Reliability Modeling of a Port Oil Transportation System’s Operation Processes

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Abstract: In the paper the semi-Markov process is used to construct a general model of a complex technical system operation. Parameters of this model are defined and the methods of their statistical identification are proposed. Using this model and methods, the operation process of a port oil transportation system is described, its parameters are statistically identified and its main characteristics are determined. Further, the joint model linking the system operation process and the system reliability is defined and applied to the reliability evaluation of the port oil transportation system in variable operating conditions.

Keywords: Semi-Markov process, system in varying operating conditions

1. Introduction

Most real transportation systems are very complex and it is difficult to analyze their reliability. Large numbers of components and subsystems and their operating complexity cause that the evaluation and optimization of their reliability quite complicated. The complexity of the system operation process and its influence changes with time the system structure and its components reliability characteristics are often very difficult to ascertain and to analyze. A convenient tool for solving this problem is semi-Markov modeling the system operation process and its common usage with the system reliability evaluation methods in order to construct a general system reliability model related to its operation process proposed in the paper. The possibility of this tool wide application in reliability evaluation of real technical systems changing during the operation their structures and components reliability characteristics like for instance piping oil transportation systems is obvious.

2. Modeling of System Operation Process

Usually the system environment and infrastructure have either an explicit or implicit strong influence on the system operation process. As a rule some of the initiating environment events and infrastructure conditions define a set of different operation states of the industrial system. Thus, we assume that the system during its operation is operating in \( v, v \in N, \) different operation states. After this assumptions, we can define the system operation process \( Z(t), t \in <0, +\infty >, \) with discrete states from the set of states \( Z = \{z_1, z_2, \ldots, z_v\}. \) If the system operation process \( Z(t) \) is semi-Markov [1]-[2], [5]-[7]

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with the conditional sojourn times \( \theta_{bl} \) at the operation states \( z_b \) when its next operation state is \( z_l, \; b, l = 1, 2, \ldots, v, \; b \neq l \), then it may be described by:

- the vector of probabilities of the system operation process initial states
  \[ p_b(0) = [p_{1}(0), p_{2}(0), \ldots, p_{v}(0)] \]
  where \( p_{b}(0) = P(Z(0) = z_b) \) for \( b = 1, 2, \ldots, v \),

- the matrix of probabilities of the system operation process transitions between the operation states
  \[ p_{ul} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1v} \\ p_{21} & p_{22} & \cdots & p_{2v} \\ \vdots & \vdots & \ddots & \vdots \\ p_{vl} & p_{v2} & \cdots & p_{vv} \end{bmatrix}, \]
  where \( p_{lb} = 0 \) for \( b = 1, 2, \ldots, v \),

- the matrix of the system operation process conditional sojourn times \( \theta_{bl} \) distribution functions
  \[ [H_{bl}(t)]_{ul} = \begin{bmatrix} H_{11}(t) & H_{12}(t) & \cdots & H_{1v}(t) \\ H_{21}(t) & H_{22}(t) & \cdots & H_{2v}(t) \\ \vdots & \vdots & \ddots & \vdots \\ H_{vl}(t) & H_{v2}(t) & \cdots & H_{vv}(t) \end{bmatrix}, \]
  where \( H_{bl}(t) = P(\theta_{bl} < t) \) for \( b, l = 1, 2, \ldots, v, \; b \neq l \), and \( H_{bb}(t) = 0 \) for \( b = 1, 2, \ldots, v \).

Under these assumptions, the mean values of the system operation process conditional sojourn times \( \theta_{bl} \) are given by

\[ M_{bl} = E[\theta_{bl}] = \int_0^\infty tH_{bl}(t) \, dt, \; b, l = 1, 2, \ldots, v, \; b \neq l. \] (1)

By the formula for total probability the unconditional distribution functions of the sojourn times \( \theta_{b} \) of the system operation process \( Z(t) \) at the operation states \( z_b, \; b = 1, 2, \ldots, v \), are given by

\[ H_{b}(t) = \sum_{l=1}^{v} p_{lb}H_{bl}(t), \; b = 1, 2, \ldots, v. \] (2)

Hence, the mean values \( E[\theta_{b}] \) of the system operation process unconditional sojourn times \( \theta_{b} \) in the particular operation states are given by

\[ M_{b} = E[\theta_{b}] = \sum_{l=1}^{v} p_{lb}M_{bl}, \; b = 1, 2, \ldots, v, \] (3)

where \( M_{bl} \) are defined by (1).

Moreover, it is well known [1], [6] that the limit values of the system operation process transient probabilities at the particular operation states

\[ p_{b}(t) = P(Z(t) = z_b) \; t \in (0, +\infty), \; b = 1, 2, \ldots, v, \]

are given by

\[ p_{b} = \lim_{t \to \infty} p_{b}(t) = \frac{\pi_{b}M_{b}}{\sum_{l=1}^{v} \pi_{l}M_{l}}, \; b = 1, 2, \ldots, v, \] (4)
where $M_b$, $b=1,2,...,v$, are defined by (3), whereas the probabilities $\pi_b$ of the vector $[\pi_b]_{1,v}$ satisfy the system of equations

\[
\begin{bmatrix}
[\pi_b] = [\pi_b] [p_{bl}]

\sum_{l=1}^{v} \pi_l = 1.
\end{bmatrix}
\] (5)

Other interesting characteristics of the operation process $Z(t)$ possible to obtain are its total sojourn times $\hat{\theta}_b$ in the particular operation states $z_b$, $b=1,2,...,v$. It is well known [1], [6] that the system operation process total sojourn times $\hat{\theta}_b$ in the particular operation states $z_b$, for sufficiently large operation time $\theta$, have approximately normal distribution with the expected value given by

\[
E[\hat{\theta}_b] = p_b \theta, \quad b=1,2,...,v,
\] (6)

where $p_b$ are given by (4).


In order to estimate parameters of the system operation process model, it is necessary to execute the following steps:

- Fix the number of states $v$ of the system operation process $Z(t)$ and to define the operation states $z_1, z_2, ..., z_v$ of the set $Z$,

- Fix the vector of realisations $[n_b(0)] = [n_1(0), n_2(0), ..., n_v(0)]$ of the numbers $n_b(0), b=1,2,...,v$, of the system operation process $Z(t)$ transients in the particular states $z_b$ at the initial moment $t=0$.

- to fix the matrix of realisations

\[
[n_{bl}] = \begin{bmatrix}
n_{11} & n_{12} & \cdots & n_{1v} \\
n_{21} & n_{22} & \cdots & n_{2v} \\
\vdots & \vdots & \ddots & \vdots \\
n_{v1} & n_{v2} & \cdots & n_{vv}
\end{bmatrix},
\]

of the numbers $n_{bl}, b,l=1,2,...,v$, of the system operation process $Z(t)$ transitions from the state $z_b$ into the state $z_l$ during the experiment time $\Theta$,

- to fix the vector of realisations

$[p(0)] = [p_1(0), p_2(0), ..., p_v(0)]$, of the initial probabilities $p_b(0), b=1,2,...,v$, of the system operation process $Z(t)$ transients in the particular states $z_b$ at the moment $t=0$, according to the formula:

\[
p_b(0) = \frac{n_b(0)}{m(0)} \quad \text{for} \quad b=1,2,...,v, \quad \text{where} \quad m(0) = \sum_{b=1}^{v} n_b(0),
\]

is the total number of the system operation process $Z(t)$ realizations at $t=0$,

- to fix the matrix of realisations
of the transition probabilities $p_{bl}, b, l = 1, 2, ..., \nu$, of the system operation process $Z(t)$ from the operation state $z_b$ into the operation state $z_l$ during the experiment time $\Theta$, according to the formula

$$p_{bl} = \frac{n_{bl}}{n_b} \text{ for } b, l = 1, 2, ..., \nu, b \neq l, \quad p_{lb} = 0 \text{ for } b = 1, 2, ..., \nu,$$

where, $n_b = \sum_{l \neq b} n_{bl}, b = 1, 2, ..., \nu,$

is the realization of the total number of the system operation process $Z(t)$ transitions from the operation state $z_b$ during the experiment time $\Theta$.

- to formulate and to verify the hypotheses about the conditional distribution functions $H_{bl}(t)$ of the system operation process $Z(t)$ sojourn times $\theta_{bl}, b, l = 1, 2, ..., \nu, b \neq l,$ in the state $z_b$ while the next transition is the state $z_l$ on the base of their realisations $\theta_{bl}^k, k = 1, 2, ..., n_{bl}$ during the experiment time $\Theta$.

4. Operation of a Port Oil Transportation System

As an example we will analyse the reliability of the port oil transportation system in its operation process [3]-[4], [8]-[9]. The considered system is composed of three terminal parts $A$, $B$ and $C$, linked by the piping transportation systems.

![Figure 1: The Schematic Representation of Port Oil Transport System](image-url)

The Oil Terminal in Dębogórze is designated for the reception from ships, the storage and sending by carriages or cars the oil products. It is also designated for receiving from carriages or cars, the storage and loading the tankers with oil products such like petrol and oil.

The unloading of tankers is performed at the pier placed in the Port of Gdynia. The pier is connected with terminal part $A$ through the transportation subsystem $S_1$ built of two piping lines composed of steel pipe segments with diameter of 600 mm. In the part $A$ there is a supporting station fortifying tankers pumps and making possible further transport of oil by the subsystem $S_2$ to the terminal part $B$. The subsystem $S_2$ is built of two piping lines.
composed of steel pipe segments of the diameter 600 mm. The terminal part \( B \) is connected with the terminal part \( C \) by the subsystem \( S_3 \). The subsystem \( S_3 \) is built of one piping line composed of steel pipe segments of the diameter 500 mm and two piping lines composed of steel pipe segments of diameter 350 mm. The terminal part \( C \) is designated for the loading the rail cisterns with oil products and for the wagon sending to the railway station of the Port of Gdynia and further to the interior of the country.

The Port Oil Transportation system consists of three subsystems \( S_1, S_2, S_3 \). Subsystem \( S_1 \) consist of \( k_n = 2 \) two identical pipelines, each composed of \( l_n = 178 \) elements. In each pipeline there are:
- 176 pipe segments,
- 2 valves.
Subsystem \( S_2 \) consist of \( k_n = 2 \) two identical pipelines, each composed of \( l_n = 719 \) elements. In each pipeline there are:
- 717 pipe segments,
- 2 valves.
Subsystem \( S_3 \) consist of two pipelines of the first type and one second type, each composed of \( l_n = 362 \) elements. In each pipeline of the first type there are:
- 360 pipe segments (\( \Omega = 350\)mm),
- 2 valves.
In pipeline of the second type there are:
- 360 pipe segments (\( \Omega = 500\)mm),
- 2 valves.

Taking into account the operation process of the considered transportation system we distinguish the following as its five operation states:

- an operation state \( z_1 \) – transport of two different kinds of medium from the terminal part \( B \) to part \( C \) using two out of three pipelines in part \( S_3 \), with the structure given in Fig. 2,

- an operation state \( z_2 \) – transport of one kind of medium from the terminal part \( C \) (from carriages) to part \( B \) using one out of three pipelines in part \( S_3 \), with the structure given in Fig. 3, and
- an operation state \( z_3 \) – transport of one kind of medium from the terminal part \( B \) through part \( A \) to the pier using one out of two pipelines in part \( S_2 \) and one out of two pipelines in part \( S_1 \), with the structure given in Fig. 4.
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Figure 3: Port Oil Transport System in Operating State $z_2$

Figure 4: Port Oil Transport System in Operating State $z_3$

• an operation state $z_4$ – transport of two kinds of medium from the pier through parts A and B to part C using both pipelines in part $S_1$, both in part $S_2$ and two out of three pipelines in part $S_3$, with the structure given in Fig. 5.

Figure 5: Port Oil Transport System in Operating State $z_4$

• an operation state $z_5$ – transport of one kind of medium from the pier through part A and B to part C using one out of two pipelines in parts $S_1$ and $S_2$ and one out of three pipelines in part $S_3$, with the structure given in Fig. 6.

Assuming arbitrarily the Releigh distribution and using preliminary approximate data coming from experts, we fix the following matrix of the conditional distribution functions:

$[H_{p}(t)] = \begin{bmatrix}
0 & 0 & 0 & 1 - e^{-3711.7t} & 0 \\
0 & 0 & 1 - e^{-19114.9t}^2 & 0 & 0 \\
1 - e^{-144469.9t}^2 & 1 - e^{-307737.7t}^2 & 0 & 0 & 0 \\
0 & 1 - e^{-949854.5t}^2 & 0 & 0 & 1 - e^{-995854.5t}^2 \\
0 & 0 & 0 & 1 - e^{-28t}^2 & 0
\end{bmatrix}$
Figure 6: Port Oil Transport System in Operating State $z_5$

of the oil terminal operation process sojourn times $\theta_{bl}$, $b, l = 1,2,3,4,5$, in the distinguished operation states $z_1$, $z_2$, $z_3$, $z_4$, $z_5$, and using the statistical methods presented in section 3, we estimate the matrix of the probabilities of transitions between the operation states

$$
[p_{bl}] = \begin{bmatrix}
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0.11 & 0.89 & 0 & 0 & 0 \\
0 & 0.5 & 0 & 0 & 0.5 \\
0 & 0 & 0 & 1 & 0
\end{bmatrix}.
$$

Further, according to (2), the unconditional distribution functions of the oil terminal operation process $Z(t)$ sojourn times $\theta_{bl}$ in the states $z_b$, $b = 1,2,3,4,5$, are given by

$$
H_1(t) = 1 - \exp[-37117.4t^2],
$$
$$
H_2(t) = 1 - \exp[-19174.9t^2],
$$
$$
H_3(t) = 1 - 0.11 \cdot \exp[-148469.5t^2] - 0.89 \cdot \exp[-107737.1t^2],
$$
$$
H_4(t) = 1 - 0.5 \cdot \exp[-969634.1t^2] - 0.5 \cdot \exp[-969634.1t^2],
$$
$$
H_5(t) = 1 - \exp[-29.1t^2],
$$

and their mean values, from (3), are:

$$
M_1 = E[\theta_{1i}] = 1 \cdot 0.005 = 0.005,
$$
$$
M_2 = E[\theta_{1i}] = 1 \cdot 0.006 = 0.006,
$$
$$
M_3 = E[\theta_{1i}] = 0.11 \cdot 0.002 + 0.89 \cdot 0.003 = 0.003,
$$
$$
M_4 = E[\theta_{1i}] = 0.5 \cdot 0.001 + 0.5 \cdot 0.001 = 0.001,
$$
$$
M_5 = E[\theta_{1i}] = 1 \cdot 0.164 = 0.164.
$$

Since, according to (5), from the system of equations
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we get

\[
[\pi_1, \pi_2, \pi_3, \pi_4, \pi_5] = [\pi_1, \pi_2, \pi_3, \pi_4, \pi_5] = [0.11, 0.89, 0, 0, 0.095, 0.0007, 0.652],
\]

then the limit values of the transient probabilities \( p_b(t) \) at the operational states \( z_b \), according to (4), are

\[
p_1 = 0.018, \quad p_2 = 0.228, \quad p_3 = 0.095, \quad p_4 = 0.007, \quad p_5 = 0.652, \quad (7)
\]

and, by (6), the expected values of the total sojourn times \( \hat{\theta}_b \), \( b = 1, 2, 3, 4, 5 \), in particular operation states for the oil terminal system operation time \( \theta = 1 \) year = 365 days are:

\[
E[\hat{\theta}_1] = 0.018 \cdot 365 \equiv 6.6 \text{ days},
\]
\[
E[\hat{\theta}_2] = 0.228 \cdot 365 \equiv 83.2 \text{ days},
\]
\[
E[\hat{\theta}_3] = 0.095 \cdot 365 \equiv 34.7 \text{ days},
\]
\[
E[\hat{\theta}_4] = 0.007 \cdot 365 \equiv 2.6 \text{ days},
\]
\[
E[\hat{\theta}_5] = 0.652 \cdot 365 \equiv 238.0 \text{ days}.
\]

5. System Reliability in Variable Operating Conditions

We assume that the changes of the system operation process \( Z(t) \) states have an influence on the system components \( E_i, \ i = 1, 2, ..., n \), reliability and the system reliability structure as well. Consequently, we denote the component \( E_i \) lifetime by \( T_i^{(b)} \) and by:

\[
R_i^{(b)}(t) = P(T_i^{(b)} > t | Z(t) = z_b) \quad \text{for} \quad t < 0, \infty, \ i = 1, 2, ..., n, \ b = 1, 2, ..., \nu,
\]

its conditional reliability function while the system is at the operational state \( z_b \), \( b = 1, 2, ..., \nu \). Similarly, we denote the system lifetime by

\[
T^{(b)} = T(T_1^{(b)}, T_2^{(b)}, ..., T_n^{(b)}) \quad \text{for} \quad t < 0, \infty, \ b = 1, 2, ..., \nu, \ n \in N,
\]

and by \( R_s^{(b)}(t) = P(T^{(b)} > t | Z(t) = z_b) \) \( \text{for} \quad t < 0, \infty, \ b = 1, 2, ..., \nu, \ n \in N, \)

where, \( R_s^{(b)}(t) = R_s(R_1^{(b)}(t), R_2^{(b)}(t), ..., R_n^{(b)}(t)) \) \( \text{for} \quad t < 0, \infty, \ b = 1, 2, ..., \nu, \ n \in N, \)

the system conditional reliability function while the system is at the operational state \( z_b \), \( b = 1, 2, ..., \nu \).

Thus, the reliability function \( R_i^{(b)}(t) \) is the conditional probability that the component \( E_i \) lifetime \( T_i^{(b)} \) is greater than \( t \), while the process \( Z(t) \) is at the operational state \( z_b \). Similarly, the reliability function \( R_s^{(b)}(t) \) is the conditional probability that the system lifetime \( T^{(b)} \) is greater than \( t \), while the process \( Z(t) \) is at the operational state \( z_b \).
In the case when the system operation time $\theta$ is large enough, the unconditional reliability function $R_n(t)$ of the system

$$R_n(t) = P(T > t) \text{ for } t \in \mathbb{R},$$

where $T$ is the unconditional lifetime of the system is given by

$$R_n(t) = \sum_{b=1}^{\nu} p_b R^{(b)}_n(t) \text{ for } t \geq 0$$

and the mean value of the system lifetime is

$$\mu = \sum_{b=1}^{\nu} p_b \mu_b,$$

where

$$\mu_b = \int_0^\infty R^{(b)}_n(t) dt,$$

and $p_b$ are given by (4), and the variance of the system lifetime is

$$\sigma^2 = 2 \int_0^\infty R_n(t) dt - [\mu]^2.$$

### 6. Port Oil Transportation System Reliability in Variable operating Conditions

Using the model considered in section 5 and the results of section 4 we determined the conditional reliability functions of the port oil transportation system in particular operational states $z_b, b=1,2,3,4,5$.

At system operational state $z_1$, the system is composed of series "2 out of 3" subsystem $S_3$, that contains three non-homogenous series subsystems with structure showed in Fig. 2. Thus, the reliability function of the system [2] is given by

$$R^{(3)}_n(t) = \sum_{b=1}^{2} p_b R^{(b)}_n(t) dt = [R^{(2)}_{3,362}(t)]^{(1)} = \exp[-6.8885t] + 2\exp[-4.3019t]$$

$$-2\exp[-6.8885t], t \geq 0.$$  

According to (10), the system lifetime mean value at the operational state $z_1$ is

$$\mu_1 = 0.364 \text{ year.}$$

At system operational state $z_2$, the system is composed of non-homogenous series-parallel subsystem $S_4$, that contains three pipelines with structure showed in Fig. 3. Thus, the reliability function of the system [2] is given by

$$R^{(2)}_n(t) = R^{(2)}_{3,362}(t) = \exp[-2.5865t] + 2\exp[-2.15098t] - 2\exp[-4.7375t]$$

$$-\exp[-4.3019t] + \exp[-6.88848t], t \geq 0.$$  

According to (10), the system lifetime mean value at the operational state $z_2$ is

$$\mu_2 = 0.807 \text{ year.}$$

At system operational state $z_3$, the system is series and composed of two non-homogenous series-parallel subsystems $S_1, S_2$, each containing two pipelines with structure showed in Fig. 4. Thus, the reliability function of the system [2] is given by

$$R^{(1)}_n(t) = R^{(1)}_{2,379}(t) R^{(1)}_{2,379}(t) = \exp[-5.6132t] - 2\exp[-6.7397t]$$

$$-2\exp[-10.0999t] + \exp[-11.2264t], t \geq 0.$$
According to (10), the system lifetime mean value at the operational state \( z_3 \) is \( \mu_3 = 0.307 \) year. (17)

At system operational state \( z_4 \), the system is series and composed of two non-homogenous series subsystems \( S_1, S_2 \), and one series “2 out of 3” subsystem \( S_3 \) with structure showed in Fig. 5. Thus, the reliability function of the system [2] is given by

\[
R_{\infty}^{(3)}(t) = R_{356}^{(4)}(t) R_{438}^{(4)}(t) \prod R_{3,364}^{(2)}(t)^{\frac{1}{4}} = \exp[-15.5284t] + 2 \exp[-15.964t] - 2\exp[-18.115t], \quad t \geq 0.
\] (18)

According to (10), the system lifetime mean value at the operational state \( z_4 \) is \( \mu_4 = 0.080 \) year. (19)

At system operational state \( z_5 \), the system is series and composed of two non-homogenous series-parallel subsystems \( S_1, S_2 \), (each contain two pipelines) and one series-parallel subsystem \( S_3 \) (contain three pipelines) with structure showed in Fig. 6. Thus, the reliability function of the system [2] is given by

\[
R_{\infty}^{(5)}(t) = R_{357}^{(3)}(t) R_{3,719}^{(3)}(t) \prod R_{3,362}^{(3)}(t) = \exp[-6.967t] + 4 \exp[-8.1997t] + 4 \exp[-10.6805t] + 4 \exp[-10.9083t] + 4 \exp[-14.0407t] + 2 \exp[-12.5807t] + 2 \exp[-12.8085t] + \exp[-13.8129t] + \exp[-16.5215t] - 8 \exp[-9.5540t] - 4 \exp[-8.0940t] - 4 \exp[-8.3218t] - 4 \exp[-11.4542t] - 2 \exp[-9.3262t] - 2 \exp[-12.0348t] - 2 \exp[-12.6864t] - 2 \exp[-15.1672t] - 2 \exp[-15.3950t] - \exp[-13.9350t], \quad t \geq 0.
\] (20)

According to (10), the system lifetime mean value at the operational state \( z_5 \) is \( \mu_5 = 0.275 \) year. (21)

Finally, considering (7) and (8), the system unconditional reliability function is given by

\[
R_{\infty}^{(n)}(t) = 0.018 \cdot R_{n}^{(1)}(t) + 0.228 \cdot R_{n}^{(2)}(t) + 0.095 \cdot R_{n}^{(3)}(t) + 0.007 \cdot R_{n}^{(4)}(t) + 0.652 \cdot R_{n}^{(5)}(t),
\] (22)

where \( R_{n}^{(1)}(t), R_{n}^{(2)}(t), R_{n}^{(3)}(t), R_{n}^{(4)}(t), R_{n}^{(5)}(t) \) are respectively given by (12), (14), (16), (18), (20). Then applying (9)-(11) and (22), we get the mean value and the standard deviation of the system unconditional lifetime given by:

\[
\mu \equiv 0.018 \cdot 0.364 + 0.228 \cdot 0.807 + 0.095 \cdot 0.307 + 0.007 \cdot 0.080 + 0.652 \cdot 0.275 \equiv 0.40 \text{ year}
\]

\[
\sigma \equiv 0.37 \text{ year.}
\] (23)

7. Conclusions

The paper proposes an approach to the solution of practically very important problem of linking the system reliability and its operation process. To involve the interactions between the system operation process and its varying in time reliability structure and components' reliability characteristics a semi-Markov model of the system operation process and the system conditional reliability functions are used. This approach gives practically important in everyday usage tool for reliability evaluation of the system with changing reliability structure and components’ reliability characteristics during its operation process. Application of the proposed method is illustrated in the reliability
evaluation of the port oil transportation system. The reliability input data concerned with the operation process and reliability functions of the components of the port oil transportation system are not precise. They are coming from experts and are concerned with the mean lifetimes of the system components and with the conditional sojourn times of the system in the operation states under arbitrary assumption that their distributions are Weibull (Releigh). Thus, the final results obtained in the system reliability characteristics evaluation are not precise as well and should be treated as an example of the proposed model possible application. In further developing of the proposed methods it seem to be possible to obtain the results useful in the complex technical systems related to their operation processes reliability evaluation, improvement and optimization.

References


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