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ANDRZEJ WDZIĘCZNY[*], MACIEJ WOROPAY[*],
ŁUKASZ MUŚLEWSKI[**]

Division and investigation of damages to technical objects and their influence on the reliability of operations of complex operation and maintenance systems

K e y w o r d s

Transport system, reliability, efficiency, maintenance, failures, operation quality

S ł o w a k l u c z o w e

System transportowy, niezawodność, skuteczność, naprawa, uszkodzenie, jakość działania

S u m m a r y

The operation and maintenance factors as well as the destructive processes of the technical object elements cause unfavourable changes in the values of the significant functional features causing failures. A damage to a technical object has been defined as exceeding admissible limiting values by significant values of the features describing its elements. Based on the analysed references in question as well as on the results of our own research, it has been found that the damages to the means of transport, being utilised within the transport systems, are a result of the interaction of various forcing factors. Some number of the damages results from natural wear of the machines, while the other damages may be caused by an inefficient repair of the previous damage. This leads to secondary damages that occurred within a short time interval. They result

[*] University of Technology and Life Sciences in Bydgoszcz, Department of Machine Maintenance, Kordeckiego St. 20, 85-225 Bydgoszcz, Poland, phone: (52) 340 84 95, e-mail: kem@utp.edu.pl.
[**] University of Technology and Life Sciences in Bydgoszcz, Department of Materials Science and Engineering, Kordeckiego St. 20, 85-225 Bydgoszcz, Poland, phone: (52) 340 87 16, e-mail: l.muslewski@wp.pl.

from inappropriate organisation of the repairs, the poor training level of the repairing team workers, limits related to pre- and post-repair diagnosis, thus directly affecting the operation reliability of the systems and the technical objects being operated and maintained within them. Based on the analysis of the investigation results, it has been found that the reason for the secondary damages is, in general, improper quality of the repairs of the primary damages to the subsystem elements. The primary damages are independent to one another, and they occur randomly (they are not connected with one another by the cause and effect links). The secondary damages are dependent, because their occurrence depends on the prior occurrence of the primary damage and the effect of its improper repair or improper repair of the next secondary damage.

1. Introduction

The operation and maintenance factors as well as the destructive processes of the technical object elements cause unfavourable changes of the values of the significant functional features followed by damages. Based on the analysed references in question [9, 10] as well as on the results of our own research, it has been found that the damages are a result of the interaction of various forcing factors. Some number of the damages result from the natural wear and tear of the equipment elements, while other damages may be caused by an ineffective repair of the damage occurred previously. The subjects of these repairs are technical objects that constitute significant links in the operation and maintenance processes. Consequently, it is obvious that such objects or their individual elements, in respect of the operation quality of the system in which they are being maintained and operated, should be characterised by an adequate level of reliability, safety, readiness, and effectiveness.

On the basis of the analysis of the results from the performed investigations, it has been found that the operation quality and particularly durability and reliability of the technical objects being subject to earlier repair or recovery is decreased.

It has been demonstrated that the cause of secondary damage occurrence is, in general, an improper quality of the primary repairs of the subsystem elements. The primary damages are independent to one another, and they occur randomly (they are not connected with one another by the cause and effect links). The secondary damages are dependent, because their occurrence depends on a prior occurrence of the primary damage and on the effect of its improper repair or on improper repair of the next secondary damage.

2. Repairs and damages of the technical objects

Based on the analysed references in question [1,2] as well as on the results of our own research, it has been found that the damages to the individual elements – technical objects within the considered systems, are a result of the interaction of various forcing factors. These factors may be divided into the following:

- Working factors – affecting a machine due to the realisation of the working process by the machine (they depend on the machine performance),
- External factors – describing the influence of the environment on the machine (they do not depend on the machine performance), and
- Antropotechnic factors – affecting the machine due to conscious or unconscious human actions (e.g. human faults made during the process of utilisation and maintenance).

The general definition of a damage to a technical object has been defined as exceeding the acceptable limiting values by the significant features describing its elements.

Three types of damages to the technical objects have been distinguished in this paper [1-3]:

- Damages caused due to the wear and tear of their elements (parametric ones);
- Damages to the elements caused due to the operator's faulty action; and,
- "Repeated" damages, meaning damages to the elements of an object, occurring within a short time interval, caused due to an improperly performed repair.

These damages concern the same assembly – technical system (technical object). Determination of the reasons for the ineffective repairs, followed by their elimination, will facilitate to reduce financial expenditures suffered by the system in which they are being operated and maintained.

A repair is considered to be effective when it assures obtaining serviceability condition, enabling to accomplish the task by a respective technical object being responsible for this, within a determined time interval and with specified level of interactions of the forcing factors.

Some number of the damages resulting from the natural wear and tear of the machine elements, while other damages may be caused by an ineffective repair of the damage that occurred previously. Subsequently, secondary damages appear within a short time interval. They result from incorrect organisation of the repairs or repair cycles and processes, the poor training level of the repair team workers, constraints related to the pre- and post-repair-diagnostic activities, etc. The time intervals occurring between the consecutive damages to the technical objects and the moments they appear were analysed in the framework of the operation and maintenance investigations carried out.

When analysing statistically the moments these damages occur, a difference between the theoretical distribution and empirical distribution of the time interval values occurring between these moments (Fig.1) was observed. The difference between the theoretical distribution and the empirical distribution occurring at the beginning of the interval $(0, t_p)$, from the moment p declines to zero. However, inside the interval (t_p, ∞) the theoretical function is consistent with the empirical distribution. This discrepancy results from the secondary damages caused by the improper quality of the repairs of the damaged elements that occur in the interval $(0, t_p)$. The analysis of the empirical data (the length of the time intervals between the damages) indicates that it is reasonable to describe the probability distribution of the correct work times with the reliability function $R(x)$ formulated as follows[4]:

$$R(x) = pe^{-\lambda x} + (1-p)R_w(t) \tag{1}$$

It is a combination of the exponential distribution $pe^{-\lambda x}$ (with unknown value of the parameters $(p\lambda)$ and the reliability function $R_w(t)$. The estimation of the distribution parameters $(p\lambda)$ with the reliability function described with the dependence (1) is a complex problem.

Assuming that for unknown distribution (of the times of correct work) focused on the limited time interval $(0, t_p)$, it is possible to estimate the values of the parameters p and λ, then for high values of t it may be adopted that: $R(t) \approx p*exp(-\lambda t)$. In that case, by using the methods of the linear regression (in the semi-logarithmic system), the values of the parameters p and λ may be evaluated for different random tests cut off from the bottom. For each approximation, a regression standard fault is calculated – $S(i)$, where i stands for the index of the day from which the data are analysed. The analysis of the changes $S(i)$, depending on the value of i, indicates that there is a minimum $s(i)$ for various i, mostly for $i = 5, 6,..., 12$.

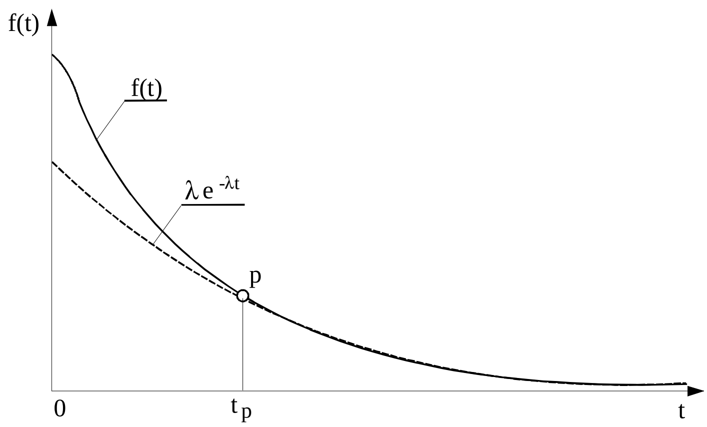

Fig. 1. Changes of the value of the exponential function and real function at the time *t*
Rys. 1. Zmiany wartości funkcji wykładniczej i rzeczywistej w czasie *t*

The changes of the real function may be described by a combination of the probability distribution with density *g(t)* and exponential distribution.

Let $\tau_i(k)$, where $i = 0, 1, 2, \ldots$, $\tau_0(k) = 0$, $k = 0, 1, 2, \ldots, n$ stand for the stream (moments) of the damages of the *k*-th technical object.

The difference $\tau_{i+1}(k) - \tau_i(k)$ for $i = 0, 1, 2, \ldots$, stands for the length of the time interval between $i+1$-st and i-th damage of the *k*-th technical object.

$Y_i(n)$ denotes superposition *n* – of the damage streams.

Let $X_i(n) = Y_i(n) - Y_{i-1}(n)$, where $i = 0, 1, 2, \ldots, Y_0 = 0$

It is assumed that the distribution of the random variable $X_i(n)$ does not depend on *i*.

According to the theorem of Grigelionis, it is known that with $n \to \infty$ the random variable *X(n)* has exponential distribution.

It is assumed that the probability density of the random variable *T* is formulated as follows:

$$f(t) = \alpha \cdot g(t) + (1-\alpha)e^{-\lambda t} \text{ dla } f(t) \geq 0 \quad (2)$$

It is a combination of the probability distribution with the density *g(t)* and the exponential distribution with the density specified with the relationship (3):

$$g_1(t) = \lambda \cdot e^{-\lambda t} \quad (3)$$

The estimation of the parameter α and λ of the density (2) is based on the assumption that the density *g(t)* takes the values above zero, and that they are relatively low and are included within the range from $\langle t_p, \infty \rangle$.

The analysis of the results of the operation and maintenance investigations regarding the moments the damages occur prove that the set of the damages may be divided into subsets of the *primary* and *secondary* damages.

It results from the fact that the consecutive moments of the damages to the same subsystems or their elements (technical objects) are concentrated sequentially after a single damage has occurred. Figure 2 shows a chosen damage stream of an exemplary subsystem.

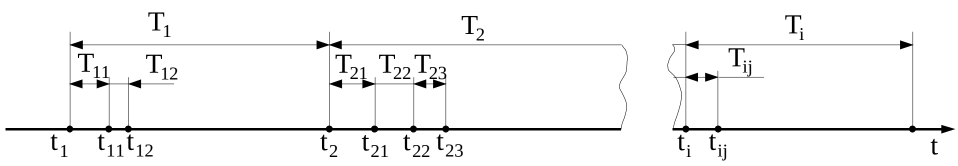

Fig. 2. Time intervals between the primary and secondary damages
Rys. 2. Przedziały czasu pomiędzy uszkodzeniami pierwotnymi i wtórnymi

As it is shown in the Figure 2, the first of the damages that occurred at the moments t_i, cause the sequences of the subsequent damages to the same subsystem (technical object) within short time intervals. These damages are called *primary*. Whereas, the next set of them, with the finite number of repetitions, occurring at the moments t_{ij}, are called *secondary*.

Based on the analysis of the investigation results, it has been found that the reason for the secondary damages is, in general, an improper quality of the repairs of the primary damages to the subsystem elements. The primary damages are independent on one another, and they occur randomly (they are not connected with one another by the cause and effect links). The secondary damages are dependent, because their occurrence depends on a previous occurrence of the primary damage and the effect of its improper repair or improper repair of the next secondary damage. It may be formulated as follows [2, 3]:

$$P(A_{tij}/B_{ti}) > P(B_{ti}) \tag{4}$$

gdzie: $t_{ij}<t_i$, $P(B_{ti})>0$

It means that the probability of occurrence of a secondary damage A_{tij} depending on the occurrence of a primary damage B_{ti} is greater than the probability of occurrence of a primary damage B_{ti}.

Reduction of the conditional probability of the occurrence of a secondary damage may be an initial point for reducing the damage intensity. It may be achieved by eliminating the damages occurring due to unreasonable realisation of the repair process.

As can be seen in the following diagram, the repair faults represent one of the most important reasons for the occurred damages to the individual subsystems. Comparison of the significant reasons for these damages is shown in the Figure 3.

Based on the analysis of our own investigations [9, 10], it has been found that a significant role in increasing the quality level and, in particular, reliability and safety of the technical system operation is played by the identification of the reasons for occurrence of the damages carried out during the time its respective systems or individual elements are repaired. Among the main reasons for the damages resulting from the repair faults, the following ones should be included:

- Using the wrong material,
- Faulty adjustment,
- Faulty repair technology,
- Using a wrong spare part,
- Using a damaged part,
- Using a part made of the wrong material,
- Using a part with a hidden technological defect,

- Using parts with the wrong dimensions,
- Faulty assembly, and
- Dirt left after the repair operations.

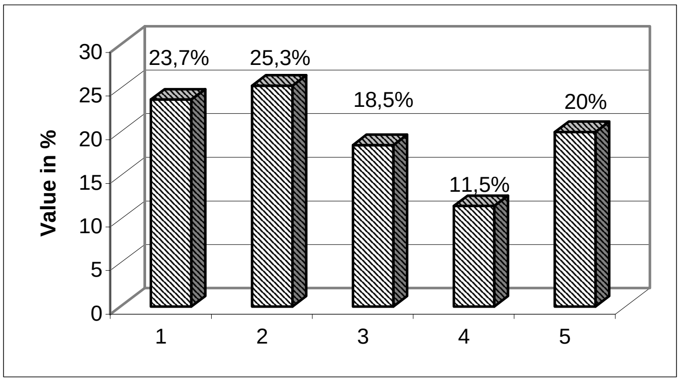

Fig. 3. Occurrence frequency of the reasons for the damages to the system elements: 1 – Repair faults, 2 – Use faults, 3 – The influence of the environment, 4 – Damages to the co-working elements, and 5 – Others
Rys. 3. Częstości występowania przyczyn uszkodzeń elementów systemu: 1 – błędy naprawy, 2 – błędy użytkowania, 3 – oddziaływanie otoczenia, 4 – uszkodzenia współpracujących elementów, 5 – inne

The analysis of the operation and maintenance investigation results prove that reduction of the number of the secondary damages is an essential problem, the solution of which makes it possible to especially improve the operation reliability level of the systems in which they are being operated and maintained.

3. The method to classify damages and evaluate repair effectiveness

In order to classify the damages as primary and secondary, the following criteria were adopted:

- Criterion of an average distance travelled or transmission (in km, kW/h or m^3) between the consecutive damages to the subsystems, as per the relationships (8) and (9), where:
  - L_u – stands for the summarised number of the damages to the system,
  - L_{um} – stands for the number of the damages of the *j*-th subsystem – element,
  - P_c – stands for the total distance travelled or energy transmission during the investigations,

$L_{śrj}$ – stands for the average transmission between two consecutive damages of the investigated *j-th* subsystem, described with the relationship (5):

$$L_{śrj} = \frac{P_c}{L_{uj}} \quad j = 1,2,\ldots,m \tag{5}$$

s_j' – standard deviation [kW/h or m³], described with the relationship (6):

$$s_j' = \pm\sqrt{\frac{\sum_{i=1}^{n}\left(L_{ij} - L_{śrj}\right)^2}{n-1}} \quad i = 1,2,...,n,\ j = 1,2,\ldots,m \tag{6}$$

where: L_{ij} – the distance travelled or transmission between the consecutive repairs of the *j*-th subsystem,

n – number of the measurements that means the value of the travelled distance or transmission between the consecutive repairs of the *j*-th subsystem,

s_j – standard deviation including the t-Student's index depending on the number of the measurements *n* and the confidence coefficient $1\text{-}\alpha$, has been described with the relationship (7):

$$s_j = f_{1-\alpha}\, s_j',\ j = 1,2,\ldots,m \tag{7}$$

- The confidence coefficient adopted in the paper is $1\text{-}\alpha = 0.95$. It is the most frequent value of this coefficient used in the statistical researches. Afterwards, the damages were classified according to the relationships (8) and (9). Previous damage to the *j*-the subsystem was a primary one L_{upj} with fulfilling the relationship (8):

$$L_{upj} = L_{ij} \geq L_{śrj} - s_j, \quad j=1,2,\ldots,m \tag{8}$$

- Previous damage to the *j*-the subsystem was secondary L_{uwj} with fulfilling the relationship (9):

$$L_{uwj} = L_{ij} < L_{śrj} - s_j, \quad j=1,2,\ldots,m \tag{9}$$

where: $L_{śrj} - s_j$ – value describing the threshold between the primary and secondary damages [*km*, *kW/h or m³*].

- Criterion of critical time s t_{kr} determined on the basis of the average time of correct operation between the consecutive damages to the specific subsystem - element.

Based on the analysis of the operation and maintenance investigation results, it was assumed that the time intervals of the correct operation between the consecutive damages to the respective subsystem may be expressed by means of an exponential distribution. While the condition of the critical time t_{kr} was set based on the dependencies described below [4,5]:

$$F(t_{kr}) = 1 - e^{-at_{kr}} \tag{10}$$

$$F(t_{kr}) = 1 - \alpha \tag{11}$$

$$f(t_{kr}) = ae^{-at_{kr}} \tag{12}$$

After comparing the equations (11) and (12) the following relationship was achieved (13):

$$1 - e^{-at_{kr}} = 1 - \alpha \tag{13}$$

Thus:

$$\alpha = e^{-at_{kr}} \tag{14}$$

By taking the logarithm of both sides of the equation the following relationship (15) was achieved:

$$-\ln\alpha = at_{kr} \tag{15}$$

After transforming the relationships (10) - (15), the critical area of the exponential distribution was obtained, which is expressed with the relationship (16).

$$t_{kr} = -\frac{1}{\hat{a}}\ln\alpha \tag{16}$$

where: α – significance level,

$\hat{a} = \frac{1}{\bar{t}}$ – estimator of a parameter with the moment method,

$\bar{t}$ – *average value of the time interval of the correct operation between he damages to the subsystem.*

In order to determine the value of the efficiency factor of the performed repairs, the following relationships and dependencies were adopted.

N(t) – summarised number of the repairs of the technical object under investigation up to the moment *t*, it is described with the relationship (17):

$$N(t) = \sum_j N_j(t),\ \text{j = 1,2,...,m} \tag{17}$$

$N_j(t)$ – number of the repairs of the j-th subsystem up to the moment t, it is described with the relationship (18):

$$N_j(t) = N_j^S(t) + N_j^N(t),\ j = 1,2,...,m \tag{18}$$

where: $N_j^S(t)$ – number of effective repairs of the j-th subsystem up to the moment t

NjN(t) – number of ineffective repairs of the j-th subsystem up to the moment t

The values $N_j^S(t)$ and $N_j^N(t)$ were determined on the basis of the following relationship:

$L_{śrj}(t)$ – average transmission, travelled distance or transmission between the repairs of the j-the subsystem, described with the dependence (19)

$$L_{śrj}(t) = \frac{L_{1j}(t) + L_{2j}(t) + ... + L_{nj}(t)}{N_j(t)} = \frac{1}{N_j(t)} \sum_{i=1}^{n} L_{ij}(t) \tag{19}$$

for $i = 1,2,...,n,\ j = 1,2,...,m$

where: $L_{ij}(t)$ – the travelled distance or transmission between the consecutive repairs of the j-th subsystem up to the moment t,

$N_j(t)$ – number of the repairs of the j-th subsystem up to the moment t.

The value of the *efficiency factor* of the performed repairs of the j-th subsystem – element is described with the relationship (20) [6,7,8]:

$$WS_j = \frac{N_j(t) - N_j^N(t)}{N_j(t)} = \frac{N_j^S(t)}{N_j(t)},\ j = 1,2,...,m \tag{20}$$

The value of this factor may be expressed with the relationship (21):

$$WS_j = \frac{N_j^S}{N_j} * 100[\%],\ j = 1,2,\ldots,m \tag{21}$$

4. Operation and maintenance investigation results

The operation and maintenance investigations concerned 21 (three different types) of selected buses, being utilised within an urban transport system. The subject of the analyses were those which were considered to be the most important from the point of view of evaluating the effectiveness of the repairs and their influence on reliability, safety and the effectiveness of the investigated system operation. The individual buses to be investigated were chosen randomly out of a set of the technical objects being operated and maintained in the system under investigation. The operation and maintenance investigations were performed by means of a passive experiment in the real conditions of the means of transport operation and maintenance system. The investigations covered a five-year bus operation and maintenance period. These investigations also included the identification of the factors affecting the occurrence of the secondary damages.

On the basis of the criterion adopted in the paper (5) and (16), the damages were classified and the values of the essential statistical parameters were determined, such as the number of primary damages (L_{up}), the number of secondary damages (L_{uw}), and the average values of the time intervals between the primary and secondary damages.

Based on the known values of the chosen distribution statistics of the real times of correct operation, the damage streams with similar values of the statistics parameters in relation to the values of the statistics determined on the basis of empirical data were generated.

Table 1. Values of the repair effectiveness for the chosen bus subsystems, expressed in % for various numbers of the secondary damages L_{uw}
Tabela 1. Wartości wskaźników skuteczności napraw wybranych podsystemów autobusów dla różnych wariantów procentowego zmniejszenia liczby uszkodzeń wtórnych L_{uw}

	Subsystem Code				
	IE	PN	NA	SI	HA
Real value of the repair effectiveness index	32.65	35.71	30.23	30.30	36.36
Value of the repair effectiveness index for the simulated data consistent with the real data	32.43	35.65	30.11	30.46	36.32
Value of the repair effectiveness index for the number of the secondary damages reduced by 25%	39.08	42.15	39.01	38.64	43.56
Value of the repair effectiveness index for the number of the secondary damages reduced by 50%	48.99	51.34	47.24	45.89	49.87
Value of the repair effectiveness index for the number of the secondary damages reduced by 75%	65.96	68.21	63.78	59.80	66.44
Value of the repair effectiveness index for the number of the secondary damages reduced by 100%	100	100	100	100	100

Fig. 4 shows the values of the repair effectiveness index, depending on the percentage reduction of the secondary damages number, being a consequence of an improved quality of the repairs of the chosen bus subsystems.

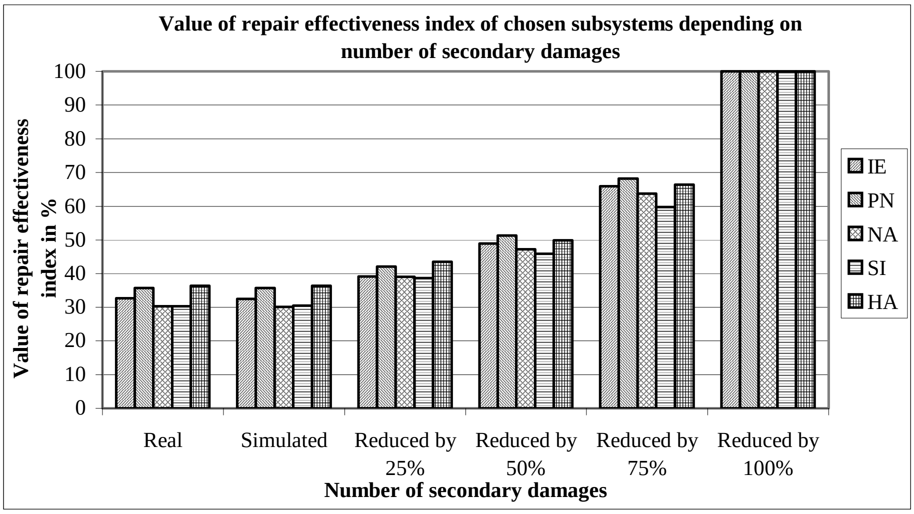

Fig. 4. Change of the value of repair effectiveness index depending on the percentage reduction of the number of secondary damages to the chosen bus subsystems
Rys. 4. Zmiana wartości wskaźnika skuteczności napraw w zależności od procentowego zmniejszenia liczby uszkodzeń wtórnych wybranych podsystemów autobusu

As it can be seen in the Fig. 4, elimination of the secondary damages in 100% causes an increase in the value of the repair effectiveness index up to one. However, elimination of the secondary damages number by *25%, 50% and 75%* causes an increase in the effectiveness index value, which of course is reflected by increased reliability of the investigated means of transport operation and maintenance system.

5. Summary

On the basis of the research performed, it may be concluded that the secondary damages to the individual elements or subsystems, being a consequence of ineffective repairs, should be eliminated in the service process, thus simultaneously increasing the operation reliability of the systems and particularly of the technical objects being operated and maintained within it. It may be accomplished by:

- Introducing technical control of the repairs being performed,
- Observing the time schedule of surveys and replacements,
- Increasing employees' qualifications,
- Appropriate employee's motivation,
- Providing the repair stands with the technological and repairing tools,

- Appropriate diagnostic activities performed before and after repairs,
- Using correct spare parts,
- Using adequate repair measures, and
- Correct assembly and disassembly.

A modern system of improving the repair effectiveness should include two major subsystems:

- A subsystem of controlling the process of assuring serviceability (repairs), and
- A subsystem of evaluating effectiveness of the repairs being performed.

The results of the operation and maintenance investigation prove that the realisation of the actions aimed at the improvement of the effectiveness of performed repairs is reasonable, and they should be considered as significant and indispensable for increasing the level of reliability, safety, effectiveness of the systems and of the technical objects being operated and maintained therein.

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Analiza zdarzeń niebezpiecznych na obiektach oceanotechnicznych na przykładzie zbiornikowców

S t r e s z c z e n i e

Czynniki eksploatacyjne i procesy destrukcyjne elementów obiektów technicznych powodują niekorzystne zmiany wartości istotnych cech funkcjonalnych, powodujących uszkodzenia. Uszkodzenie obiektu technicznego zdefiniowano jako przekroczenie dopuszczalnych wartości granicznych przez istotne cechy opisujące jego elementy. Na podstawie analizy literatury przedmiotu oraz wyników badań własnych stwierdzono, że uszkodzenia środków transportu, użytkowanych w systemach transportowych, są wynikiem oddziaływania różnorodnych czynników wymuszających. Pewna liczba uszkodzeń wynika z naturalnego zużywania się elementów maszyn, natomiast inne uszkodzenia mogą być spowodowane nieskuteczną naprawą poprzednio powstałego uszkodzenia. Skutkiem tego powstają tzw. uszkodzenia wtórne w krótkim przedziale czasu. Są one wynikiem niewłaściwej organizacji napraw, słabego wyszkolenia pracowników brygad naprawczych, ograniczeń związanych z diagnozowaniem przednaprawczym i ponaprawczym, co z kolei bezpośrednio wpływa na niezawodność działania systemów i eksploatowanych w nich obiektów technicznych. Na podstawie analizy wyników badań stwierdzono, że przyczyną powstawania uszkodzeń wtórnych jest, z reguły, niewłaściwa jakość napraw pierwotnych uszkodzeń elementów podsystemów. Uszkodzenia pierwotne są niezależne od siebie i występują w sposób losowy (nie są ze sobą związane więzią przyczynowo-skutkową). Uszkodzenia wtórne są zależne, ponieważ ich wystąpienie jest uwarunkowane wcześniejszym wystąpieniem uszkodzenia pierwotnego i skutkiem niewłaściwej jego naprawy lub naprawy następnego uszkodzenia wtórnego.