SIMULATION MODEL OF RISK EVALUATION IN TRANSPORT SYSTEM

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Abstract
The article presents the description of the developed simulation model of technical objects operation and maintenance process carried out in transport system. The simulation model of operation and maintenance process discussed in the paper allows for the evaluation of quality of technical system performance from the point of view of selected evaluation criteria: the risk of the occurrence of undesired events as well as availability of technical objects. The simulation model of the operation and maintenance process of technical objects was developed on the basis of the mathematical model of this process (semi-Markov model). On the basis of the results of tests performed in an existing means of transport operation system, input data of the model were established and simulation experiments performed. As a result, typical values for the analyzed characteristics of technical system operation quality.

Key words: *risk; availability; simulation model; operation and maintenance process.*

INTRODUCTION

One of the methods enabling effective assessment of operation quality of complex systems of technical objects is application of mathematical models for a description and analysis of the operation and maintenance processes of technical objects. Due to a significant complexity of processes carried out in existing systems of technical objects operation, there appears the need to implement appropriate methods and tools, including stochastic models (*Lee, 2000; Kulkarni, 1995*), matrix calculus (*Grabski, 2014; Zastempowski & Bochat, 2015*) as well as computer simulation programs providing effective carrying out of the tests of the models of analyzed operation processes as well as an analysis of results obtained (*Marbach & Tsitsiklis, 2001; Migawa, Knopik, Neubauer & Perczyński, 2017; Muślewski, Migawa & Knopik, 2016*). These models provide the possibility of assessment and control of operation quality of complex technical systems according to selected criteria such as costs, reliability, availability and also risk connected with the technical objects functioning. Depending on the kind of analyzed research problems, appropriate methods of delineating optimal and quasi-optimal solutions were implemented. Semi-Markov decisive model of availability control in which the selection of optimal strategy was carried out with the help of genetic algorithm was presented in the paper (*Migawa, Knopik & Wawrzyniak, 2016*). However, the issues connected to the evaluation of safety and risk were presented in the paper (*Grabski, 2010*) which contains the model of safety control developed with the use of decisive semi-Markov processes and Howard's algorithm. In the paper (*Migawa, Knopik, Sołtysiak & Kolber, 2017*) the semi-Markov model of risk evaluation in transport system is discussed as well.
In the case of risk connected with operation of technical systems, numerous methods are used for threat or safety level evaluation and analysis, including qualitative methods, analytical and graphic methods as well as quantitative methods. Although these methods make it possible to evaluate, control and reduce the value of risk to acceptable levels, they do not take into consideration, or do it only to a limited degree, the influence of important parameters of technical objects operation process. There is no connection between the evaluation of risk and fulfilling the criteria pertaining to providing the possibility to correctly carry out assigned tasks, e.g. taking into consideration the required level of availability, reliability as well as the values of economic indexes in the system of technical objects operation. Such an approach requires not only taking into consideration risk, but also an additional criterion of the evaluation of technical system. The objective of the paper is to develop and present the results of the tests of the simulation model of operation process the use of which makes it possible to evaluate the risk of the occurrence of undesired events, at the same time taking into consideration the requirements facing the operation systems regarding the level of availability of technical objects for carrying out the assigned transportation task.

MATERIALS AND METHODS

The presented approach involves determination of the risk connected with functioning of one technical object (transport mean). The risk associated with functioning of a single transport mean has been determined on the basis of a simulation model of the operation and maintenance process. The simulation model was built on the basis of an event model and a mathematical model (semi-Markov model) of this process. The event model of the operation and maintenance process was created on the basis of the analysis of the space of operation and maintenance states and events connected with technical objects (transport means) operating in the analysed real transport system. Applying semi-Markov processes in the mathematical operation and maintenance process, the following assumptions were made:

- the modelled process has a finite number of states $i = 1, 2, \dots, m$,
- if the technological object at moment t is in state i, then $X(t) = i$,
- random process $X(t)$ being a mathematical model of the operation and maintenance process is homogenous,
- at moment $t = 0$ the process is in state i, i.e. $P\{X(0) = i\} = 1$.

Limit probabilities p_i^* of remaining in states of the analyzed process $X(t)$ were determined based on limit theorem for semi-Markov processes (*Grabski*, *2014*), then:

- value of the unit risk of functioning disruption of transport means is described with the formula (1)

$$r(\delta) = \sum_{i \in S_U} p_i^* \cdot c_i = \frac{\sum_{i \in S_U} \pi_i \cdot \overline{\Theta_i} \cdot c_i}{\sum_{i \in S} \pi_i \cdot \overline{\Theta_i}} \qquad (1)$$

- value of the technical object availability function is described with the formula (2)

$$A(\delta) = \sum_{i \in S_A} p_i^* = \frac{\sum_{i \in S_A} \pi_i \cdot \overline{\Theta_i}}{\sum_{i \in S} \pi_i \cdot \overline{\Theta_i}} \qquad (2)$$

where:

c_i – values of unit cost generated in the states of process $X(t)$,

$\overline{\Theta_i}$ – average values of unconditional duration of the states of process $X(t)$,

π_i – values of probabilities of stationary distribution of the complex Markov chain,

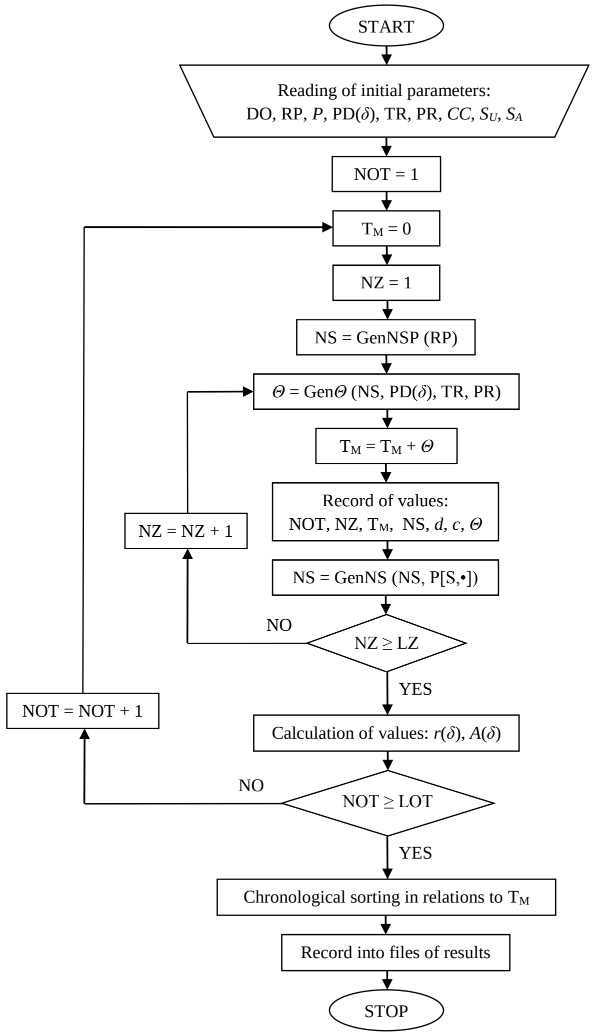
p_i^* – values of limit probabilities of remaining in states of semi-Markov model process $X(t)$,

$S_U \subset S = \{1,2,\dots,m\}$ – the set of unwelcome states of semi-Markov model process $X(t)$,

$S_A \subset S = \{1,2,\dots,m\}$ – the set of availability states of semi-Markov model process $X(t)$.

The results of the tests of the semi-Markov model of operation and maintenance process used in the evaluation of risk in the transport system was discussed in the paper (*Migawa, Knopik, Sołtysiak & Kolber, 2017*).

In order to provide the possibility of considering different computational variants, e.g. through changing the parameters of the modeled process or a number of analyzed technical objects, a program has been created for simulation of a model of technical objects operation process. The program developed for simulation of the operation process makes it possible to perform simulation experiments for different numbers of operational events (changes in the process states), intervals of simulation time both for an individual technical object and a group of technical objects. In the simulation program, successive duration times of the operation process states are determined by generating pseudorandom numbers yielding values form exponential, gamma, normal, logarithmic-normal and Weibull distributions. The structure of the simulation program was created so that the simulation experiment will be able to reflect a set of the analyzed technical objects and the sequence of events happening to each technical object in the analyzed real system. In Fig. 1 there is a block scheme depicting operation of the program for the model of technical objects operation process.



DO (general data characterizing the simulation experiment):
LOT – number of technical objects used in the simulation experiment,
LZ – number of a technical object events in the simulation experiment,
m – number of the process states, defined on the basis of a set of the modeled operation process states,
LD – number of decisions possible to be made in particular states of the modeled operation process,
Lδ – number of strategies δ possible to be used in the simulation experiment;

RP (the process initial distribution);
P (matrix of probabilities of the process states changes);
PD (matrix of probability of decision choice in the process states);
TR, PR (types and parameters of time distributions of being in particular states of the process);
CC (matrix of unit costs in the process states);
S_U (set of the process unwelcome states);
S_A (set of the process availability states);
GenNSP – generation of the model initial state number;
GenNS – generation of the model current state;
GenΘ – generation of the time value of being in the model state.

Fig. 1 Block scheme depicting operation of the program for technical objects operation process simulation model

In each moment of the simulation experiment in which the modeled operation process undergoes change (for the analyzed technical object) the following data is being entered into the file of results: number of the technical object NOT, number of the current event NZ, time of the current event (current time of model T_M), number of the model current state NS, current decision *d*, value of unit cost *c* related to the object's being in the process current state, generated value of the object's being in a current state Θ.
Next, values of functions applied in the simulation program are determined for the set of data generated during the simulation experiment:

– value of the unit risk of functioning disruption of transport means while carrying out the operation and maintenance process is described with the formula (3)

$$r(\delta)=\frac{\sum_{k=1}^{Z}\Theta_k(S_U)\cdot c_k(S_U)}{\sum_{k=1}^{Z}\Theta_k} \tag{3}$$

– value of the technical object availability function is described with the formula (4)

$$A(\delta)=\frac{\sum_{k=1}^{Z}\Theta_k\left(S_A\right)}{\sum_{k=1}^{Z}\Theta_k} \tag{4}$$

where:

Θ_k – k-th time of the object's being in the modeled operation process states $S=\{1,2,\ldots,m\}$,

$\Theta_k\left(S_U\right)$ – k-th time of the object's being in the modeled operation process states belonging to unwelcome states $S_U\subset S=\{1,2,\ldots,m\}$,

$c_k\left(S_U\right)$ – k-th performance of a unit cost connected with being in the unwelcome states of the modeled operation process $S_U\subset S=\{1,2,\ldots,m\}$,

$\Theta_k\left(S_A\right)$ – k-th time of the object's being in the modeled operation process states belonging to availability states $S_A\subset S=\{1,2,\ldots,m\}$,

Z = LOT · LZ – number of events (changes of the model states) for a specified number of technical objects.

RESULTS AND DISCUSSION

Fig. 2 depicts a directed graph of imaging of the considered process of technical objects operation and maintenance. The analyzed model of the process of operation and maintenance distinguishes the following states: 1 – stopover at depot parking space, 2 – carrying out of transport task, 3 – downtime caused by damage (unwelcome event), 4 – downtime caused by an accident or collision (unwelcome event), 5 – intervention and rescue action after accident or collision (unwelcome event), 6 – repair after an unwelcome event, 7 – preventive diagnosis, 8 – preventive repair, 9 – supply, 10 – servicing (operation day, periodical, seasonal).

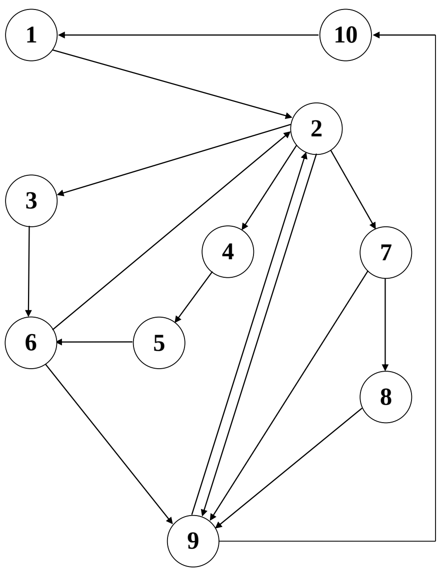


Fig. 2 A directed graph depicting operation and maintenance process of transport means

In the presented model the following unwelcome states of technical object have been distinguished: 3, 4, 5, 6; and the following availability states of technical object have been distinguished: 1, 2.

For the analyzed model of the operation and maintenance process of transport means, basing on the functioning data, values were estimated for the elements of matrix of passage probabilities:

$$P = \begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.2320 & 0.0030 & 0 & 0 & 0.4988 & 0 & 0.2661 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0.4702 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5298 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.0799 & 0.9201 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0.2242 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.7758 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

Below in Fig. 3 and in Tab. 1 sample tests results for the operation process model obtained from input data processed after being provided from a real system of technical objects operation have been shown.

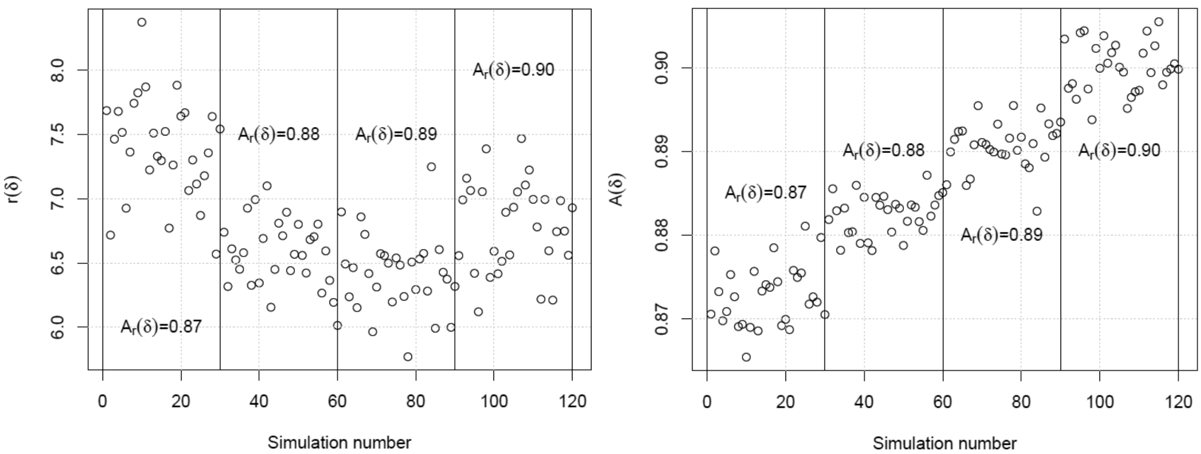


Fig. 3 Values of unit risk $r(\delta)$ [PLN/h] as well as availability of technical object $A(\delta)$ on the basis of simulation experiments for individual control strategies

Tab. 1 Values of statistics determined for unit risk and availability of a technical object

	$A_r(\delta)$=0.87		$A_r(\delta)$=0.88		$A_r(\delta)$=0.89		$A_r(\delta)$=0.90	
Statistic	$r(\delta)$ PLN/h	$A(\delta)$	$r(\delta)$ PLN/h	$A(\delta)$	$r(\delta)$ PLN/h	$A(\delta)$	$r(\delta)$ PLN/h	$A(\delta)$
Mean	7.398	0.8728	6.567	0.8825	6.417	0.8907	6.789	0.9001
Standard deviation	0.394	0.0037	0.260	0.0024	0.299	0.0029	0.349	0.0030
Minimum	6.569	0.8655	6.013	0.8782	5.769	0.8829	6.120	0.8938
1 Quartile	7.190	0.8698	6.378	0.8805	6.249	0.8896	6.558	0.8976
Median	7.414	0.8727	6.573	0.8831	6.446	0.8909	6.837	0.8999
3 Quartile	7.663	0.8752	6.732	0.8843	6.552	0.8923	7.039	0.9025
Maximum	8.375	0.8811	7.100	0.8872	7.249	0.8955	7.469	0.9055

The performed experiments involved 30 simulations of the operation process for four selected strategies δ, so that the designated availability of technical objects $A(\delta)$ was at least equal to required availability $A_r(\delta)$ for appropriate realization of transport tasks (for $A_r(\delta)$ = 0.87, 0.88, 0.89, 0.90). As a result of the realization of simulation experiments, sets of 30 values of unit risk $r(\delta)$ as well as 30 values of technical object availability $A(\delta)$ were obtained. Tab. 1 shows the results of simulation experiments: mean values, values of standard deviation and values of positional statistics (minimum, 1 quartile, median, 3 quartile, maximum), determined for the considered characteristics of the technical objects operation process quality and selected strategies δ. On the basis of obtained results, it is noticeable that in terms of required availability $A_r(\delta)$ from 0.87 to 0.89, the increase of availability is accompanied by a decrease of mean risk value $r(\delta)$ from 7.398 to 6.417 [PLN/h] respectively. However, obtaining a higher level of availability of technical objects (for $A_r(\delta) > 0.90$) is connected with an increase of risk value up to the level $r(\delta) = 6.789$ [PLN/h]. This results from the need to provide additional operations and means connected with treatment of technical objects (both due to higher unit costs as well as treatment period).

CONCLUSIONS

On the basis of results obtained, it is possible to conclude that ensuring a higher level of technical object availability does not have to cause a decrease in risk of occurrence of undesired events in operation system. This may result from the fact that the increase of the level of availability of technical objects does not influence the decrease of probability of occurrence of undesired events, as it only necessitates additional costs to be incurred in connection with removing the effects of such events. On the basis of a detailed analysis of the results of tests it was concluded that it had been caused by an increase in time of remaining at states of maintaining worthiness of technical objects.

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