MODELLING OF OPERATIONAL PROCESSES OF BULK CARGO TRANSPORTATION SYSTEM

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ABSTRACT

A general analytical model of industrial systems infrastructure influence on their operation processes is constructed. Next, as its particular case a detailed model of port infrastructure influence on port transportation systems operation processes is obtained to apply and test it to selected transportation systems used in Gdynia Port.

1 INTRODUCTION

In the paper 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 cases, for selected port transportation systems, their operation states are defined, the relationships between them are fixed and particular models of their operation processes are constructed and their main characteristics are determined. Finally, on the basis of theoretical results, a computer software is proposed and its accuracy is practically tested. The paper aims mainly to propose the basis for new and to develop existing methods, tools and software capable of supporting intelligent modelling and decision support systems, in controlling and optimising the safety and reliability of complex real industrial systems related to their operation processes, with their primarily applications in the coastal transportation sector.

2 MODELLING 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 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 $Z(t)$, $t \in < 0,+\infty >,$ 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 (Grabski [1], Soszynska [5]-[6]) with the conditional sojourn times θ_{bl} at the operation states z_b when its next operation state is z_l, $b, l = 1,2,...,v,$ $b \neq l,$ then it may be described by:
- the vector of probabilities of the system operation process initial states

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

where

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

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

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

where

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

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

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

where

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

and

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

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

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

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, $b = 1,2,...,v$, are given by

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

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

$$M_b = E[\theta_b] = \sum_{l=1}^{v} p_{bl} M_{bl} \, , \; b = 1,2,\ldots,v, \tag{3}$$

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

$$p_b(t) = P(Z(t) = z_b) \, , \; t \in <0,+\infty), \; b = 1,2,\ldots,v,$$

are given by

$$p_b = \lim_{t \to \infty} p_b(t) = \frac{\pi_b M_b}{\sum_{l=1}^{v} \pi_l M_l}, \; b = 1,2,\ldots,v, \tag{4}$$

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

$$\begin{cases} [\pi_b] = [\pi_b][p_{bl}] \\ \sum_{l=1}^{v} \pi_l = 1. \end{cases} \tag{5}$$

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, $b = 1,2,\ldots,v.$ 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

$$E[\hat{\theta}_b] = p_b \theta, \; b = 1,2,\ldots,v, \tag{6}$$

where p_b are given by (4).

3 APPLICATION – OPERATION PROCESS OF BULK CARGO TRANSPORTATION SYSTEM

As an example will be analysed the reliability of the bulk conveyor system in its operation process (Kołowrocki [2], Kołowrocki & Kwiatuszewska-Sarnecka [3]). The bulk conveyor system is the part of the Baltic Bulk Terminal of the Port of Gdynia assigned to load ships with bulk cargo from Terminal Storage. Three self-acting loading machines, the transportation system composed of belt conveyors and the coastal loading system carry out the loading of the ships.
In the conveyor reloading system we distinguish the following transportation subsystems:
S_1, S_2, S_3 – the belt conveyors.
In the conveyor loading system we distinguish the following transportation subsystems:

S_4 – the dosage conveyor, S_5 – the horizontal conveyor, S_6 – the horizontal conveyor, S_7 – the sloping conveyors, S_8 – the dosage conveyor with buffer, S_9 – the loading system, S_7 – the dosage conveyor with buffer, S_8 – the sloping conveyor, S_9 – the loading system.
The whole bulk cargo transportation system consists of:
- the subsystem S_1 composed of 1 rubber belt, 2 drums, set of 121 bow rollers, set of 23 belt supporting rollers,
- the subsystem S_2 composed of 1 rubber belt, 2 drums, set of 44 bow rollers, set of 14 belt supporting rollers,
- the subsystem S_3 composed of 1 rubber belt, 2 drums, set of 185 bow rollers, set of 60 belt supporting rollers,
- the subsystem S_4 composed of three identical belt conveyors, each composed of 1 rubber belt, 2 drums, set of 12 bow rollers, set of 3 belt supporting rollers,
- the subsystem S_5 composed of 1 rubber belt, 2 drums, set of 125 bow rollers, set of 45 belt supporting rollers,
- the subsystem S_6 composed of 1 rubber belt, 2 drums, set of 65 bow rollers, set of 20 belt supporting rollers,
- the subsystem S_7 composed of 1 rubber belt, 2 drums, set of 12 bow rollers, set of 3 belt supporting rollers,
- the subsystem S_8 composed of 1 rubber belt, 2 drums, set of 162 bow rollers, set of 53 belt supporting rollers,
- the subsystem S_9 composed of 3 rubber belts, 6 drums, set of 64 bow rollers, set of 20 belt supporting rollers.

The transporting subsystems have steel covers and they are provided with drives in the form of electrical engines with gears. In their reliability analysis we omit their drives, as they are mechanisms of different types. We also omit their covers as they have a high reliability and, practically, do not fail.

The structure of the bulk cargo loading transportation system is given in *Figure 1*.

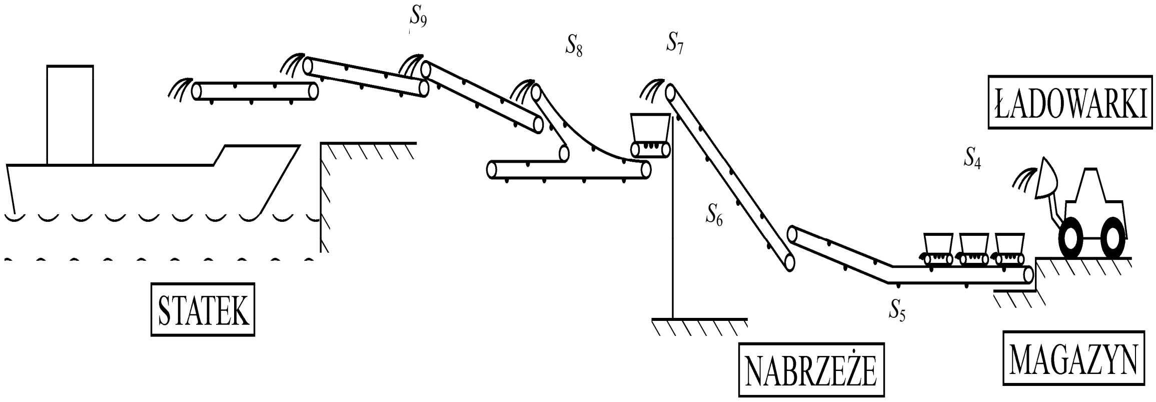

Figure 1. General scheme of bulk cargo transportation system

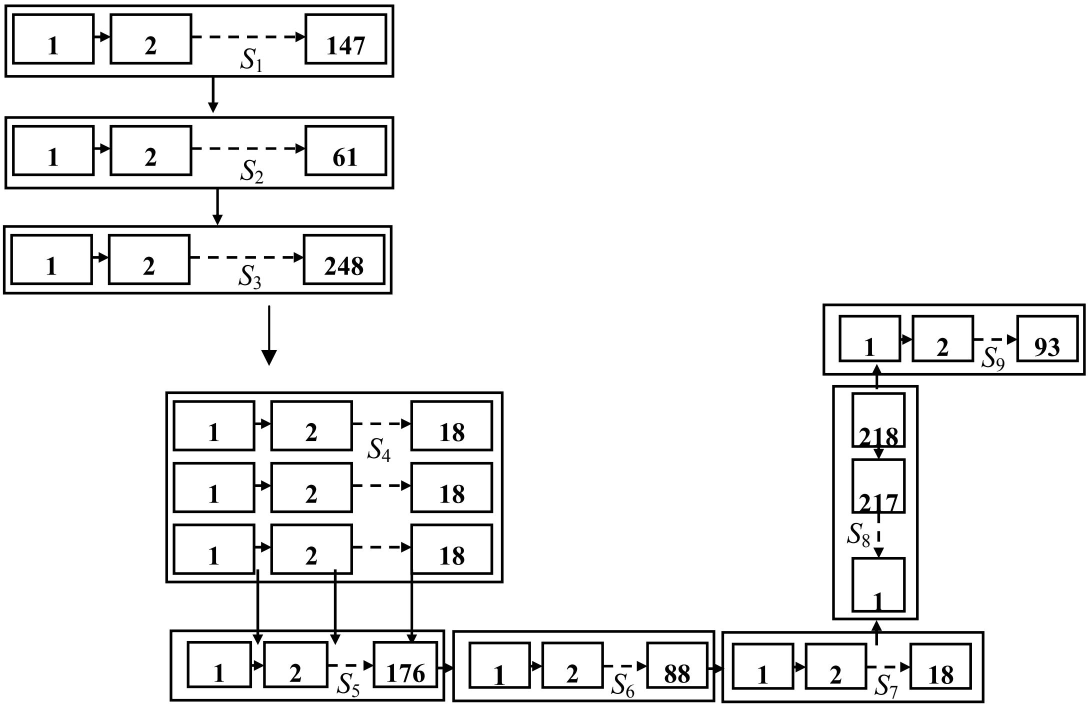

Figure 2. Detailed scheme of bulk cargo transportation system

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

- an operation state z_1 – the discharging rail wagons to storage tanks or hall when subsystems S_1, S_2, S_3, are used, with the structure given in *Figure 3.*

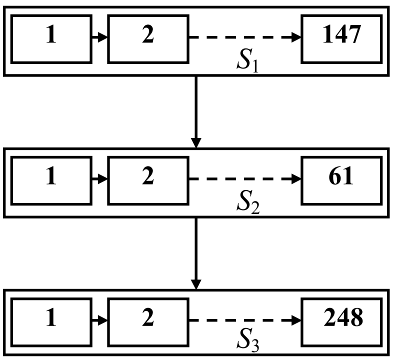

Figure 3. The scheme of the bulk cargo transportation system at the operation state z_1

- an operation state z_2 – the loading of fertilizers from storage tanks or hall on board the ship is done by using S_4, S_5, S_6, S_7, S_8 , S_9, subsystems, with the structure given in *Figure 4*.

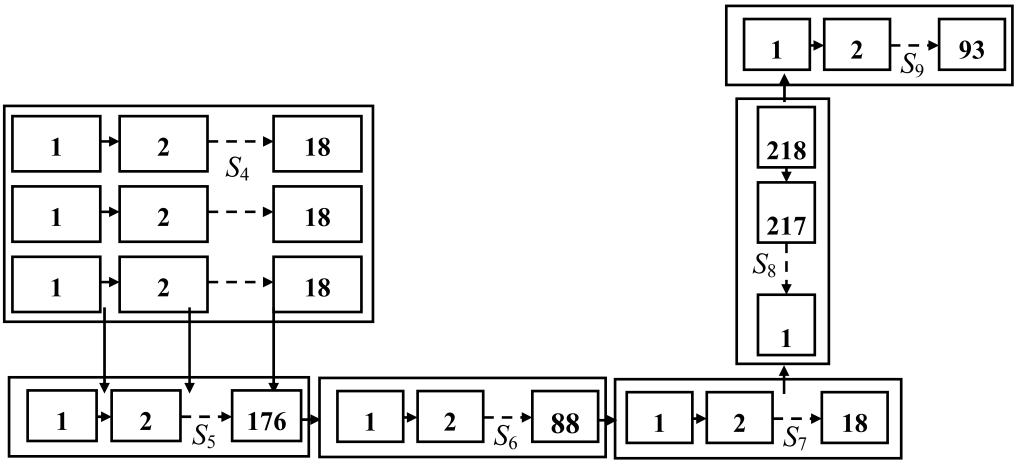

Figure 4. The scheme of the bulk cargo transportation system at the operation state z_2

- an operation state z_3 – the loading of fertilizers from rail wagons on board the ship is done by using S_1, S_2, S_3, S_6, S_7, S_8 , S_9 subsystems, with the structure given in *Figure 5*.

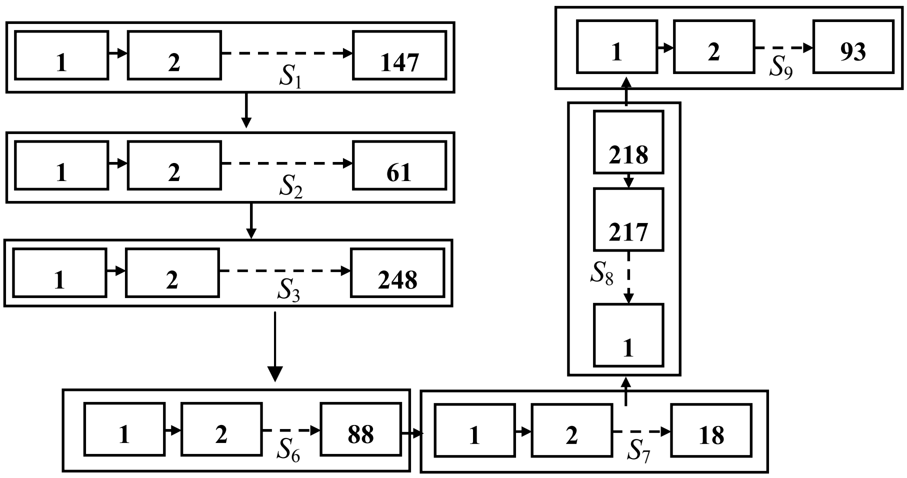

Figure 5. The scheme of the bulk cargo transportation system at the operation state z_3

Moreover, we arbitrarily, slightly using an expert opinion, assume the following matrix of the conditional distribution functions of the system sojourn times θ_{bl}, $b, l = 1,2,3,$

$$[H_{bl}(t)] = \begin{bmatrix} 0 & 1-e^{-0.01935t^2} & 1-e^{-0.00882t^2} \\ 1-e^{-0.08190t^2} & 0 & 0 \\ 1-e^{-0.03697t^2} & 0 & 0 \end{bmatrix}$$

and the matrix of the probabilities of transitions between the states

$$[p_{bl}] = \begin{bmatrix} 0 & 0.37 & 0.63 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}.$$

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

$$H_1(t) = 1 - 0.37\exp[-0.01935t^2] - 0.63\exp[-0.00882t^2],$$

$$H_2(t) = 1 - \exp[-0.08190t^2],$$

$$H_3(t) = 1 - \exp[-0.03697t^2],$$

and their mean values, from (3), are

$$M_1 = E[\theta_1] = 8.2,$$

$$M_2 = E[\theta_2] = 3.1,$$

$$M_3 = E[\theta_3] = 4.6.$$

Since from the system of equations

$$\begin{cases} [\pi_1, \pi_2, \pi_3] = [\pi_1, \pi_2, \pi_3] \begin{bmatrix} 0 & 0.37 & 0.63 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}, \\ \pi_1 + \pi_2 + \pi_3 = 1 \end{cases}$$

we get

$$\pi_1 = 0.5, \ \pi_2 = 0.185, \ \pi_3 = 0.315,$$

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

$$p_1 = 0.6694, \ p_2 = 0.0937, \ p_3 = 0.2367. \tag{7}$$

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

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

are given by

$$E[\hat{\theta}_1] = 0.6694 \cdot 365 \cong 244 \text{ days},$$

$$E[\hat{\theta}_2] = 0.0937 \cdot 365 \cong 35 \text{ days},$$

$$E[\hat{\theta}_3] = 0.2367 \cdot 365 \cong 86 \text{ days}.$$

4 RELIABILITY OF SYSTEMS IN VARIABLE OPERATION PROCESS

We assume that the changes of the 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. Thus, we denote the conditional reliability function of the system component E_i while the system is at the operational state z_b, $b = 1,2,...,v,$ by

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

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

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

where

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

and

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

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 $\boldsymbol{R}_n^{(b)}(t)$ 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

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

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

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

and the mean value of the system lifetime is

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

where

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

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

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

5 RELIABILITY OF BULK CARGO TRANSPORTATION SYSTEM IN VARIABLE OPERATION PROCESS

Using the model considering in section 3, the results of section 4 and the results given in Kołowrocki & Kwiatuszewska [3], by (7) and (8), we have

$$\boldsymbol{R}_n\ (t) \cong 0.6696 \cdot \boldsymbol{R}_n^{(1)}(t) + 0.0937 \cdot \boldsymbol{R}_n^{(2)}(t) + 0.2367 \cdot \boldsymbol{R}_n^{(3)}(t) \tag{11}$$

where $\boldsymbol{R}_n^{(1)}(t)$, $\boldsymbol{R}_n^{(2)}(t)$, $\boldsymbol{R}_n^{(3)}(t)$ are determined and given in [3].
Since according to the results given in [3]

$$\mu_1 = \int_0^\infty \boldsymbol{R}_n^{(1)}(t)dt = 0.0253,$$

$$\mu_2 = \int_0^\infty \boldsymbol{R}_n^{(2)}(t)dt = 0.0193,$$

$$\mu_3 = \int_0^\infty \boldsymbol{R}_n^{(3)}(t)dt = 0.0132,$$

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

$$\mu \cong 0.6696 \cdot 0.0253 + 0.0937 \cdot 0.0193 + 0.2367 \cdot 0.0132\ \cong 0.0219 \text{ year},$$

$$\sigma \cong \sqrt{0.0005037} \cong 0.0224$$

6 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 and risk evaluation of the bulk cargo transportation system. The reliability input data concerned with the operation process and reliability functions of the components of the port bulk cargo 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 exponential. 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 and availability evaluation, improvement and maintenance optimization.

References

1. Grabski F. *Semi-Markov Models of Systems Reliability and Operations.* Warsaw: Systems Research Institute, Polish Academy of Sciences; 2002.
2. Kołowrocki K. *Reliability of Large Systems*. Elsevier, 2004.
3. Kołowrocki K. Kwiatuszewska-Sarnecka B. *Ocena niezawodności i gotowości portowego systemu transportu towarów sypkich*. Zeszyty Naukowe Akademii Morskiej w Szczecinie 6, Materiały XI Międzynarodowej Konferencji Naukowo-Technicznej „Inżynieria Ruchu Morskiego – IMR 2005, Świnoujście, 2005, 199-210.
4. Kołowrocki K., Soszyńska J. Reliability and availability of complex systems. Quality and Reliability Engineering International. Vol. 22, Issue 1, J. Wiley & Sons Ltd., 2006, 79-99.
5. Kołowrocki K., Soszyńska J. Reliability, availability and risk evaluation of large systems. *Proc. Risk, Quality and Reliability International Conference*. Keynote Speech, Ostrava, 2007, 95-106.
6. Kwiatuszewska-Sarnecka B. Reliability improvement of large multi-state series-parallel systems. International Journal of Automation and Computing 2, 2006, 157-164.
7. Kwiatuszewska-Sarnecka B. Reliability improvement of large parallel-series systems. International Journal of Materials & Structural Reliability, Vol. 4, No 2, 2006, 149-159.