MODELLING ENVIRONMENT AND INFRASTRUCTURE INFLUENCE ON RELIABILITY AND OPERATION PROCESSES OF PORT TRANSPORTATION SYSTEMS

MODELOWANIE WPŁYWU ŚRODOWISKA ORAZ INFRASTRUKTURY NA NIEZAWODNOŚĆ I PROCESY EKSPLOATACYJNE PORTOWYCH SYSTEMÓW TRANSPORTOWYCH

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Abstract: In the paper a probabilistic model of industrial systems environment and infrastructure influence on their operation processes is proposed. Semi-markov processes are used to construct a general model of complex industrial systems' operation processes. Main characteristics of this model are determined as well. In particular case, for a port grain transportation system, its operation states are defined, the relationships between them are fixed and particular model of its operation process is constructed and its main characteristics are determined. The joint model of the system operation process and the system reliability is constructed and applied to the reliability evaluation of port grain transportation system.

Keywords: system, reliability, operation, port, transport

Streszczenie: W artykule zaproponowany jest model probabilistyczny wpływu środowiska oraz infrastruktury systemów przemysłowych na ich proces eksploatacji. Do skonstruowania modelu ogólnego procesów eksploatacji złożonych systemów przemysłowych zastosowane są procesy semi-markowskie. Wyznaczone są także główne charakterystyki tego modelu. W szczególnym przypadku dla portowego systemu transportu zboża, zdefiniowane są jego stany eksploatacyjne, ustalone są relacje między nimi oraz zbudowany jest jego szczegółowy proces eksploatacji oraz wyznaczone są jego główne charakterystyki. Zbudowany jest łączny model procesu eksploatacji i niezawodności systemu i zastosowany do oceny niezawodności portowego systemu transportu zboża.

Słowa kluczowe: system, niezawodność, eksploatacja, port, transport

MODELLING ENVIRONMENT AND INFRASTRUCTURE INFLUENCE ON RELIABILITY AND OPERATION PROCESSES OF PORT TRANSPORTATION SYSTEMS

1. Introduction

Most real transportation systems are very complex and it is difficult to analyse their reliability. Large numbers of components and subsystems and their operating complexity cause that the evaluation and optimisation of their reliability is complicated. The complexity of the systems' operation processes and their influence on changing in time the systems' structures and their components' reliability characteristics is often very difficult to fix and to analyse. A convenient tool for solving this problem is semi-markov modelling of the systems operation processes. Therefore, the common usage of the system's reliability evaluation methods and semi-markov modelling the system's exploitation process in order to construct a general system reliability model related to its operation process is proposed in the paper. Statistical methods of the general model unknown parameters estimation are proposed. Main characteristics of this model are determined. Computer programme for determining these all values is shortly described. The way of its application to reliability evaluation of a port grain transportation system is illustrated.

2. Modelling system operation process

Usually the system environment and infrastructure have either an explicite or implicate 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 may 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 $Z(t)$, $t \in \langle 0, +\infty \rangle$, with discrete states from the set of states $Z = \{z_1, z_2, \dots, z_v\}$. If the system operation process $Z(t)$ is semi-markov [1], [5]-[6] with the conditional sojourn times θ_{bl} at the operation

states z_b when its next operation state is z_l , $b, l = 1, 2, \dots, v$, $b \neq l$, then it may be described by:

- the vector of probabilities of the system operation process initial states

$$[p_b(0)]_{1 \times v} = [p_1(0), p_2(0), \dots, p_v(0)],$$

where

$$p_b(0) = P(Z(0) = z_b) \text{ for } b = 1, 2, \dots, v,$$

- the matrix of probabilities of the system operation process transitions between the operation states

$$[p_{bl}]_{v \times v} = \begin{bmatrix} p_{11} & p_{12} & \dots & p_{1v} \\ p_{21} & p_{22} & \dots & p_{2v} \\ \dots & & & \\ p_{v1} & p_{v2} & \dots & p_{vv} \end{bmatrix},$$

where

$$p_{bb} = 0 \text{ for } b = 1, 2, \dots, v,$$

- the matrix of the system operation process conditional sojourn times θ_{bl} distribution functions

$$[H_{bl}(t)]_{v \times v} = \begin{bmatrix} H_{11}(t) & H_{12}(t) & \dots & H_{1v}(t) \\ H_{21}(t) & H_{22}(t) & \dots & H_{2v}(t) \\ \dots & & & \\ H_{v1}(t) & H_{v2}(t) & \dots & H_{vv}(t) \end{bmatrix},$$

where

$$H_{bl}(t) = P(\theta_{bl} < t) \text{ for } b, l = 1, 2, \dots, v, \quad b \neq l,$$

and

$$H_{bb}(t) = 0 \text{ for } b = 1, 2, \dots, v.$$

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

$$M_{bl} = E[\theta_{bl}] = \int_0^{\infty} t dH_{bl}(t), \quad b, l = 1, 2, \dots, v, \quad b \neq l. \quad (1)$$

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

$$H_b(t) = \sum_{l=1}^v p_{bl} H_{bl}(t), \quad b = 1, 2, \dots, v. \quad (2)$$

Hence, the mean values $E[\theta_b]$ of the system operation process unconditional sojourn times θ_b in the particular operation states are given by

$$M_b = E[\theta_b] = \sum_{l=1}^v p_{bl} M_{bl}, \quad b = 1, 2, \dots, v, \quad (3)$$

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

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

$$p_b(t) = P(Z(t) = z_b), \quad t \in (0, +\infty), \quad b = 1, 2, \dots, v,$$

are given by

$$p_b = \lim_{t \rightarrow \infty} p_b(t) = \frac{\pi_b M_b}{\sum_{l=1}^v \pi_l M_l}, \quad b = 1, 2, \dots, v, \quad (4)$$

where M_b , $b = 1, 2, \dots, \nu$, are defined by (3), whereas the probabilities π_b of the vector $[\pi_b]_{1 \times \nu}$ satisfy the system of equations

$$\begin{cases} [\pi_b] = [\pi_b][p_{bl}] \\ \sum_{l=1}^{\nu} \pi_l = 1. \end{cases} \quad (5)$$

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 , $b = 1, 2, \dots, \nu$. It is well known [1] that the system operation process total sojourn times $\hat{\theta}_b$ in the particular operation states z_b , for sufficiently large operation time θ , have approximately normal distribution with the expected value given by

$$E[\hat{\theta}_b] = p_b \theta, \quad b = 1, 2, \dots, \nu, \quad (6)$$

where p_b are given by (4).

3. Statistical identification of unknown parameters of system operation process general model

In order to estimate parameters of the system operation process model the following step should be done:

- to fix the number of states ν of the system operation process $Z(t)$ and to define the operation states $z_1, z_2, \dots, z_\nu$ of the set Z ,
- to fix the vector of realisations

$$[n_b(0)] = [n_1(0), n_2(0), \dots, n_\nu(0)],$$

of the numbers $n_b(0)$, $b = 1, 2, \dots, \nu$, 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

$$[n_{bl}] = \begin{bmatrix} n_{11} & n_{12} & \dots & n_{1\nu} \\ n_{21} & n_{22} & \dots & n_{2\nu} \\ \dots & & & \\ n_{\nu 1} & n_{\nu 2} & \dots & n_{\nu\nu} \end{bmatrix},$$

of the numbers n_{bl} , $b, l = 1, 2, \dots, \nu$, of the system operation process $Z(t)$ transitions from the state z_b into the state z_l during the experiment time Θ ,
 - to fix the vector of realisations

$$[p(0)] = [p_1(0), p_2(0), \dots, p_\nu(0)],$$

of the initial probabilities $p_b(0)$, $b = 1, 2, \dots, \nu$, of the system operation process $Z(t)$ transients in the particular states z_b at the moment $t = 0$, according to the formula

$$p_b(0) = \frac{n_b(0)}{n(0)} \text{ for } b = 1, 2, \dots, \nu,$$

where

$$n(0) = \sum_{b=1}^{\nu} n_b(0),$$

is the total number of the system operation process $Z(t)$ realisations at $t = 0$,
 - to fix the matrix of realisations

$$[p_{bl}] = \begin{bmatrix} p_{11} & p_{12} & \dots & p_{1m} \\ p_{21} & p_{22} & \dots & p_{2m} \\ \dots & & & \\ p_{m1} & p_{m2} & \dots & p_{mm} \end{bmatrix},$$

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

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

where

$$n_b = \sum_{l \neq b}^{\nu} n_{bl}, \quad b = 1, 2, \dots, \nu,$$

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

4. Computer programme

To accerelate the evaluation of unknown parameters of the system general operation process model on the basis of statistical data a computer programme is elaborated [7]. The programming language is Python. All necessary parameters of the general model are possible to be statistically identified and the hypotheses on the conditional distribution functions $H_{bl}(t)$ are possible to be testified in particular cases when they are uniform, triangle, doble trapezium, exponantial, Weibull and normal. Moreover, all distinquished characteristics of the system operation process $Z(t)$ can be calculated.

5. Identification of port grain elevator operation process

As an example we will analyse the reliability of the port grain elevator in its operation process [2], [3]-[4]. The basic elevator function is loading railway trucks with grain. In loading the railway trucks with grain the following elevator transportation subsystems take part: S_l – horizontal conveyors of

the first type, S_2 – vertical bucket elevators, S_3 – horizontal conveyors of the second type, S_4 – worm conveyors.

The structure of the port grain transportation system is given in (Fig. 1).

Fig. 1. The scheme of the grain transportation system

The subsystem S_1 consists of 2 identical belt conveyors of the first type, each composed of 129 components. In each conveyor there are 1 ribbon belt, 2 drums, 117 channelled rollers and 9 supporting rollers. The subsystem S_2 consists of 3 identical bucket elevators, each composed of 743 components. In each elevator there are 1 belt, 2 two drums, and 740 buckets. The subsystem S_3 consists of 2 identical belt conveyors of the second type, each composed of 139 components. In each conveyor there are 1 belt, 2 drums, 117 channelled rollers and 19 supporting rollers. The subsystem S_4 consists of 3 chain conveyors. Two of these are composed of 162 components and the remaining one is composed of 242 components. In two conveyors of them there are 2 driving wheels and 160 links. The third conveyor is composed of 2 driving wheels and 240 links.

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

- the operation state z_1 when the system operation with the largest efficiency when all components of the subsystems are used, with the structure given in (Fig. 1),
- the operation state z_2 when the system operation with less efficiency system when the first conveyor of subsystem S_1 the first and second elevators of subsystem S_2 the first conveyor of subsystem S_3 and the first

and second conveyors of subsystem S_4 are used, with the structure given in (Fig. 2),

Fig. 2. The scheme of the grain transportation system at the operation state z_2

- the operation state z_3 when the system operation with least efficiency when only the first conveyor of subsystem S_1 the first elevator of subsystem S_2 the first conveyor of subsystem S_3 and the first conveyor of subsystem S_4 are used, with the structure given in (Fig. 3).

Fig. 3. The scheme of the grain transportation system at operation state z_3

Moreover, we almost arbitrarily, i.e. slightly using an expert opinion, assume the following matrix of the conditional distribution functions

$$[H_{bl}(t)] = \begin{bmatrix} 0 & 1 - e^{-6.06t^2} & 1 - e^{-19.64t^2} \\ 1 - e^{-314.16t^2} & 0 & 1 - e^{-19.64t^2} \\ 1 - e^{-122.72t^2} & 1 - e^{-314.16t^2} & 0 \end{bmatrix}$$

of the elevator operation process sojourn times θ_{bl} , $b, l = 1, 2, 3$, in the distinguished operation states z_1, z_2, z_3 and the matrix of the probabilities of transitions between the operation states

$$[p_{bl}] = \begin{bmatrix} 0 & 0.357 & 0.643 \\ 0.8 & 0 & 0.2 \\ 0.385 & 0.615 & 0 \end{bmatrix}.$$

Further, according to (2), the unconditional distribution functions of the elevator operation process $Z(t)$ sojourn times θ_b in the states z_b , $b = 1, 2, 3$, are given by

$$H_1(t) = 1 - 0.357 \exp[-6.06t^2] - 0.643 \exp[-19.64t^2],$$

$$H_2(t) = 1 - 0.8 \exp[-314.16t^2] - 0.2 \exp[-19.64t^2],$$

$$H_3(t) = 1 - 0.385 \exp[-122.72t^2] - 0.615 \exp[-314.16t^2],$$

and their mean values, from (3), are

$$M_1 = E[\theta_1] = 0.357 \cdot 0.36 + 0.643 \cdot 0.2 \cong 0.257,$$

$$M_2 = E[\theta_2] = 0.8 \cdot 0.05 + 0.2 \cdot 0.2 \cong 0.08,$$

$$M_3 = E[\theta_3] = 0.385 \cdot 0.08 + 0.615 \cdot 0.05 \cong 0.062.$$

Since from the system of equations

$$\begin{cases} [\pi_1, \pi_2, \pi_3] = [\pi_1, \pi_2, \pi_3] \begin{bmatrix} 0 & 0.357 & 0.643 \\ 0.8 & 0 & 0.2 \\ 0.385 & 0.615 & 0 \end{bmatrix}, \\ \pi_1 + \pi_2 + \pi_3 = 1 \end{cases}$$

we get

$$\pi_1 = 0.374, \pi_2 = 0.321, \pi_3 = 0.305,$$

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

$$p_1 = 0.684, p_2 = 0.183, p_3 = 0.133. \quad (7)$$

And, by (6), the expected values of the total sojourn times $\hat{\theta}_b$, $b = 1, 2, 3$, in particular operation states for the elevator operation time

$$\theta = 1 \text{ year} = 365 \text{ days}$$

are given by

$$E[\hat{\theta}_1] = 0.684 \cdot 365 \cong 249.7 \text{ days},$$

$$E[\hat{\theta}_2] = 0.183 \cdot 365 \cong 66.8 \text{ days},$$

$$E[\hat{\theta}_3] = 0.133 \cdot 365 \cong 48.5 \text{ days}.$$

6. Reliability of system in variable operation process

We assume that the changes of the system operation process $Z(t)$ states have an influence on the system components E_i , $i = 1, 2, \dots, n$, reliability and the system reliability structure as well. Thus, we denote the conditional reliability function of the system component E_i while the system is at the operational state z_b , $b = 1, 2, \dots, \nu$, by

$$R_i^{(b)}(t) = P(T_i^{(b)} > t | Z(t) = z_b) \text{ for } t \in < 0, \infty), i = 1, 2, \dots, n, b = 1, 2, \dots, \nu,$$

and the conditional reliability function of the system while the system is at the operational state z_b , $b = 1, 2, \dots, \nu$, by

$$R_n^{(b)}(t) = P(T^{(b)} > t | Z(t) = z_b) \text{ for } t \in < 0, \infty), b = 1, 2, \dots, \nu, n \in N,$$

where

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

and

$$\mathbf{R}_n^{(b)}(t) = \mathbf{R}_n(R_1^{(b)}(t), R_2^{(b)}(t), \dots, R_n^{(b)}(t)) \text{ for } t \in \langle 0, \infty), b = 1, 2, \dots, \nu, n \in N.$$

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 operation state z_b . Similarly, the reliability function $\mathbf{R}_n^{(b)}(t)$ is the conditional probability that the system lifetime $T^{(b)}$ is greater than t , while the process $Z(t)$ is at the operation state z_b . In the case when the system operation time θ is large enough, the unconditional reliability function of the system

$$\mathbf{R}_n(t) = P(T > t) \text{ for } t \in \langle 0, \infty),$$

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

$$\mathbf{R}_n(t) \cong \sum_{b=1}^{\nu} p_b \mathbf{R}_n^{(b)}(t) \text{ for } t \geq 0 \quad (8)$$

and the mean value of the system lifetime is

$$\mu \cong \sum_{b=1}^{\nu} p_b \mu_b, \quad (9)$$

where

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

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

$$\sigma^2 = 2 \int_0^{\infty} t \mathbf{R}_n(t) dt - [\mu]^2. \quad (10)$$

7. Reliability of port grain elevator in variable operation process

Using the model considering in section 6, the results of section 5 and the results given in [4], by (7) and (8), we have

$$\mathbf{R}_n(t) \cong 0.684 \cdot \mathbf{R}_n^{(1)}(t) + 0.183 \cdot \mathbf{R}_n^{(2)}(t) + 0.133 \cdot \mathbf{R}_n^{(3)}(t) \quad (11)$$

where $\mathbf{R}_n^{(1)}(t)$, $\mathbf{R}_n^{(2)}(t)$, $\mathbf{R}_n^{(3)}(t)$ are the system reliability functions in particular operation states determined by (34), (38) and (42) in [4].

Since according to the results given in [4]

$$\mu_1 = \int_0^{\infty} R_n^{(1)}(t)dt = 0.01197, \quad \mu_2 = \int_0^{\infty} R_n^{(2)}(t)dt = 0.0086,$$

$$\mu_3 = \int_0^{\infty} R_n^{(3)}(t)dt = 0.0054,$$

then applying (11), (9) and (10), we get the mean value and the standard deviation of the system unconditional lifetime given by

$$\mu \cong 0.684 \cdot 0.01197 + 0.183 \cdot 0.0086 + 0.133 \cdot 0.0054 \cong 0.011,$$

$$\sigma \cong \sqrt{0.000048} \cong 0.007.$$

8. Conclusions

The paper proposes an approach to the solution of practically very important problem of linking the systems' reliability and their operation processes. To involve the interactions between the systems' operation processes and their varying in time reliability structures and components' reliability characteristics a semi-markov model of the systems' operation processes and system conditional reliability functions are used. This approach gives practically important in everyday usage tool for reliability evaluation of the systems with changing reliability structures and components' reliability characteristics during their operation processes. Application of the proposed method is illustrated in the reliability evaluation of the port grain transportation system. The reliability input data concerned with the operation process and reliability functions of the components of the port grain 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. 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 optimisation.

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