Evaluation of reliability of quickly repairable components of transshipment machines and mechanisms

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Abstract. When calculating the reliability indicators of transshipment machines and mechanisms, the required values are not always obtained explicitly due to systematic difficulties (complex distribution laws) or limited initial data. The optimal stock of spare parts for transshipment machines and mechanisms depends on the reliability indicators, and the nature and intensity of their use. Downtime due to the failure of transshipment machines and mechanisms used for ship handling leads to greater losses than downtime of these machines in the warehouse. Failures of transshipment machines and mechanisms can be due to the failure of non-repairable and quickly repairable components, and those with a long repair time. To calculate the main reliability indicators of quickly repairable components, the most common laws of distribution of random variables were employed. The paper considers the methodological aspects of the probabilistic reliability estimate of quickly repairable components of transshipment machines and mechanisms.

1. Introduction
Most of the transshipment machines and mechanisms (TMM) with long life time are repairable, that is TMM failures arising during operation can be eliminated during repair work. The technically sound state of TMM during operation is maintained by routine maintenance and repair work. TMM operation requires significant labor and material costs, as well as time, to maintain and repair TMM. Production experience shows that the operational costs usually significantly exceed the corresponding costs of product manufacturing. Works to maintain and restore the operability of TMM is divided into routine maintenance and repair work, which, in turn, are subdivided into planned preventive maintenance and emergency work carried out when failures or emergencies occur.

The study of operational reliability of TMM shows that the correct choice of operating conditions for TMM and the provision of spare parts significantly affect the level of operational reliability [1]. The reliability of machines is considered during designing, ensured during manufacturing and maintained at the required level during operation. In practice, the role of operation in terms of reliability is not always limited to maintaining the initial level. Sometimes this level is insufficient due to changes in the design operating conditions. Therefore, in the process of operation, the reliability of machines is often increased by upgrading individual units, assemblies or control systems [2].

An integrated approach at the design, production and operation stages that implies a qualitative and quantitative analysis of the causes of failures, analysis of the impact of external (operational) and
internal (design and production) factors on the operability, as well as physical processes in machines during operation, ensure their reliability.

TMM maintainability affects material costs and downtime duration. Maintainability is closely related to reliability and durability. Thus, TMM with high reliability are characterized by low labor costs and funds for maintaining their operability. TMM differ in indicators and methods for evaluating the reliability of repairable objects with short-term permissible interruptions in operation.

With regard to the above, evaluate the reliability of quickly repairable components of transshipment machines and mechanisms.

2. Methods for evaluating the reliability of quickly repairable components of TMM

In practice, the calculation of the reliability indicators of transshipment machines is usually hindered by incomplete and contradictory data on the values of individual indicators available in the literature sources. This necessitates the use of averaged reliability indicators and the introduction of various assumptions into the calculation. In this case, the calculation results are very approximate. An approximate calculation of reliability indicators indicates the rationality of using one or another layout diagram of a transshipment machine and/or its structural unit [3].

The operation of the restored (repaired) object consists of a number of successive periods \( A_1, A_2, \ldots, A_n \), each of which includes the operating time \( \xi_1, \xi_2, \ldots, \xi_n \) between successive failures and recovery intervals \( \theta_1, \theta_2, \ldots, \theta_n \) after each failure (Fig. 1).

![Figure 1. Object failure and restoration cycles](image)

The moments of restoring the object after the next failure \( t_1, t_2, \ldots, t_n \) form a random process called the restoration process. Consider that the recovery time is an insignificant fraction of cycles \( A_1, \ldots, A_n \), \( \theta_i << \xi_i \) and can be neglected. Then \( \xi_1 \approx A_1, \ t_1 \approx \xi_1, \ t_2 \approx \xi_1 + \xi_2, \ldots \) etc. [4].

The total operating time to the \( n \)-th failure \( t_n = \xi_1 + \xi_2 + \ldots + \xi_n \) contains a sequence of random points that form a flow of failures. Suppose that after each failure the operability of the object is fully restored and the distribution function of its operating time to failure \( F(t) \) in each failure–restoration cycle remains unchanged. In this case, the moments of time \( t_1, \ldots, t_n \) are independent random variables and the distribution function of the total operating time \( t_n \) to the \( n \)-th failure is determined recursively:
\[ F_n(t) = P[t_n < t] = \int_0^t F_{n-1}(t - \tau) dF(\tau), n > 1 \]  

In this case, \( F_{n}(t) = F(t) \). As before, \( F(t) \) is the function of distribution of the operating time of the object to failure.

Denote \( \nu(t) \geq n, \) when \( t_n < t \). Hence, \( P[\nu(\geq n)] = P[t_n < t] = F_n(t) \) and

\[ P[\nu(t) = n] = F_n(t) - F_{n+1}(t) \]  

In particular, with an exponential distribution of the operating time to failure with the parameter \( \lambda_0 \):

\[ P[\nu(t) = n] = \frac{(\lambda_0 t)^n}{n!} e^{-\lambda_0 t} \]  

Average number of failures (restorations) over time \( t \):

\[ M[\nu|\nu = n] = \sum_{n=1}^{n} nP[\nu(t) = n] \]  

is called the leading function, or the function of restorations, in the theory of reliability, given that after each failure the object is restored. Denote \( M[\nu|\nu(t) = n] = H(t) \). Equations (2) and (4) yield the leading function:

\[ H(t) = \sum_{n=1}^{n} n[F_n(t) - F_{n+1}(t)] = \sum_{n=1}^{n} nF(t) - \sum_{n=2}^{n} (n-1)F_n(t) = \sum_{n=1}^{n} F_n(t) \]  

The statistical value of the average life time during tests (observations) without replacing failed objects can be calculated using the equation

\[ \overline{\tau}_0 = \frac{1}{n_c} \left[ \sum_{i=1}^{k} n_i + (N - n_c)T \right] \]  

where \( n_c = \sum_{i=1}^{k} n_i \) – total number of failed objects (failures); \( k \) – total number of operating time points, failures (the number of operating time intervals of the test period \( T \)); \( i = 1,...,k \) – operating time factor at the time of failure; \( n_i \) – number of failures at the operating time \( t_i \); \( t_i \) – operating time of failure (center of operating time interval); \( N \) – number of objects delivered for testing; \( T \) – duration of tests (observations).

When testing with the replacement of failed objects: \( \overline{\tau}_0 = \frac{NT}{n_c} \)

An important numerical characteristic of reliability is the variance of operating time to failure:

\[ D[\zeta] = M[(\zeta - \overline{\tau}_0)^2] = \sigma_0^2 = \int_0^\infty (t - \overline{\tau}_0)^2 dF(t) = M[\nu^2] - \overline{\tau}_0^2 = \int_0^\infty t^2 dF(t) - \overline{\tau}_0^2 \]  

The value of \( \sigma_0 \) determines the mean square deviation of the operating time to failure of the component from the mean value. Statistical value:

\[ \sigma_0^2 = \frac{1}{N-1} \left[ \sum_{i=1}^{k} n_i (t_i - \overline{\tau}_0)^2 + (N - n_c)(\overline{\tau} - \overline{\tau}_0)^2 \right] \]  

Here are the same designations as in equation (6).

If a long operating period \( t \gg T_0 \) is considered and the statistical values \( T_0 \) and \( \sigma_0^2 \) are known [equations (6), (7) and (8)], the approximate equality [5] is true:

\[ H(t) \approx \frac{t}{T_0} + (\sigma_0^2 - T_0^2) / (2T_0^2) \]  

for any non-lattice distribution function \( F(t) \), provided that it has distribution density \( f(t) \).
By definition, the main function characterizes the average number of failures or restorations for the calculated operating time and, therefore, it is one of the most important characteristics of the reliability of the restored object. Using this function, other reliability indicators can be defined. In particular, the average number of failures in the given operating time interval \([t_1, t_2]\):

\[ \nu(t_{1,2}) = H(t_2) - H(t_1) \]  

(10)

the variance of the number of failures:

\[ D[\nu(t)] = 2 \int_0^t H(t - \tau) dH(t) + H(t) - \nu^2(t) \]  

(11)

mean time of failure-free operation of the restored object:

\[ T_0 = \lim_{t \to 0} \frac{H(t)}{t} \]  

(12)

Derivatives of the function \(H(t)\):

\[ \omega(t) = H'(t) = \sum_{n=1}^{\infty} f_n(t) \quad \text{and} \quad f_n(t) = F_n'(t) \]  

(13)

are called restoration density, or failure rate.

Equation (13) shows that \(\omega(t)\) determines the average number of restorations (failures) per unit of time, if this unit is small, and at the same time it corresponds to the probability of failure in a small unit of time under the assumption that two or more failures are unlikely to occur. The last assumption makes it possible to use another term of the queuing theory for the function \(\omega(t)\) – the parameter of the flow of failures. Since all three terms are available in the literature, remember the difference between the terms “failure rate” (in relation to non-repairable products) and “failures rate”. The first term is the conditional probability of failure in an infinitely small time interval after time \(t\), provided that the component has not failed before time \(t\). The second term is the unconditional probability of failure of a repairable component in a short time interval after \(t\). The function \(\omega(t)\) is referred to as “parameter of the flow of failures”.

If the operating times between failures show similar distribution density \(f(t)\), the flow of failures satisfies the integral equation:

\[ \omega(t) = f(t) + \int_0^t f(t - \tau) \omega(\tau) d\tau \]  

(14)

Equation (14) is solved by numerical methods. Laplace transform can sometimes be used. Consider the equation [6]:

\[ L[\int_0^t f(t - \tau) \omega(\tau) d\tau] = L[f(t)]L[\omega(t)] \]

where \(L\) is the symbol of the Laplace transform from equation (14), we obtain:

\[ L[\omega(t)] = \frac{L[f(t)]}{1 - L[f(t)]} \]  

(15)

For example, \(f(t) = \lambda_0 t e^{-\lambda_0 t} \) (\(\Gamma\)-distribution at \(p = 2\)).

Laplace transform:

\[ L[f(t)] = \frac{\lambda_0^2}{(S + \lambda_0)^2} \]

Hence:

\[ L[\omega(t)] = \frac{\lambda_0^2}{S(S + 2\lambda_0)} \]  

(16)

The original function \(\omega(t)\) corresponding to image (16) is equal to

\[ \omega(t) = 0.5\lambda_0 (1 - e^{-\lambda_0 t}) \]  

(17)

Below are equations to determine \(\omega(t)\) for some distribution laws.
Exponential law (Fig. 2).

\[
F(t) = 1 - \exp(-\lambda_0 t); F(t) = \exp(-\lambda_0 t) \\
F(t) = 1 - \exp(-\lambda_0 t); T_0 = \frac{1}{\lambda_0}; \sigma^2 = \frac{1}{\lambda_0^2}
\]

Third and fourth central moments \( \mu_2 = 2\lambda_2 \), \( \mu_2 = 9\lambda_2 \). The variation coefficient \( \eta = 1 \).

![Exponential distribution law](image)

Asymmetry coefficients \( \nu_1 = 2 \) and excess \( \nu_2 = 6 \).

With exponential law (18):

\[
\omega(t) = \omega_0 = \lambda_0
\]

Normal law (Fig. 3)

\[
F(t) = \frac{1}{\sigma_0 \sqrt{2\pi}} \int_{-\infty}^{t} \exp\left[-\frac{(\tau - T_0)^2}{2\sigma_0^2}\right] d\tau \\
f(t) = \frac{1}{\sigma_0 \sqrt{2\pi}} \int_{-\infty}^{t} \exp\left[-\frac{(\tau - T_0)^2}{2\sigma_0^2}\right] d\tau \\
\bar{F}(t) = \frac{1}{\sigma_0 \sqrt{2\pi}} \int_{-\infty}^{t} \exp\left[-\frac{(\tau - T_0)^2}{2\sigma_0^2}\right] d\tau
\]

With normal law (19):

\[
\omega(t) = \sum_{n=1}^{\infty} \frac{1}{\sigma \sqrt{2\pi n}} \exp\left[-\frac{(t - nT_0)^2}{2\pi \sigma^2}\right]
\]
Figure 3. Normal distribution law

Gamma distribution (G-distribution) (Fig. 4)

\[
F(t) = \left[ \int_0^t e^{-\lambda \tau} \frac{\tau^{p-1}}{T(p)} d\tau \right]^{\delta} \\
f(t) = \left[ \int_0^t e^{-\lambda \tau} \frac{\tau^{p-1}}{T(p)} d\tau \right]^{\delta-1}
\]

where \( \Gamma(p) = \int_0^\infty t^{p-1}e^{-t} dt \) – tabulated gamma function [6]. Note that \( \Gamma(1) = 1 \); \( \Gamma(0.5) = \sqrt{\pi} \); \( \Gamma(n+1) = n! \), where \( n=1,2,3,... \).

With \( \Gamma \)-distribution (21):

\[
\omega(t) = \sum_{n=1}^{\infty} \frac{\lambda^n p^n \tau^{n-1}}{T(np)} e^{-\lambda \tau}
\]

An approximate value of the failure flow parameter based on static data:

\[
\bar{\omega}(t) = \frac{\sum_{i=1}^{N} m_i (t + \Delta t) - \sum_{i=1}^{N} m_i (t)}{\Delta t N}
\]

where \( m_i (t + \Delta t) \), \( m_i (t) \) – number of failures of the \( i \)-th object, respectively, during the operating time \( t + \Delta t \) and \( t \); \( \Delta t \) – small interval of the operating time in comparison with \( t \); \( N \) – number of restored objects that are observed.

For a number of systems, after some operating time \( T_0 \), the function \( H(t) \) becomes linear, that is

Figure 4. Gamma distribution
\( \omega(t) = \omega_0 = \text{const.} \), and the equation is true:

\[
H_i = H(T_0) + \omega_0(t - T_0)
\]  

(24)

Figure 5. Dependence \( \omega(t) \) for the normal distribution law at \( \sigma_0 = 0.5T_0 \)

In particular, for portal cranes, the running-in period is 3÷4 thous. hours of operation, after which the flow of failures is stabilized with the parameter \( \omega_0 = 0.015 \div 0.03 \) for the components of electrical equipment and \( \omega_0 = 0.01 \div 0.003 \) for the parts of mechanisms [7].

If the distribution \( F(t) \) exhibits density \( f(t) \to 0 \) at \( t \to \infty \), then:

\[
\lim_{t \to \infty} \omega(t) = \omega_0 = \frac{1}{T_0}
\]  

(25)

This equation shows that the restoration process becomes stationary with time for all types \( F(t) \), if \( f(t) \to 0 \), and its local characteristics do not depend on time [8]. The conclusion is very important, since it significantly simplifies the calculation of reliability indicators for a number of restored objects, including transshipment machines with sufficiently large operating time.

Figure 5 shows the dependence \( \omega(t) \) constructed using equation (20) for the normal distribution function \( F(t) \). The \( \omega(t) \) graph confirms equation (25). The parameter \( \omega(t) \) is characterized by damped oscillations relative to \( \omega_0 = 1/T_0 \). The attenuation intensity is inversely proportional to the standard deviation of the operating time to failure \( \sigma_0 \). In particular, for \( \sigma_0 = 0.5T_0 \), one can assume that \( \omega(t) = \omega_0 = 1/T_0 \) at \( t \geq 1.5T_0 \) (error \( \delta < 4\% \)).

In the general case, it is rather difficult to estimate \( \omega(t) \) from a known distribution density. Therefore, the inequality [5, 9] may seem useful for estimating \( \omega(t) \):

\[
f(t) \leq \omega(t) \leq [\max_{x \in dy} f(x)] \frac{F(t)}{F(t)}
\]  

(26)

In practical calculations, the ratio is often used [5, 9]:

\[
\nu(t) = \frac{1}{\sigma^2 T_0^{3/2}} \left[ \frac{t - T_0}{\sigma^2 T_0^{3/2}} \right] < x = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-\frac{u^2}{2}} du = \Phi(x)
\]  

(27)
which shows that with an increase in the operating time, the distribution of a random number of failures tends to normal with an average \( M[v(t)] = \frac{t}{T_0} \) and variance \( D[v(t)] = \frac{\sigma^2}{T_0^2} \).

Therefore, for \( t \gg T_0 \):

\[
P[v(t) < n] = F(n) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{n} \exp\left[-\frac{(n - \frac{t}{T_0})^2}{2 \frac{\sigma^2}{T_0^2}}\right] dv \tag{28}
\]

Based on equation (28), it is possible to calculate the required number of repairs for the period \( t \) or the number of spare parts if the part is replaced in case of failure [4]. From this equation, it follows that with probability \( P \) the required number of spare parts (repairs) does not exceed:

\[
n_0 = \frac{t}{T_0} + x_p \sqrt{\frac{\sigma^2}{T_0^2}} \tag{29}
\]

where \( x_p \) – quantile of order \( P \) of the normal distribution is determined from the condition \( \Phi(x_p) = P \).

It should be noted that equation (29) gives a satisfactory solution only for \( t \gg T_0 \).

**Representative example 1.** Calculate the number of spare parts for the operating time \( t = 25 \) thous. hours, if the mean time of failure-free operation is \( T_0 = 600 \) hours, the standard deviation of the operating time to failure \( \sigma_0 = 200 \) hours. The specified probability of providing spare parts is \( P = 0.99 \).

Solution.

According to the table of normal distribution from the condition \( \Phi(x_p) = 0.99 \), we find \( x_p = 2.33 \). Using equation (29), we calculate the required number of spare parts:

\[
n_0 = \frac{25}{0.6} + 2.33\sqrt{\frac{0.2^2}{0.6}} = 50
\]

Distribution of the residual life life of the object \( \xi \), that is, the probability of failure-free operation in the operating time interval \( [t = t + x] \), provided that at the moment \( t \) the object is operable [5]:

\[
P(\xi > x) = F(t + x) + \int_0^t F(t + x - \tau) \phi(\tau) d\tau. \tag{30}
\]

Distribution of the stationary residual life time:

\[
\lim_{t \to \infty} P(\xi > x) = P(\xi > x) = \frac{1}{T_0} \int_0^\infty F(\tau) d\tau \tag{31}
\]

Sometimes it is convenient to use this equation in a different form:

\[
\lim_{t \to \infty} P(\xi > x) = 1 - \frac{1}{T_0} \int_0^\infty F(\tau) d\tau = \int_0^\infty F(\tau) d\tau \tag{32}
\]
The average remaining life time:

\[
M[\xi_t^0] = \int_0^\infty P(\xi > x)dx = \int_0^\infty \left[ \frac{1}{T_0} \int_0^\infty F(\tau) d\tau \right] dt = \frac{1}{T_0} \int_0^\infty F(\tau) d\tau + \int_0^\infty \tau F(\tau) dt = \\
= \frac{1}{T_0} \left\{ \frac{t^2}{2} \int_0^\infty F(t) d\tau \right\} - \frac{1}{2} \int_0^\infty t^2 dF(t) = \frac{1}{2T_0} \int_0^\infty t^2 dF(t) = \frac{1}{2T_0} M[t^2]
\]

Considering that \( M[t^2] = T_0^2 + \sigma_0^2 \), finally we get:

\[
M[\xi_t^c] = \frac{T_0}{2} + \frac{\sigma_0^2}{2T_0}
\]  \hspace{1cm} (33)

For the objects with an ordinary flow of failures without consequences (the probability of two or more simultaneous failures is negligible and the probability of failures in any interval of operating time does not depend on failures in other intervals):

\[
P(\xi > x) = e^{-[H(t+x)-H(t)]} = e^{-\int_0^{t+x} \lambda_0 dt}
\]  \hspace{1cm} (34)

For the stationary state, \( \omega(t) = \omega \theta \) and

\[
P(\xi > x) = e^{-\omega \theta x}
\]  \hspace{1cm} (35)

Most technical systems have the feature of an ordinary flow of failures without consequences (Poisson flow). Therefore, when calculating the reliability of transshipment machines, equation (34) is often used.

**Weibull-Gnedenko law** is represented by the distribution function and density, as well as the reliability function:

\[
F(t) = 1 - \exp\left[ -\left(\lambda_0 t^p\right)^p \right] \\
f(t) = p\lambda_0 t^{p-1} \exp\left[-\left(\lambda_0 t^p\right)^p\right] \\
\overline{F}(t) = \exp\left[-\left(\lambda_0 t^p\right)^p\right]
\]  \hspace{1cm} (36)

for \( t > 0 \), with distribution parameters \( p > 0 \) (determines the distribution shape) and \( \lambda_0 > 0 \) (determines the scale).

Mean time to failure \( T_0 \), its variance \( \sigma_0^2 \) and failure rate \( \lambda(t) \):

\[
T_0 = \frac{\lambda_0}{p} \Gamma(1 + 1/p) \\
\sigma_0^2 = \lambda_0^2 \left[ \Gamma(1 + 2/p) - \Gamma^2(1 + 1/p) \right] \\
\lambda(t) = p\lambda_0 t^{p-1}
\]  \hspace{1cm} (37)

The Weibull-Gnedenko law contains a class of exponential distributions \( (p = 1) \). For \( p > 0 \), this law is close to normal, that is it can characterize gradual(wear) failures \[2\]. At \( p < 1 \), the Weibull-Gnedenko law describes well the reliability of low-wear objects with hidden defects, when the failures are increased at the beginning of operation, and then the failures are decreased as the hidden defects are eliminated.

**Representative example 2.** Calculate the probability of failure-free operation of the restored object during the operating time \( t = 0.8 \) thou. hours until the next scheduled repair, as well as the average stationary residual life time and the stationary value of the failure flow parameter. The object reliability function corresponds to the Weibull-Gnedenko law:

\[
\overline{F}(t) = \exp\left[-\left(0.5t\right)^2\right]
\]  \hspace{1cm} (38)

Solution.
According to the above conditions, $\lambda_0 = 0.5, p = 2$.

Using equations (36), we determine: mean time to failures:

$T_0 = \lambda_0^{-1} \Gamma\left(1 + \frac{1}{p}\right) = 0.5^{-1} \Gamma(1 + 0.5) = 1.78$ (thous. machine hours);

variance:

$\sigma_0^2 = \lambda_0^{-2} \left[ \Gamma\left(1 + \frac{2}{p}\right) - \Gamma^2\left(1 + \frac{1}{p}\right) \right] = 0.5^{-2} \left[ \Gamma(2) - \Gamma^2(1.5) \right] = 0.83$

Use equation (32). It is evident that the integral is equal to (39):

$$\int_0^t e^{-(\lambda_0 t)p} dt = \sum_{n=0}^{\infty} p^n \lambda_0^n \frac{1}{n!} \left(1 + \frac{1}{n+1}\right) e^{-(\lambda_0 t)p}$$

Substituting the values $T_0 = 1.78, t = 0.8, \lambda_0 = 0.5, p = 2, n = 1$ (according to the above condition, it is necessary to calculate the reliability until the next scheduled repair) into equation (32) with regard to equation (39), we have:

$$P\{\xi > 0.8\} = 1 - \frac{1}{1.78} e^{-(0.5 \times 0.8)^2} \approx 0.6$$

that is, the probability of failure-free operation before the next scheduled repair $P = 0.6$.

The average value of the stationary residual life time according to equation (33):

$M[\xi] = 1.78/2 + 0.83/2 \times 1.78 = 1.12$ thous. h.

The stationary value of the failure flow parameter: $\omega_0 = 1/T_0 = 1/1.78 = 0.56$ (1/thous. h) [4].

The analysis of the results of solutions to representative examples show that the evaluation of reliability of quickly repairable components allows scheduled preventive and restoration work quickly and in a timely manner, thereby reducing the downtime of transshipment machines and mechanisms.

**Conclusion**

The reliability of machines is ensured during design and manufacture and is further maintained at the required level during operation. In operation, reliability is not always maintained at the initial level. This level often becomes insufficient due to changes in the design operating conditions. Therefore, in the process of operation, the reliability of machines is often increased by upgrading of individual units, assemblies or control systems.

Development of science and technology in the field of creating advanced structural materials, methods for hardening and increasing the wear resistance of repairable components, new drive systems with favorable characteristics, the development of modern devices for automatic monitoring of the technical condition of machines and automatic control units, including controllers and microprocessors, create the necessary conditions for solving these problems. When using control computers in combination with the theory of optimal control, not only the productivity of transshipment machines increases, but their operating modes are stabilized, the total number of starts during the working cycle is reduced, dynamic loads are limited and, therefore, the reliability of operation is increased.

The probabilistic estimate of the reliability of quickly repairable components of transshipment machines and mechanisms minimizes their stocks until the next scheduled repair and ensures TMM readiness for transshipment operations.

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