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CIVIL ENGINEERING

# Maintaining technical readiness in the context of military exploitation systems

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**Abstract.** Readiness and reliability is a special attribute of rescue systems (army, police, fire service), where performance at the highest level is more important than economic efficiency. For this reason, special attention is given to the process of renewal of technical objects. In such systems, a preventive strategy is most often used. Though this is a safe model, it does not always take into account the specifics of the use of a technical object. Moreover, in some situations, it forces the end of life of a device that could still continue to operate as intended. The article analyzes precisely such technical objects, removed from operation after just 10 years of use. It was shown that such approach is not justified and that modern management strategies must be implemented also in relation to machinery and equipment operating in rescue systems. The most important achievements of the article are the use of reliability analysis methods in the systems where it is not common, and the indication of the benefits of such analysis. It has been shown that knowing the characteristics of reliability, you can consciously control each process and make decisions in this regard based on the technical condition of the facility and not on instructions. In the case under study, this would make it possible to undermine the decision to withdraw the analyzed objects from operation.

**Key words:** readiness; reliability; safety; technical objects; preventive maintenance strategy; renewal process.

## 1. INTRODUCTION

The main task of rescue and law enforcement services is to ensure the protection of life, health, property or the environment, as part of their actions [1]. The impact of this activity on national security is undeniable [2]. Therefore, such systems are subject to different rules than those applying to traditional economic units (enterprises). The purpose of the latter is to make a profit, and their success is measured by various indicators and metrics, primarily related to the value of revenue, turnover, efficiency [3], productivity [4], etc.

For the rescue and law enforcement services, efficiency is crucial. It is influenced by many factors, primarily by the degree of training of the staff, their skills and experience, as well as the readiness, technical level and availability of the technical equipment owned [5]. These are expressed in the realization of tasks at the required quality level, i.e. under certain conditions, in a certain place, quantity and time. The elements of such an assessment form a set of measures related to the efficiency, readiness and reliability of the entire system [6] and of each element individually [7].

The guarantee for correct use comes from the properly implemented process of operation. Preventive refurbishment strategies are most commonly used for systems where human life and health depend on the performance of individual components [8]. This is also a popular strategy in various industrial areas such as manufacturing systems [9] or transportation [10] and power systems [11].

The preventive method requires detailed planning of the maintenance schedule [12], but this makes it simple, understandable, and available to carry out without specialized knowledge, which is ideal for hierarchical systems with high staff turnover, such as the military [13]. A properly constructed maintenance plan balances the trade-off between reducing the risk of failure and conserving maintenance resources, thereby improving system readiness and reducing system operating costs [14]. At its core is an assumption about the life cycle of the device and the potential risk of damage [15]. Preventive maintenance can be scheduled according to the passage of a certain time or the performance of a certain job. This method is not without its drawbacks. It carries the risk of frequent equipment failures, longer response times to malfunctions (e.g. due to lack of parts). It can cause costly equipment downtime, be the cause of higher replacement cost for failed components, decrease in performance of technical objects and shorter equipment life [16]. Consequently, it can cause delays in completing tasks and functioning under time pressure.

Preventive maintenance, however, in spite of being associated with regular expenses for planning and carrying it out, is more economical than reactive maintenance, which consists primarily of taking corrective and remedial actions when adverse events occur [17].

The most recent concept of maintenance is predictive maintenance, the idea of which is to precisely adjust the activities to the individual, current needs of machines [18]. This strategy is based on anticipating future object conditions and taking appropriate corrective, maintenance and preventive actions in advance. The difficulty of implementing this strategy stems from the need to reliably assess their condition through systematic collection and analysis of key information, continuous

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control of their technical condition and continuous monitoring of the desired parameters [19]. Failure can be prevented only by predicting with a sufficiently high probability when it will occur [20]. This strategy helps to avoid the costs of performing unnecessary maintenance activities when the technical object does not actually require it, but its implementation requires many adjustments in organization. Among the key ones, it is necessary to select the most important devices in relation to which it is worth implementing such a system in order to improve their reliability, to define the data needed to monitor the cause and mode of failure, to determine the appropriate failure prediction algorithms and the system for monitoring this algorithm in real time [21]. Such a procedure requires appropriate infrastructure to collect and distribute the data acquired from the sensors, including the internet. It is therefore not only a technological, but also organizational challenge. This is probably why such solutions are implemented primarily in market enterprises. State organizations, limited by budget, development and the nature of their tasks, rely primarily on preventive strategy. However, the model used to determine the optimal preventive refurbishment periods should also be adapted to the specifics and operating conditions of the object under consideration. Only then will the implementation of maintenance according to the schedule of the preventive model be justified. Meanwhile, despite the opportunities created by modern methods of forecasting technical condition in rescue systems, especially state ones, these processes are carried out on the basis of old manuals developed for non-modernized technology. This is popular in task-oriented public service or law enforcement units like the army. Strictly perceived timelines determine not only maintenance periods but also maximum lifetimes, which are not always justified for some technical objects. An example of such a device is presented in this paper, in which a group of homogeneous technical objects is studied. Their maximum life is based on the guidelines contained in the manuals dating back to the 1960s, while, in the author's opinion, it is not adjusted to the real conditions of use and could be successfully extended, as presented in this study.

There are two main objectives of the article. The first of them is the analysis of the process of using technical equipment operating in national operation systems in the context of the adopted operating strategy. The second objective is to present the inadequacies of using the chosen strategy and the need to modernize outdated policies often in place in state rescue or law enforcement agencies.

The structure of the article is as follows. The introduction reviews the literature, highlights the specifics of operation systems of rescue and law enforcement services, characterizes the methods used to maintain the proper technical condition of technical objects, indicates the existing problem and formulates the purpose of the study. The method of the study and the mathematical analysis tools used are then presented. In the following section, the parameters of the static models are estimated and evaluated with reference to the stated objectives of the study. The article concludes with a summary of the analyses and final conclusions.

## 2. MATERIALS AND METHODS

In practice, it is rare to have full access to performance data covering overall characteristics of technical objects. It is also difficult to collect a research sample that was put into operation at exactly the same time. Moreover, very often, due to the lack of reliable data, obtaining complete and accurate reliability information is impossible and therefore certain assumptions and simplifications are made in reliability analyses, especially concerning the form of distribution, and most often average values are used for approximate analyses and calculations, which may give only approximate results. Since in the study being analyzed the author had a complete set of observations from the moment of putting into operation until decommissioning, in the first stage of the study, goodness of fit between empirical distributions and parametric distributions was tested and on this basis the selected reliability characteristics were determined. This study was preceded by the computation of basic descriptive statistics to compare the results for each technical object. The algorithm of the analyses performed is presented in Fig. 1.

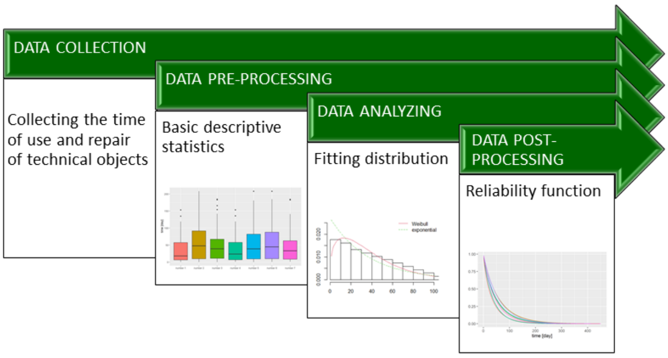

**Fig. 1.** Algorithm of the study

The simplest of the distributions used in reliability theory is exponential distribution [22]. It exhibits a property called memorylessness, which means that the probability of an object's fitness is independent of the length of time it has been in use, therefore a used undamaged object is assumed to be as reliable as a new object [23]. However, because exponential distribution, which does not take into account changes due to use and aging processes, is applied to objects, the study uses a model that accounts for changes over time. The best fitting results (according to Akaike criterion) were obtained for the two-parameter Weibull distribution, which is an extension of exponential distribution in that in exponential distribution the damage intensity $\lambda$ (distribution parameter) has a constant value, while in the Weibull distribution damage intensity is monotonically variable.

A repairable component reliability model, i.e. a component renewal process model with non-negligible refurbishment interval, was used for the study. A study of total lifetime (10 years) was performed, since after this time, according to regulations in force, the studied objects are decommissioned. It was checked how the basic reliability indicators evolve after that time. The distribution of operating times of objects was assumed to have a Weibull distribution, which is defined by the following probability density function:

$$f(t)=\frac{\beta}{\Theta}\left(\frac{t}{\Theta}\right)^{\beta-1}e^{\left[-\left(\frac{t}{\Theta}\right)^{\beta}\right]}, \tag{1}$$

where $\beta$ is the shape parameter and $\Theta$ is the scale parameter, while $t\geq 0$, $\beta>0$, $\Theta>0$.

The reliability function is expressed by the formula below:

$$R(t)=e^{\left[-\left(\frac{t}{\Theta}\right)^{\beta}\right]}. \tag{2}$$

In contrast, damage intensity is calculated as follows:

$$\lambda=\frac{\beta}{\Theta}\left(\frac{t}{\Theta}\right)^{\beta-1}. \tag{3}$$

The function of expected remaining uptime, on the other hand, was determined from the following relationship [23]:

$$r(t)=E\left[T-t\,|\,T\geq t\right], \quad t\geq 0.$$

Thus:

$$r(t)=\int_{t}^{\infty}\frac{R(x)}{R(t)}\,\mathrm{d}x=\frac{1}{R(t)}\int_{t}^{\infty}R(x)\,\mathrm{d}x \tag{4}$$

for a Weibull distribution, while the expected remaining uptime is expressed by the formula below:

$$r(t)=\int_{t}^{\infty}\frac{\exp(-\beta x^{\alpha})}{\exp(-\beta t^{\alpha})}\,\mathrm{d}x=\int_{t}^{\infty}\exp\left[\beta\left(t^{\alpha}-x^{\alpha}\right)\right]\mathrm{d}x. \tag{5}$$

The goodness of fit between empirical distribution and parametric distribution was tested using the Kolmogorov-Smirnov test. The K–S test uses the $\lambda$ statistic, which is based on a comparison of empirical distribution with tabulated theoretical distribution. At the significance level of $\alpha$, the null hypothesis is:

$$H_0:\ F_{\text{data}}(x)=F_0(x), \tag{6}$$

where: $F_{\text{data}}(x)$ – the distribution function of empirical distribution, $F_0(x)$ – the distribution function of theoretical distribution.

The K–S test statistic measures the largest distance between the EDF (*empirical distribution function)* $F_{\text{data}}(x)$ and the theoretical function $F_0(x)$ measured in a vertical direction. The test statistic (for a two-tailed test) is given by:

$$D=\sup\left|F_0(x)-F_{\text{data}}(x)\right|. \tag{7}$$

For a one-tailed test, absolute values shall be omitted from the formula. If $D$ is greater than the critical value, the null hypothesis is rejected.

## 3. RESULTS AND DISCUSSION

In the empirical study, first the basic descriptive statistics of operating time of all the technical objects studied were evaluated separately. The calculated values are presented in Table 1.

**Table 1**

Basic descriptive statistics for the objects studied

| Object No. | Number of observations | Average [day] | Median [day] | Min [day] | Max [day] | Sd [day] |
|---|---|---|---|---|---|---|
| No. 1 | 18 | 273 | 292 | 167 | 367 | 70 |
| No. 2 | 20 | 258 | 266 | 105 | 383 | 78 |
| No. 3 | 20 | 264 | 283 | 144 | 357 | 61 |
| No. 4 | 20 | 262 | 282 | 150 | 355 | 59 |
| No. 5 | 17 | 262 | 270 | 163 | 374 | 69 |
| No. 6 | 21 | 256 | 277 | 113 | 324 | 60 |
| No. 7 | 20 | 268 | 287 | 98 | 364 | 66 |

It is worth noting that the calculated parameters are similar over the 10 years analyzed (Fig. 2). The number of observations – or periods of trouble-free use – is similar, ranging from 17 to 21, which means two repairs per calendar year on average. The average operating times are also similar and all are greater than 260 days, meaning operation for more than 9 months on average. The smallest recorded value during the study period is 97 days, i.e. over 3 months. On the other hand, the maximum time is 374 days and means more than a year of operation of the object without any technical intervention, so it can be concluded that failures do not occur frequently.

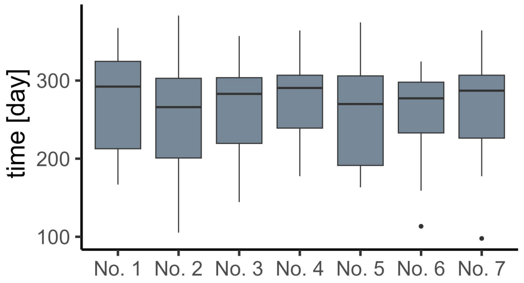

**Fig. 2.** Box-and-whisker plot of time of normal operation until failure for all objects

In the next step, the goodness of fit between empirical distributions of operating time until failure and the two-parameter Weibull distribution were presented, and the basic characteristics of this distribution were determined. The analysis was performed for all studied objects. A detailed description of the study is presented for object No. 1. The study of the other objects was carried out similarly, so only the final results are presented for clarity.

According to the presented methodology (Section 2), the goodness of fit between empirical distribution and parametric distribution was tested using the Kolmogorov-Smirnov test. The results of the K–S test for testing the goodness of fit between empirical distribution of operating time until failure and the Weibull distribution for object No. 1 are presented in Table 2.

**Table 2**

Results of the K–S test of operating time (object No. 1)

| | Weibull |
|---|---|
| D Statistics | 0.13289 |
| p-value | 0.8678 |

The goodness of fit is shown in Fig. 3, where the distribution functions of theoretical and empirical distributions as well as the categorized probability-probability (P–P) plot, allowing to determine how well a given theoretical distribution reflects the empirical data distribution, are presented.

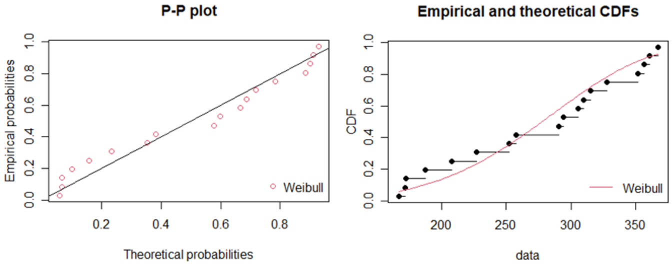

**Fig. 3.** Fitting the Weibull distribution to the empirical data for object No. 1

Analogous estimates of the Weibull distribution parameters were made for the operating time of the other technical objects, confirming, in each case, goodness of fit by means of the K–S test (no basis for rejecting the null hypothesis). All the obtained results are presented in Table 3.

**Table 3**

Estimated parameters of exponential and Weibull distributions for the operating time of individual objects

| | Weibull shape | Weibull scale | D-statistic | p-value |
|---|---|---|---|---|
| No. 1 | 4.787 | 299.81 | 0.133 | 0.868 |
| No. 2 | 3.938 | 285.14 | 0.112 | 0.938 |
| No. 3 | 5.521 | 286.88 | 0.164 | 0.601 |
| No. 4 | 5.616 | 284.66 | 0.162 | 0.615 |
| No. 5 | 4.453 | 288.12 | 0.145 | 0.818 |
| No. 6 | 5.786 | 277.43 | 0.155 | 0.642 |
| No. 7 | 5.146 | 291.44 | 0.146 | 0.736 |

This allowed the calculation of basic reliability parameters. First, damage intensity was analyzed by determining its change over time according to (3). Damage intensity $\lambda(t)$ is a function expressing the relative deterioration of object reliability per time unit $\Delta t$. It expresses the conditional probability of element failure in the time interval of $(t, t+\Delta t)$, provided that the element was operational at time $t$. It is a local (in terms of time) characteristic of the reliability (durability) of the element and is seen as the basic characteristic of the lifetime of the object. The determined damage intensity functions for individual objects according to the Weibull distribution are presented in Fig. 4.

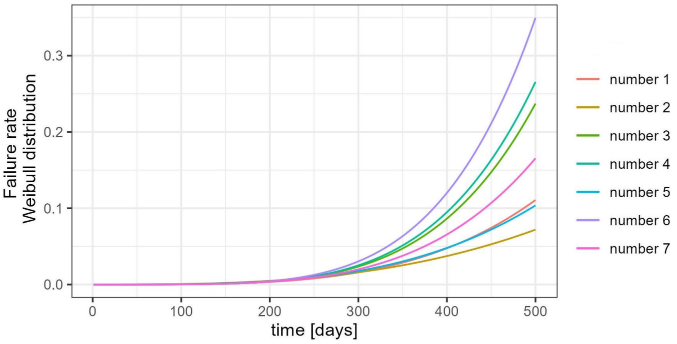

**Fig. 4.** Damage intensity function plots according to Weibull distribution

Damage intensity function $\lambda(t)$ varies over time, and three major stages are distinguished according to this waveform. The first type is an intensively decreasing function; this is when hidden defects in construction, assembly, technological inaccuracies, oversights during checks and mistakes are revealed. Thus, at the beginning of the use of a technology product, damage intensity is high, after which it decreases and remains constant.

The second possibility is the increasing type, when the unfitness is revealed due to the accumulation of irreversible physical and chemical changes, the continuous aging of materials, their wear, deformation of the structure, gradual change in the value of the parameters of the object, up to and beyond the acceptable limits. Thus, at the beginning of use, the intensity of damage is constant, and from a certain time, due to aging, it increases rapidly.

There is also a third type, which is a combination of types one and two, when initially damage intensity decreases rapidly, then maintains a constant level indicating damage stabilization, until a boundary time is reached when the trend changes from decreasing to increasing.

Based on the above plot and theory, it can be concluded that the damage intensity function is consistent with type two – it is increasing – at the beginning the increase is not significant, as the malfunctions rate starts to increase more intensively around the 300th day. It is worth noting that the studied objects are subjected to annual inspections and, therefore, the increase in the damage intensity function takes place exactly after roughly one year of operation. During this period, the equipment is subjected to a maintenance process that restores it to a serviceable condition that again allows for nearly a year of damage-free operation. This allows us to conclude that the lifetime characteristics of the tested objects are very good.

Next, the reliability function was determined following the Weibull distribution according to (2). The waveform of the reliability function for the studied objects is presented in Fig. 5.

The reliability function allows for the calculation of the probability of failure in a specific time $t$. Reliability is defined as the probability of an event, which consists in the fact that a techni-

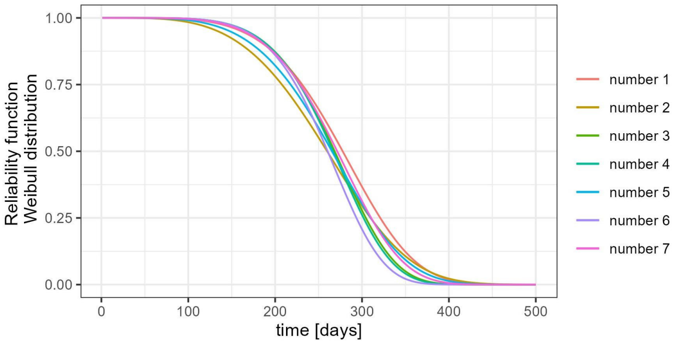

**Fig. 5.** Graph of reliability function $R(t)$ according to Weibull distribution

cal object used under specific conditions will be able to meet the requirements imposed on it in a specific period of time of use. Therefore, the reliability of the tested objects is very satisfying, and regular renewal treatments help maintain its high level. As can be clearly seen in Fig. 5, the waveform of the reliability function for all the studied objects is very similar. The function between zero and almost 100 days is constant, then begins to decrease gradually. There is a definite decrease in the reliability function between 200 and 400 days. Similarly, this coincides with the timing of annual inspections. Thus, it can be seen that periodic refurbishments are conducive to maintaining a level of reliability that ensures almost a year's trouble-free operation.

It is worth noting that the reliability of an object that has already been in use for a certain period of time is generally different than the reliability of the same object at the start of its use [23]. Therefore, in the analyzed case, it is expedient to determine an additional parameter, i.e. reliability of the object in use. It is described by a function whose value at each point is equal to the conditional expected value of the object's remaining uptime. This function is called expected remaining time and is calculated from (4). Based on it, the function waveforms were determined for all the objects. The results are presented in Fig. 6.

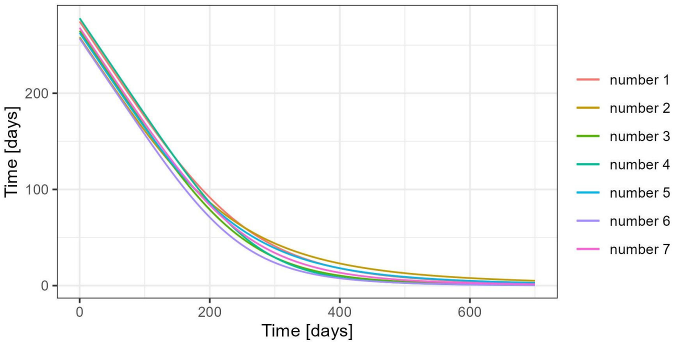

**Fig. 6.** Graph of the function of the expected remaining uptime of objects

The remaining expected time of correct operation is a parameter that not only characterizes the level of reliability, taking into account the aging processes occurring in technical objects, but also provides information on the risk associated with failure-free operation in operational processes. The function of the expected remaining uptime of objects has a slightly different waveform than the reliability function. This is a decreasing function, which means that each additional day promotes a decrease in the remaining uptime and reliability of this object. However, the low function values are again only reached at the scheduled inspection date, i.e. around the 400th day of operation.

The results obtained in this study mainly show the consistency of the function waveforms for the different objects – all of them wear very similarly, which allows us to conclude that the sample reflects the population well.

The obtained characteristics show the long reliability and uptime of the objects, i.e. around one year, which, as already emphasized, is a result of the annual periodic inspections taking place during this time. During these inspections, the condition of the object is verified and refurbishment measures are carried out in relation to the identified needs. As the analysis shows, these processes permit the analogous time of correct operation of the objects over the entire period studied. Therefore, the obtained results do not justify discontinuing the operation of the studied objects and qualifying them as unfit for use. They can be successfully used for further periods of time. Conscientiousness of periodic inspections and regular refurbishments provide the guarantee for a long time of their reliability.

## 4. CONCLUSIONS

The use of reliability testing methods is common in the literature, however, in some operation systems, users underestimate their potential and do not make key decisions based on them. The novelty of the article lies in the fact that an analysis of systems in which the implementation of the task at the highest level is more important than economic efficiency is performed. Therefore, the assumption of this article was to demonstrate the legitimacy of such practices even in structures where it is not popular. The Weibull distribution was used for this purpose, as it turned out to be the most accurate distribution describing the working time until failure (the moment of reporting the fault or the service time). This made it possible to determine the basic characteristics of reliability.

It is worth emphasizing that, among other things, the remaining expected time of correct operation was calculated, which characterizes the reliability of the element better than the expected operating time, which is more popular in the literature, because it takes into account the aging processes occurring in technical objects.

Knowing the reliability distribution, it is possible to consciously control any process, but there are situations where decommissioning of an object is due to the requirements set out in its manual rather than actual wear and tear. This applies, as in the presented article, in particular to objects in case of which very high reliability is required, most often performing tasks in the systems of rescue and law enforcement services. Therefore, early decommissioning decisions are made to maintain a high level of safety. Such situations also apply to institutions that follow old manuals which do not take modern diagnostic methods into account. Therefore, the purpose of the article was to point out that this approach is not always valid. A ten-year operating period of seven objects was analyzed and no significant deviations from the mean values were found among the objects throughout the study period. This allowed the sample to be considered representative. The analysis of the reliability function and the function of the expected remaining uptime of the objects allowed to formulate a conclusion about the almost one-year period of correct operation of the device. This is because annual inspections and refurbishments allow for another year of virtually trouble-free use. Based on the presented study, it should be concluded that the decommissioning of the analyzed objects was not justified.

With reference to the above, the key achievements of the article can be summarized in the following points:

1. The use of reliability analysis methods in systems where it is not common has been proposed and the benefits of such analysis have been indicated.
2. It was shown that knowing the characteristics of reliability, it is possible to consciously control each process and make decisions in this area.
3. It has been shown that in the analyzed case, annual inspections and renewals determine the next year of operation with practically no faults, which allowed to undermine the decision to withdraw the analyzed objects from operation.
4. The need to use additional diagnostic methods to make a reliable assessment of the reliability of objects in the tested system was indicated.

Summarizing the study conducted, it would be advisable to use other diagnostic methods that assure users of the high reliability of objects and the safety of the system in which they operate. Predictive maintenance tools and techniques, which are based on predicting the future condition of objects and taking appropriate corrective, maintenance and preventive actions in advance, can be a proposal in this respect. Adapting diagnostic methods to individual objects, especially in the analyzed case, would be advisable and would allow to extend the period of their operation. This will become the subject of further research.

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