Fig. 4. Comparison of the results of answers to questions No. 1 to No. 6
Source: Own study

The data presented show that the areas of particular interest should be to the following problems:
- public procurement,
- availability of spare parts,

– information and document circulation,
– efficiency of processes taking place in the maintenance and repair system.

Some of the analysis results were also presented graphically, divided into thematic groups of responses. The first group included questions regarding the impact of the susceptibility of a technical object on maintenance and repair activities (Fig. 4). The average assessment of respondents in relation to the analysed exploitation sphere is at an average level, and the remaining results are generally evenly distributed on both sides of the average value.

The characteristics of this group of responses are also presented according to the criterion of respondents' belonging to the type of Armed Forces (Fig. 5 – Fig. 8).

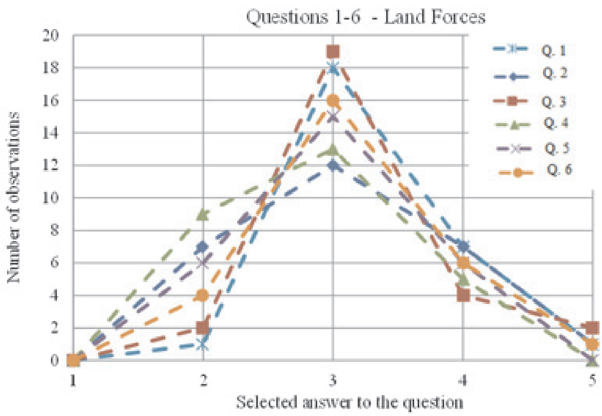


Fig. 5. Comparison of the results of answers to questions No. 1 to No. 6 – Armed Forces
Source: Own study

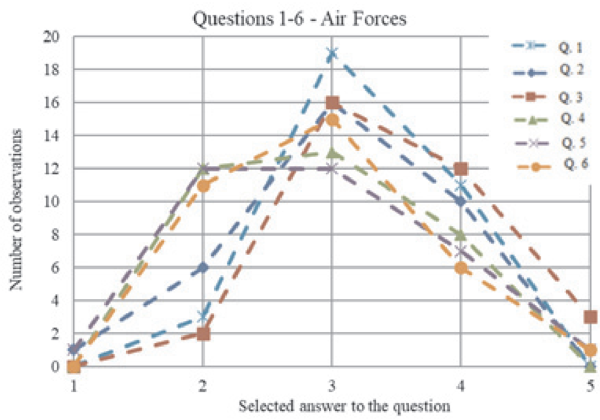


Fig. 6. Comparison of the results of answers to questions No. 1 to No. 6 – Air forces
Source: Own study

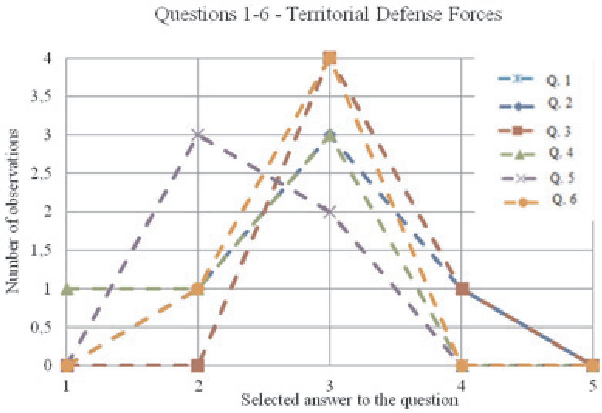


Fig. 7. Comparison of the results of answers to questions No. 1 to No. 6 – Territorial Defense Forces
Source: Own study

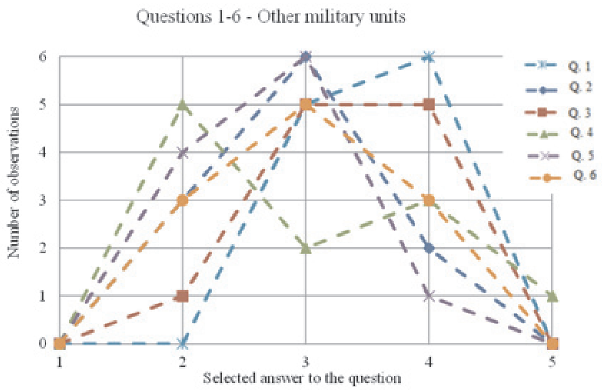


Fig. 8. Comparison of the results of answers to questions No. 1 to No. 6 – Other military units
Source: Own study

The nature of the individual dependencies here is quite diverse – the distribution of responses from the respondents of the Land Forces and the Air Force is closest to the summary characteristics. In the case of respondents belonging to the Territorial Defense Forces, despite the use of equipment with a relatively low level of technical complexity, a low level of efficiency of the maintenance and repair system is also noted. Moreover, in relation to the characteristics of other military units (Fig. 8), attention should be paid to the characteristics of the operational efficiency of the maintenance and repair system. There are two peaks on it, but the maximum is centered around the “rather low” value.

The second group included questions about the stock of spare parts, the time needed to restore the equipment's operational condition and the competences of service station staff – question numbers from 7 to 9. The distribution of respondents' answers is presented in the form of a table (Table 2), which clearly shows the nature and diversity of the answers.

Table. 2. Summary of respondents' answers to questions 7 to 9

| | No (1) | Probably not (2) | On average (3) | Probably yes (4) | Yes (5) |
|---|---|---|---|---|---|
| 7. Accuracy of spare parts inventories | 9 | 40 | 30 | 15 | 1 |
| 8. Adequate equipment recovery time | 8 | 39 | 24 | 19 | 5 |
| 9. Competencies of servi-ce stations | 5 | 15 | 28 | 36 | 11 |
| Scale of respondents' answers | 0 - 8 | 9 - 16 | 17 - 24 | 25 - 32 | 33 - 40 |

Source: Own study

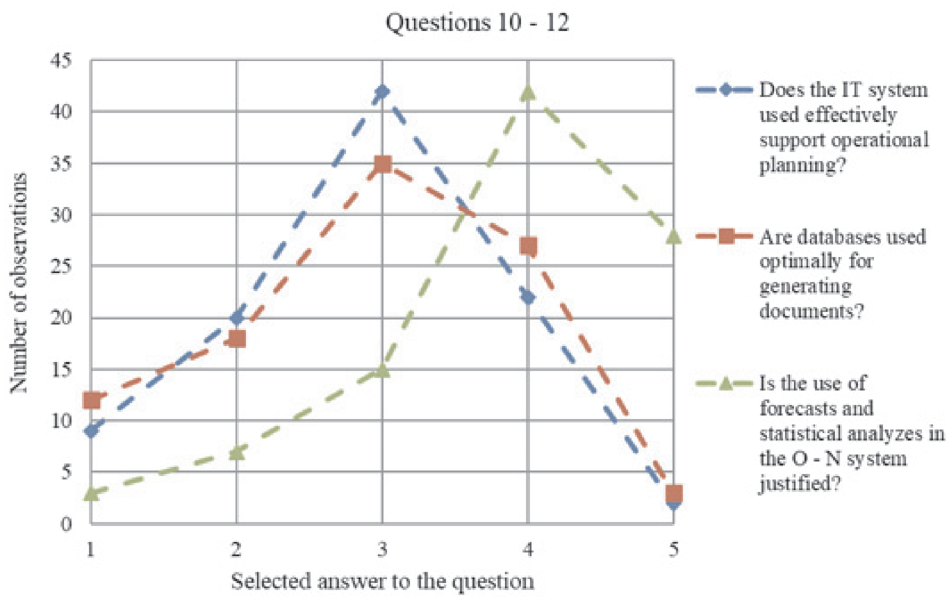


Fig. 9. Comparison of the results of answers to questions No. 10 to No. 12
Source: Own study

It is easy to see that the time needed to restore military equipment does not meet the expectations of system participants. One of the factors significantly affecting the course of processes is the inadequate level and accuracy of warehouse stocks. Most respondents positively assess the competences of service points. In this case, the nature of the respondents' answers is similar in each of the groups of the types of Armed Forces.

The third group included questions about the IT system, databases and the use of forecasting and statistical analysis methods in spare parts planning. The general characteristics are presented in Fig. 9, and they result from the respondents' expectation of increased use of statistical analyses and forecasting in the maintenance and repair system.

## Correlations of expert-respondents' answers

In order to determine the nature of the impact of factors and the interdependence of respondents' answers to questions, treated as random variables *X* and *Y* describing a specific problem, linear correlation measures were used – Pearson's linear correlation coefficient $r_{XY}$. It is a correlation estimator of the unknown parameter $\rho_{XY}$, the limits of variability of which are: $\rho_{XY} = -1$, in the case of a negative functional relationship, and $\rho_{XY} = 1$, in the case of a positive functional relationship. The linear correlation coefficient, $\rho_{XY}$, is defined as (3):

$$\rho_{XY} = cov\left(X,Y\right)/\left[D\left(X\right)D\left(Y\right)\right], \tag{3}$$

where:
- $D(X)$, $D(Y)$ – are standard deviations of the distributions of random variables *X* and *Y*,
- $\mathrm{cov}(X, Y)$ – is the covariance of random variables *X* and *Y*.

The correlation coefficient (3) effectively measures the degree and indicates the direction of correlation between random variables *X* and *Y* only when both regressions are linear or nearly linear. In cases of non-linear regression, the Pearson's linear correlation coefficient underestimates the actual strength of interdependence of the observed random variables.

Figure 10 shows in a graphical form the correlation matrix of the set of questions presented to the second group of experts, with the coefficient values marked according to the colour scale. There are visible areas of varying correlation between pairs of questions, ranging from a clearly negative correlation, which is demonstrated in many questions by question No. 2 regarding damage to equipment, through areas of slight and average correlation, to pairs of questions with a clear positive correlation.

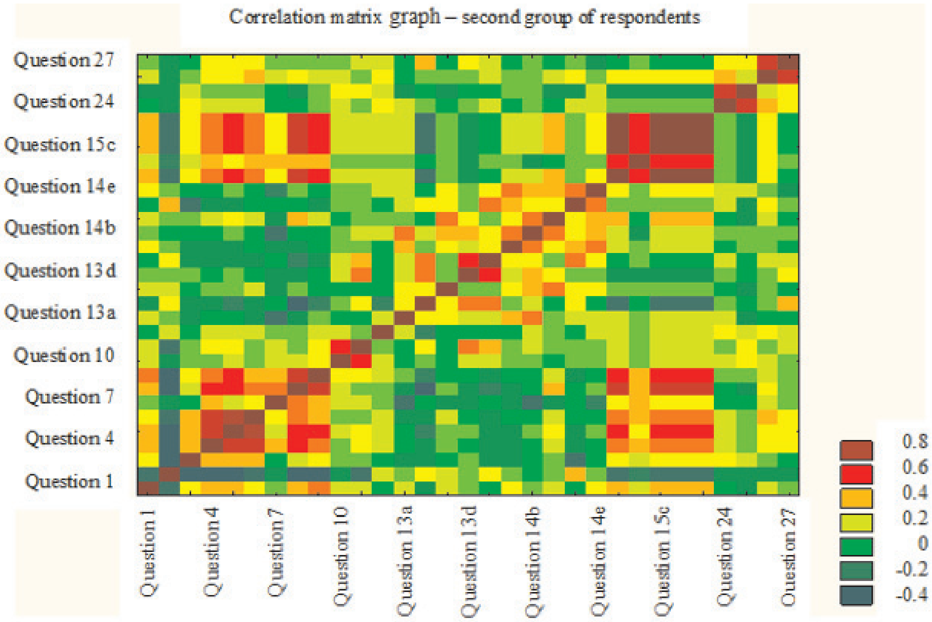


Fig. 10. Graphical form of the correlation matrix of the responses of the second group of experts
Source: Own study

Such a significantly high positive correlation occurs in the range of questions from numbers 4 to 6 and 15a to 15d. Questions numbered 4-6 concern the efficiency of the maintenance and repair system, the efficiency and effectiveness of restoring the serviceability of the equipment. The subject of questions number 15(a-e) concern the problems related to the effectiveness of the maintenance and repair system in terms of input/output, economics of operation in the context of the reasonableness of the incurred costs, staff qualifications and modernity of management methods. The above-mentioned issues, also in the intuitive sense, seem to be well correlated and the results obtained can confirm this.

For selected pairs of questions outside the above range, due to the statistical significance of their correlation determined on the basis of the correlation table (Fig. 10), three-dimensional graphs of the number of answers for these questions are presented (Fig. 11, 12).

Fig. 11 shows that, according to respondents, there is a correlation between the impact of the IT system and planning mechanisms on increasing the time of maintenance and repairs in the range of answers: average – relevant.

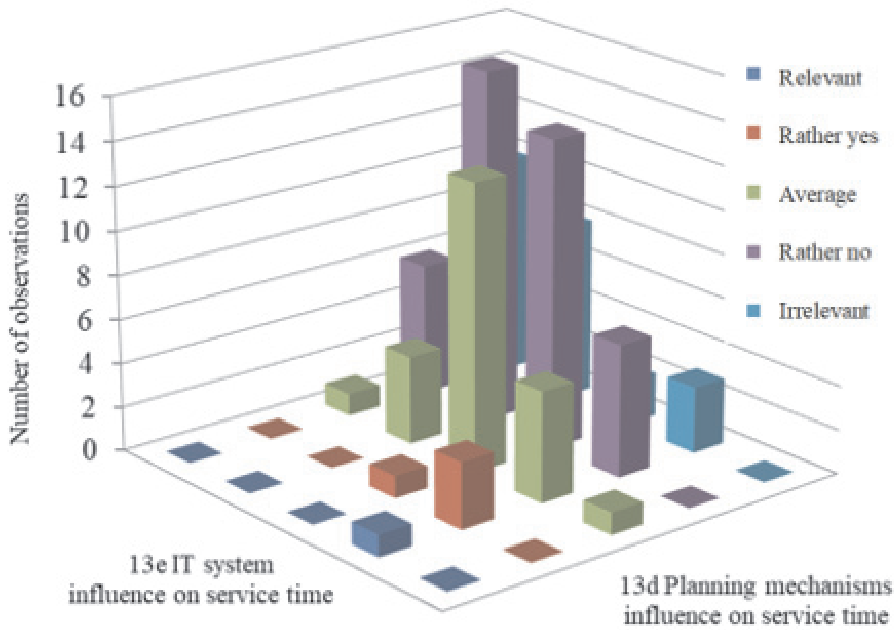


Fig. 11. Correlation of the number of answers to questions 13e and 13d, r = 0.55
Source: Own study

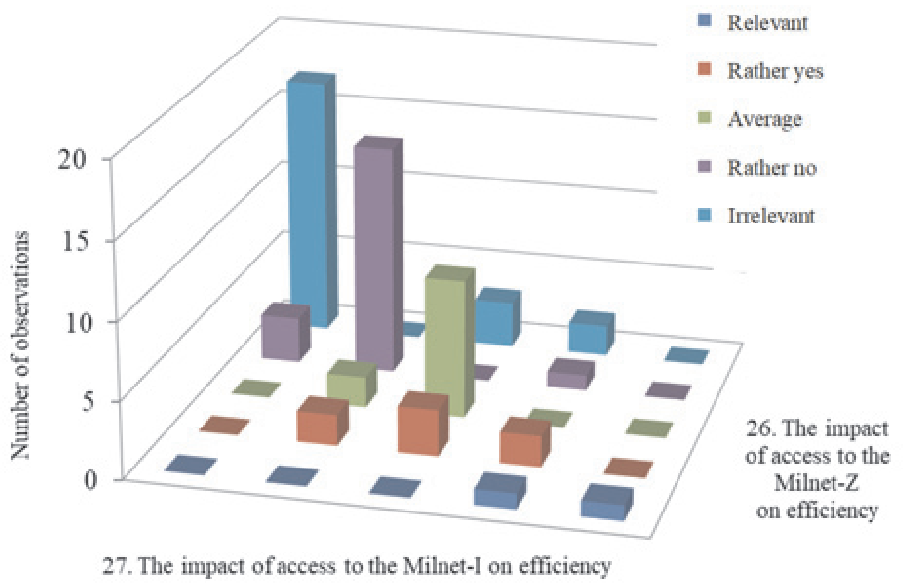


Fig. 12. Correlation of the number of answers to questions 26 (explicit network) and 27 (implicit network), r = 0.64
Source: Own study

Fig. 12 shows that there is a correlation between the opinion that service points should be equipped with a proprietary (Milnet-Z) computer network and a public for Armed Forces (Milnet-I) computer network with an average value of yes (relevant). Other rankings show a significant correlation:

– the impact of tender procedures on both the extension of service and repair times as well as the availability of spare parts,
– availability of prior data on exploitational events, and knowledge of the military equipment in use in the context of assessing system operation.

## Using fuzzy logic to assess task completion time

Fuzzy systems are analysis methods and techniques that are used to illustrate imprecise, undefined or non-specific information that cannot be captured by classical theory and two-valued logic. The basic object in the theory is a fuzzy set – each element may belong to the set, may not belong to it, or may belong to it only to a certain extent. The membership of each element in the fuzzy set is described by the membership function. A linguistic variable has characteristics described by linguistic values, e.g. young, old, short, tall. Linguistic space is the set of all possible linguistic values describing a given variable. The mathematical description of the fuzzy set *A* in the considered space *X* is the set of pairs (4):

$$A = \left\{ \left( x, \mu_A(x) \right) : x \in X \right\}, \tag{4}$$

where:

– $x$ – is element of the set,
– $\mu_A$(x) – membership function of element $x$ in set $A$ taking values in the range <0; 1>.

Membership functions in the theory of fuzzy sets have various forms, e.g. polygons or continuous surfaces of the fuzzy model. Fig. 13 shows the membership function of the triangular form used in the study, and its mathematical description is given by the expression (5).

$$\mu_A(x;a,b,c) = \begin{cases} 0; c \le x \ge a; \\ \dfrac{x-a}{b-a}; a \le x \le b;, \\ \dfrac{c-x}{c-b}; b \le x \le c; \end{cases} \tag{5}$$

The Fuzzy Inference System (FIS) allows mapping the input space to the output space. Its operation is conditioned by inference rules of the form: (If…, then…). Rules can be defined by an expert or describe the physical properties of objects. The course of the fuzzy reasoning process is shown in Fig. 14.

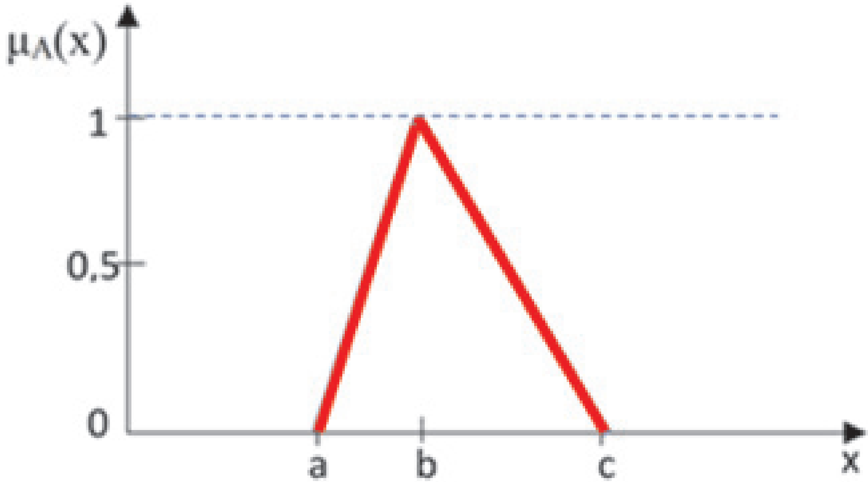


Fig. 13. Triangular membership function
Source: Own study

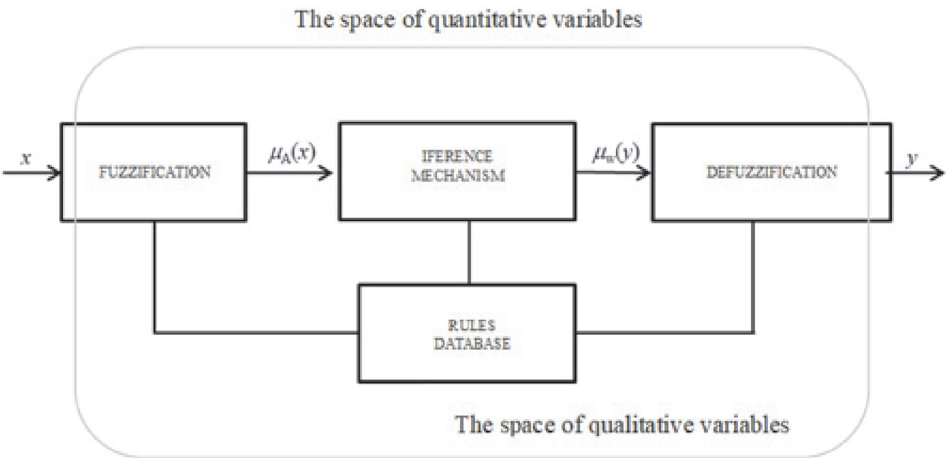


Fig. 14. Fuzzy inference scheme
Source: Own study

Fuzzification is the process of diluting discrete variables *x* into fuzzy variables, i.e. determining the degree of belonging of variable *x* to defined fuzzy sets. Inference is an inference process during which the inference block "determines" the values of the resulting membership function $\mu_w(y)$ based on the input membership functions. Determining the output value of the membership function is possible based on a database of fuzzy inference rules containing appropriate premises (antecedents) and the resulting conclusions (consequences). The last stage of fuzzy inference is defuzzification, i.e. changing the resulting membership function $\mu_w(y)$ into a sharp value of the output (control) signal. The defuzzification mechanisms include the following methods: center of maximum, first and last maximum, and the center of gravity method (Grzesik, 2012).

Fuzzy logic was used to assess the efficiency of carrying out maintenance and repair tasks and to build a model determining the probability of completing repair or maintenance without undue delay (PNBZZ). The main factors influencing the repair time "without undue delay" included: availability of spare parts in the warehouse, document circulation time and procedures carried out by public procurement units. The probabilities of completing tasks without delays due to the above partial processes were determined.

It should be emphasized that in the event of equipment failure or the need to perform maintenance activities, it is necessary to carry out appropriate administrative procedures related to the circulation of documents: Technical Service Card, Technical Condition Report, updating operational documentation, or issuing documents related to the collection of spare parts from the warehouse, and even searching for and transferring technical material resources between organizational units. Some of the technical resources are also obtained as a result of procedures required by the Public Procurement Law, which extends the implementation time of tasks. The model for implementing repairs with obtaining funds under the procedures of the Public Procurement Law is the most complex. The problem of using forecasting methods and planning needs in the field of systemic security for the implementation of maintenance and repair tasks is of appropriate importance here.

As a result of the analysis of the surveys, a fuzzy controller was developed in which membership functions were determined for the factors: document flow (DK), availability of spare parts (TSM), tender procedures (PZP), as well as a database of inference rules. The range of the output signal was also determined. The controller diagram is shown in Fig. 15.

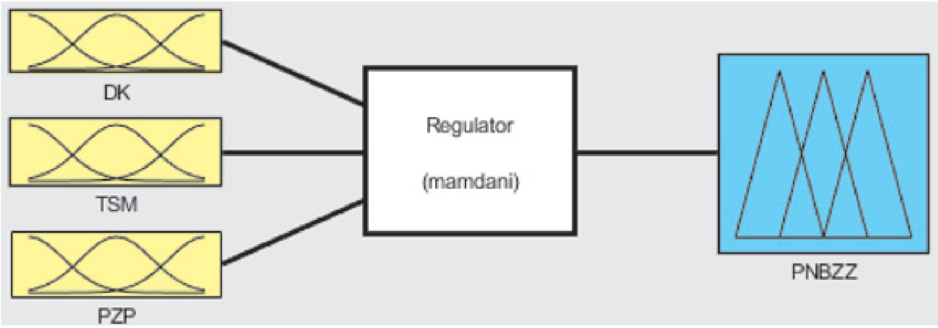


Fig. 15. Fuzzy controller developed in MatLab
Source: Own study

Three trapezoidal membership functions were adopted for each input parameter, which determine the range and characteristics of their changes. The membership functions in each case contain three linguistic variables: short, standard, long. In the case of the output signal, which determines the probability of repair completion without undue delay, six membership functions (triangular) were adopted, respectively: "very small", "small", "medium", "large", "very large" and "expected". The course of the membership function of the selected input signal ("document circulation time - DK") and output signal is shown in Fig. 16 and 17. Their scope and values were determined on the basis of the answers of experts participating in the survey.

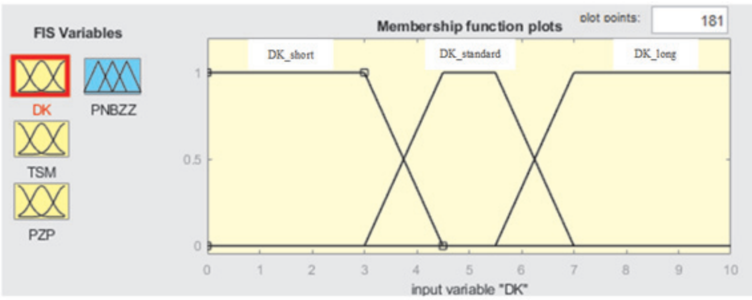


Fig. 16. Functions of the signal "document circulation time - DK"
Source: Own study

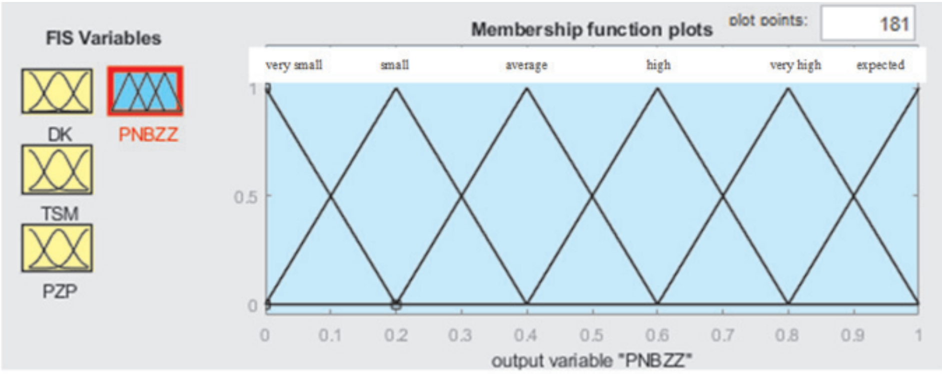


Fig. 17. Membership functions of the PNBZZ output signal
Source: Own study

In the next stage, a database of inference rules was built, enabling the determination of the output value of the fuzzy model based on the input parameters and membership function. The number of inference rules was determined by the formula (6):

$$r_w = z_r^{\,w}, \tag{6}$$

where:
- $r_w$ – number of inference rules,
- $z_r$ – number of fuzzy sets of the model,
- $w$ – number of model inputs.

In the case of the analyzed model, twenty-seven inference rules ($r_w$) were obtained – the number of variations with repetitions for three input parameters ($w$) of three fuzzy sets of the model ($z_r$). The fuzzy inference rules were as follows: If "document circulation time = short" and "waiting time for spare parts = short" and "tender procedure time = short" then "repair time without unnecessary delay = expected". Selected rules from the list of rules are presented in Table 3, indicating the rules for their creation.

Table. 3. Reasoning rules used in the model of performing maintenance tasks

| No. | Document circulation time (DK) | Waiting time for spare parts (TSM) | Time of the public procurement procedure (PZP) | Probability of repair/ service without undue delay (PNBZZ) |
|---|---|---|---|---|
| 1 | short | short | short | expected |
| … | … | … | … | … |
| 14 | standard | standard | standard | average |
| … | … | … | … | … |
| 27 | long | long | long | very small |

Source: Own study

The model adopts an inference mechanism based on the minimum-maximum method. The premises are joined by a conjunction, which makes the conclusion have the minimum value of the activated membership functions. The evaluation of the premises is implemented in the form of a logical product (MIN operator), and the resulting membership function is implemented using an aggregation block implemented in the form of a logical sum (MAX operator). The resulting membership function belongs to the set of fuzzy numbers, so an appropriate defuzzification (sharpening) method must be used. The model uses the centroid method, which takes into account all active rules in the sharpening process. Determining the acute value involves calculating the $y_c$ coordinate of the center of gravity of the area under the curve defined by the resulting membership function. The operation of the inference rules and the output state after the defuzzification process can be observed in the rules view of the MatLab program (Fuzzy Logic Toolbox) – Fig. 18. The controller shows the shape of the input and output membership functions.

In the case presented in Fig. 18, the values of the input parameters were determined: DK = 5, TSM = 10, PZP = 35. The adopted values constitute fifty percent of the maximum value of the defined parameters. In order to determine PNBZZ, the following rules were activated: No. 13 and No. 14. On this basis, the MatLab environment made it possible to calculate the value of the output parameter, which in this case is equal to 0.573.

Probability surfaces for repair/maintenance of equipment without undue delay (PNBZZ) were determined in three-dimensional configurations, i.e. depending on: (TSM, PZP) – Fig. 19, (TSM, DK) – Fig. 20, (PZP, DK) – Fig. 21.

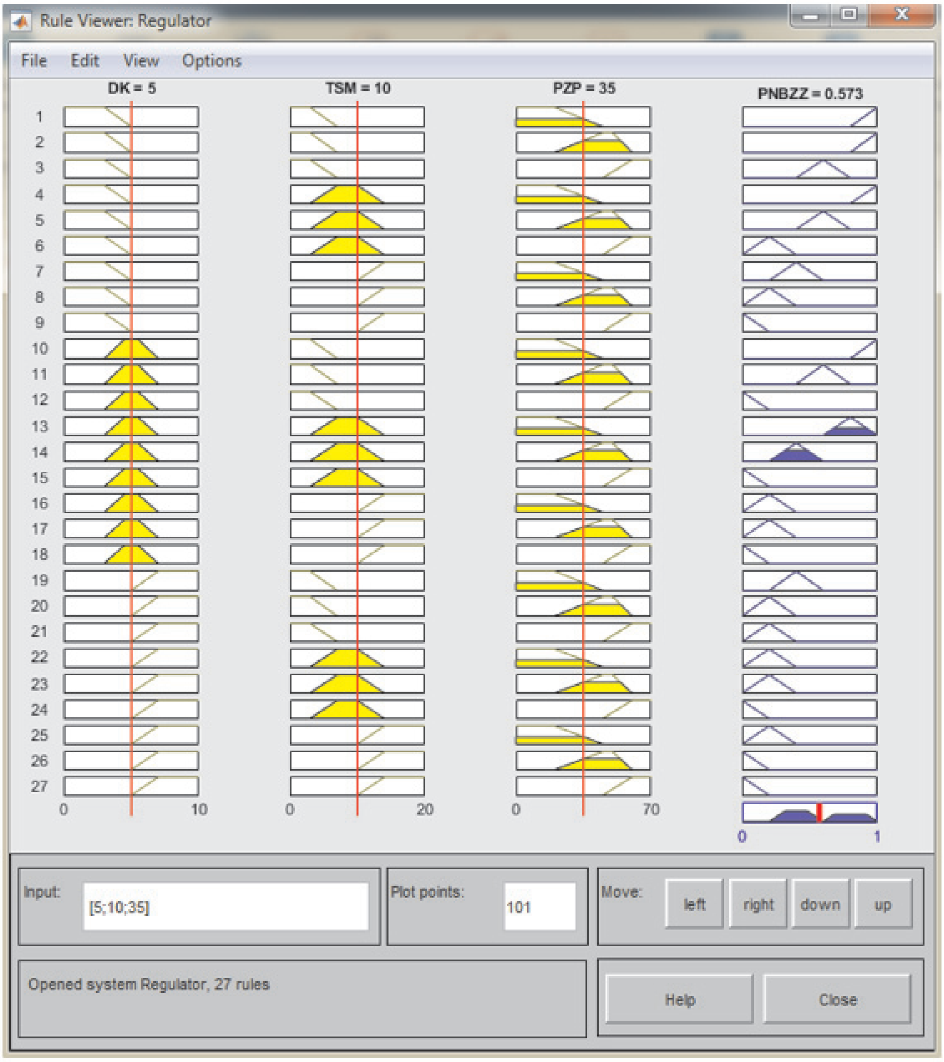


Fig. 18. Widok regulatora wnioskowania w oprogramowaniu MatLab
Source: Own study

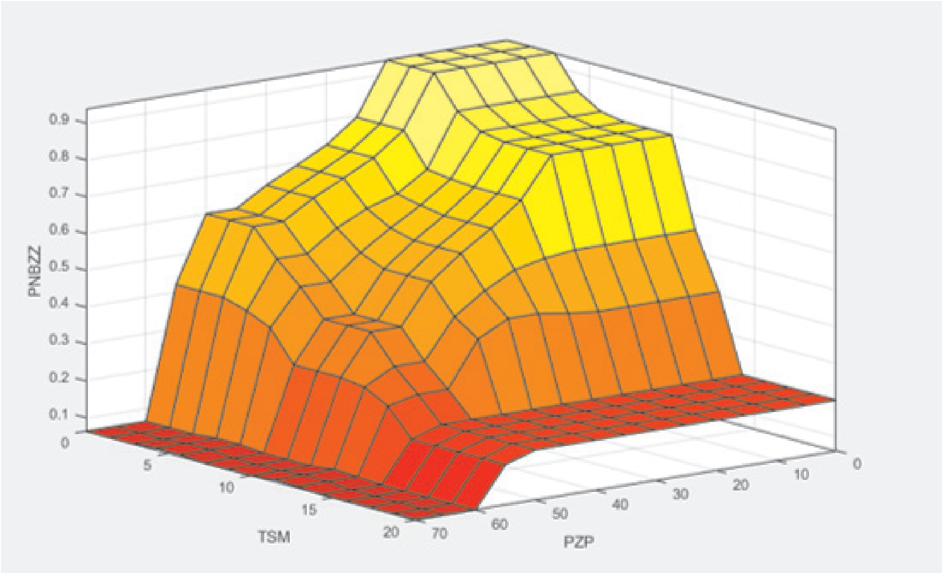


Fig. 19. Dependence of PNBZZ on the availability of TSM and the time of the PZP procedure
Source: Own study

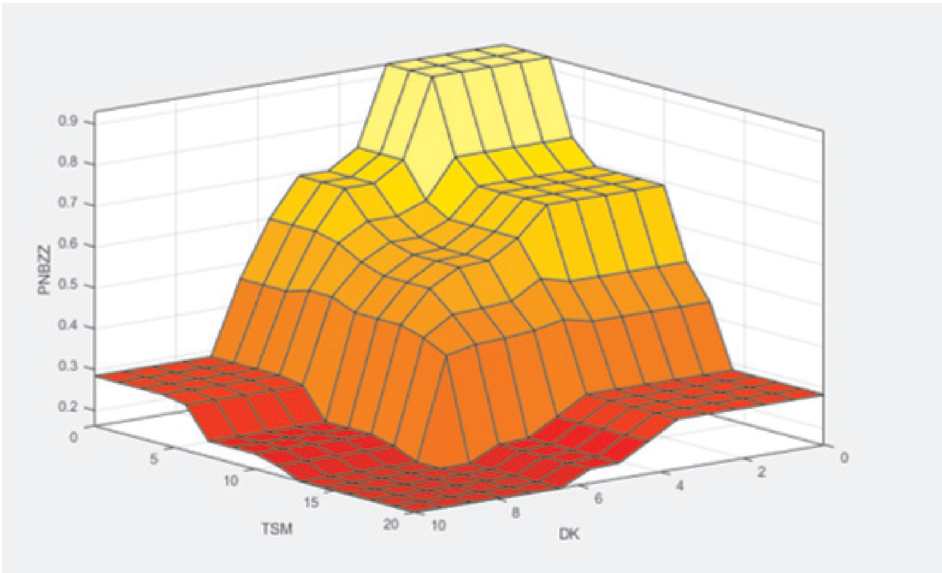


Fig. 20. Dependence of PNBZZ on the availability of TSM and the circulation time of documents DK
Source: Own study

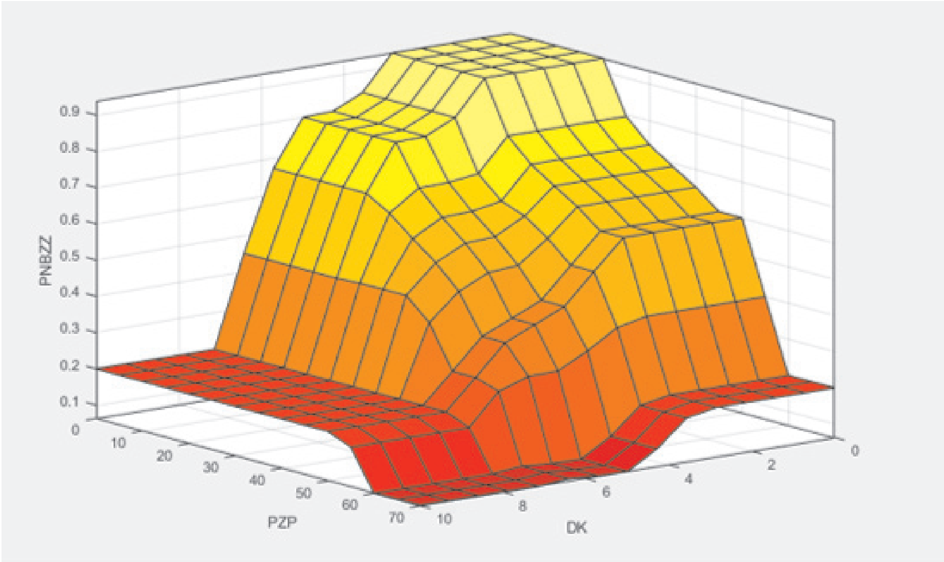


Fig. 21. Dependence of PNBZZ on the time of PZP procedures and the circulation of DK documents

Source: Own study

It should be noted that the time of circulation of documents – DK has a significant impact on obtaining a high value of the probability of completing the task without excessive delay – PNBZZ. The DK parameter also has a very significant impact on the value of PZP and TSM. Also for the TSM parameter, leaving the range of the linguistic value "short" causes a significant delay in the implementation of repairs. The time values defined by experts for the PZP parameter membership function are very high. Therefore, in order to reduce the implementation time of the renewal task, it is necessary to define a procedure based on the electronic circulation of documents within the relationship between the military unit cells and the PZP unit, and to look for methods of forecasting and planning resources that allow maintaining the optimal structure and level of inventories.

In order to verify the adopted assumptions and confirm the formulated conclusions, preliminary, limited research was carried out on the characteristics of damage and the repair process of two groups of vehicles in a selected military unit. It was found that both for the resource measured by mileage (in kilometers) and by the value of operating time (in days), the empirical distribution of damage can, with high and sufficient accuracy, be reproduced with an exponential distribution. It was also found that in the case of a significant number of repairs, the downtime at the service station significantly exceeds the value of the required workload (fig. 22) – it should be also emphasized that these measures are not directly comparable.

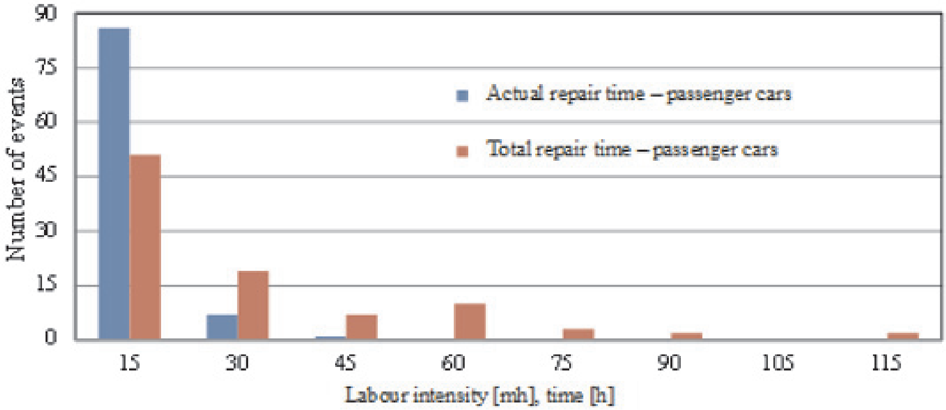


Fig. 22. Histogram of the actual and total repair time for passenger cars
Source: Own study

## Conclusions

The requirements for maintaining a high degree of technical readiness of military equipment and a high degree of operational readiness of the national defense system force continuous improvement and rationalization of the process of managing military technical equipment. An effective way to meet these requirements is to scientifically identify the operating conditions and causes of failures of the exploitation system and to take reasonable actions based on the results of such assessment.

The presented analysis indicates the validity of optimizing and rationalizing the processes taking place in the maintenance and repair system. Areas of particular interest, based on the results of a survey of a randomly selected sample of respondents, should be: availability of spare parts and the method of obtaining them, planning procedures, document circulation, economics and management of service and repair potential, and the availability of financial resources.

Conclusions resulting from research on the functioning of the technical equipment maintenance system in the Polish Army indicates that a significant part of the processes related to the exploitation of equipment is carried out using tools used in the operation of earlier generation equipment. This does not ensure a sufficient level of effectiveness and efficiency of the system. Areas requiring particularly precise analysis and improvement are:

1. equipment operation planning – searching for preventive/proactive strategies due to the implementation of tender procedures in the context of unplanned operational tasks,

2. creation and use of databases on operational events of technical facilities for the needs of computer decision-making algorithms,
3. procedures for information circulation, including those involving public procurement units,
4. implementation time and fluency of the procedures used,
5. planning the level and structure of technical stocks of material resources,
6. searching for innovative methods of managing the maintenance and repair base.

The results of the survey indicate that the basic parameters for evaluation the functioning of the maintenance and repair system: efficiency, economics, modernity of management and task implementation were rated by the survey participants as "average" in most responses. The personnel qualifications parameter has its maximum in the "fairly high" area, but a significant part of the answers is also in the "average" response area. This also indicates the need to develop and improve the system of servicing and repairing military equipment in the armed forces and to optimize the processes implemented in this area.

There are significant disruptions in the functioning of the military equipment maintenance and repair system, which determines the intensity of servicing and long-term downtime of equipment in the maintenance system. The main factors resulting in the inability to perform repairs without undue delay, which have a significant impact on the extension of service and repair times, are: improper planning of spare parts inventories, the need to comply with the principles of public procurement law in this regard, as well as the long period of circulation of paper documents, procedures their processing and decision-making.

The factor emphasized by expert-respondents that significantly influences the functioning of the system is the legal context, i.e. the Public Procurement Law. According to experts, this significantly limits the effectiveness of restoring the equipment's functionality, resulting in excessive extension of the time required for repairs or scheduled equipment maintenance. Due to the above, it is necessary to analyse the scope of possibilities of implementing a strategy for the operation of military equipment based on preventive inspections. This would reduce the number of repairs and, consequently, the processes of obtaining technical material resources involving public procurement units.

In general, the appropriate model for the reliability of the tested military equipment is the exponential distribution. This is also confirmed by the analysis of the research results of other authors in the field of military equipment reliability models. This creates the possibility of implementing strategies in the maintenance and repair system of military equipment based on knowledge of the features and characteristics of equipment reliability, e.g. the RCM strategy – Reliability Centered Maintenance. This, combined with an efficiently functioning diagnostic system, would significantly reduce the number of equipment damages and forced repairs.

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