



AN EXAMPLE OF A TECHNICAL OBJECT OPERATION PROCESS MODEL DESCRIBING INFLUENCE OF ENGINE DAMAGES ON THE OPERATION PROCESS COURSE

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Abstract

The authors of this paper present, a method for building a model of technical objects operation whose sequence of successive operation states, their duration times, incomes and costs connected with the objects being in these states and the way a given state is reached depend not only on the object current state but also on other factors.

The model describes, among others, influence of damages of the powertrain, being a compression-ignition internal combustion piston engine, of the analyzed object on the operation process of that object. The analysed technical object is a means of transport (a vehicle).

A simplified computing model has been presented in order to illustrate the discussion.

The model of operation process was built basing on the analysis of spaces of states and operation events concerning technical objects used in a real transportation system. In result of identification of the analyzed system and its multi-state process of technical objects operation, operation states and possible transitions between these states, significant for this research, have been determined.

Sets of source data indispensable for the model assessment and its initial verification were obtained on the basis of experimental tests with the use of passive experiment method from a real research object.

In order to perform mathematical modelling of the technical object operation process the Markov decision process was applied.

Keywords: *operation process, Markov decision process, state of object, operation state, damage*

1. Introduction

The authors of this paper present, a method for building a model of technical objects operation whose sequence of successive operation states, their duration times, incomes and costs connected with the objects being in these states and the way a given state is reached depend not only on the object current state but also on other factors. A simplified computing model has been presented in order to illustrate the discussion.

A natural model of a vehicle (technical object) operation is a random process with a finite state space S and a set of parameters R^+ (subset of natural numbers ≥ 0) [5, 11, 12]. Homogenous stochastic processes, including Markov and semi-Markov processes [10, 11, 12, 13] are commonly used for modeling of operation state changes. This is an oversimplification of real processes. In result of identification of the process of urban bus transportation it was found to be a nonhomogeneous process. Also, due to the research objective and the need to model a sequence of the object states, whose changes depend not only on the previous states but also on other factors, the operation process was analyzed using the theory of Markov decision processes.

Stochastic model $\{X_t, D_t, t \in T\}$, $t \geq 0$, being a specific case of Markov decision process, was used. In practical applications it must be decided whether there are reasons to reject the assumptions connected with the mathematical apparatus.

It has been assumed that each of the operated and maintained technical objects, at the specific moment in time t , $t > 0$, may be in only one of the distinguished states, forming a finite set of the operation and maintenance states of an object.

The model of the process of changes of the maintenance states of technical objects is the stochastic process $\{X_t, t \in T\}$, $t \geq 0$ with finite set (space) of states $S = \{1, 2, 3, \dots, n\}$.

Probability of changing the state in a single process step $\{X_t, t \in T\}$ from the state i , $i \in S$ to the state j , $j \in S$, provided that the condition a , $a \in A$ is met is denoted as p_{ij}^a , $\sum_{j \in S} p_{ij}^a = 1$, $p_{ij}^a \geq 0$, for $i, j \in S$ and $a \in A$.

The sequence of the process states $\{X_t, t \in T\}$ is a non-homogeneous Markov chain.

The stochastic process described that way is a special event of a non-stationary Markov decision process.

Due to the character of this paper, only selected assumptions of the simplified vehicle operation process model have been presented. The values of indices characterizing the analyzed process are determined with the use of computer simulation of Markov decision process, being a mathematical model of technical objects operation process.

2. Mathematical model of the operation process

In the next section the main assumptions accepted for the description of stochastic process $\{X_t, D_t, t \in T\}$, $t \geq 0$, being a mathematical model of the analyzed operation system, are discussed.

It is assumed that the process of operation state changes can be described by a stochastic process

$$\{X_t, t \in T\}, t \geq 0, \quad (1)$$

with a finite state space:

$$S = \{1, 2, \dots, n\}, n \in \mathbb{N}, \quad (2)$$

where:

\mathbb{N} – set of natural numbers ,

T – subset of real numbers.

For the needs of this research, it is accepted that the states of the discussed stochastic process correspond to operation states of the technical object (vehicle).

Alternative k , accepted upon entering state i , is denoted as $(i \in S, k \in \mathbb{N})$. Finite set A_i , of alternatives (decisions) corresponds to each state i , $i \in S$.

Sets of alternatives have to be equal for each state in terms of quantity. Also states, for which the set of alternatives is a single-elements set, can occur. States, for which there is no possibility to choose an alternative, are referred to as non-decision states. Some literature sources refer to non-decision states as to such for which the set of alternatives in s an empty set [4]. It appears that

acceptance of one-element sets of alternatives is more consistent for a description of the analyzed process $\{X_t, D_t, t \in T\}$, $t \geq 0$.

It is accepted that elements of set A_i , $i \in S$ are elements a_{ik} , ($i \in S, k \in N$), that is:

$$A_i = \{a_{i,1}, a_{i,2}, \dots, a_{i,\bar{i}}\}, \quad (3)$$

where:

\bar{i} - denotes capacity of set A_i .

The set of all the subsets of alternatives is denoted as A , that is:

$$A = \bigcup_{i \in S} A_i. \quad (4)$$

Generally, application of a given alternative upon process $\{X_t, t \in T\}$ entering $i \in S$ State, can have an influence on the process successive state $j \in S$ and the state features (time of being in the state – type of distribution and its parameters, costs or profits obtained by the systems in this particular state, etc.).

The alternatives can represent given modes of operation, events, decisions, etc. which can be assigned to the state of the modeled process [6, 7, 8, 9, 12, 13, 14]. In a real system of operation there can be different ways of maintenance, repair, surveys, operation modes and scopes, e.g. different transportation routes, on which the vehicle is used. Acceptance of a given alternative can affect: costs, income, frequency and kinds of failures, times of operation states, sequences of states, etc. [12, 13, 14.]

Stochastic process:

$$\{D_t, t \in T\}, t \geq 0, \quad (5)$$

with a finite set of alternatives A describes the selection method of $a \in A$ alternatives.

Change of process $\{D_t, t \in T\}$ state occurs in times t , of process $\{X_t, t \in T\}$ state changes, In times t_n $n \in N$ of process $\{X_t, t \in T\}$ state changes alternative $a \in A$ is chosen. If in time t_n , state i is the state of process $\{X_t, t \in T\}$ then $a \in A_i$.

Process $\{X_t, D_t\}$, $t \geq 0$ with a finite state set S and finite set of alternatives A , is called a stochastic decision process. In result of this process, a sequence of states and decisions is obtained from initial time t_0 to time t_n :

$$h_{t_n} = \{i_{t_0}, a_{t_0}, i_{t_1}, a_{t_1}, \dots, i_{t_n}, a_{t_n}\}, \quad (6)$$

which is called the process history until time t_n .

Further, it is assumed that the analyzed stochastic decision process:

$$\{X_{t_n}, D_{t_n}\}_{n=1}^{\infty}, \quad (7)$$

is Markov decision process. A set of possible implementations of Markov decision process is set $W = \{S \times A\}^{\infty}$. It is also assumed that the probability of choosing alternative $a_{t_n} \in A$ depends merely on state $i_{t_{n-1}} \in S$, and does not depend on the process history $h_{t_{n-1}}$.

In this case the sequence of process $\{X_t, t \in T\}$ states is a nonhomogeneous Markov chain [1, 2, 3].

In order to define the analyzed stochastic decision process $\{X_t, D_t\}$, $t \geq 0$ it is also necessary to define:

- method for choice of alternatives for process $\{D_t, t \in T\}$.
- initial distribution of $\{X_t, t \in T\}$,
- conditional probabilities of process $\{X_t, t \in T\}$ state changes,
- random variables of process $\{X_t, t \in T\}$ states times.

Simplifying, the rule used for determination of choice of alternative $a \in A$, upon entering state $i \in S$, is referred to as a strategy. The manner of choosing the alternative upon entering the process state can be of random or determined character.

Formula:

$$p = [p_1, p_2, \dots, p_n], \sum_{i \in S} p_i = 1, p_i \geq 0, i \in S, \quad (8)$$

is used for determination of $\{X_t, t \in T\}$. Giving values of p_i of elements of the initial distribution vector p , determines the probability that, in time t , process $\{X_t, t \in T\}$ will be in state i .

The probability, that upon entering state i , process $\{X_t, t \in T\}$ will, in one step, change its state from state $i, i \in S$ into $j, j \in S$, for accepted alternative $a \in A_i$, has been denoted as p_{ij}^a .

Condition:

$$\sum_{j \in S} p_{ij}^a = 1, p_{ij}^a \geq 0, i, j \in S, a \in A_i, \quad (9)$$

is satisfied.

Stochastic matrix $P^{(i,a)}$, defining conditional probability of transition p_{ij}^a , can be assigned to each state $i \in S$ and alternative $a \in A_i$. The set of matrixes assigned to state $i \in S$ has capacity equal to \bar{i} (capacity of set A_i).

Matrix $P^{(i,a)}$ is a matrix made up of stochastic verses, which determine probabilities of transition from a state marked with the verse number to all the remaining states. Element p_{ij}^a , situated on an intersection of a verse with number i and a column with number j in matrix $P^{(i,a)}$, is the probability of transition from state $i \in S$ to state $j \in S$ as long as alternative $a \in A_i$ has been used upon entering state $i \in S$.

Random variable, denoting duration time of state $i \in S$ of process $\{X_t, t \in T\}$, when the successive state is $j \in S$, and when upon entering state i decision $a \in A_i$ is made about distribution defined by distribution function $F_{ij}^a(t)$, is denoted as T_{ij}^a .

For the purpose of simplification it was assumed that:

$$F_{ij}^a(t) = F_i^a(t) = F_{ia}(t), i, j \in S, a \in A_i. \quad (10)$$

This means that the duration time of state $i \in S$ does not depend on the process successive state. Function $F_{ia}(t)$ is a function of state $i \in S$ duration time distribution on condition that, decision a is made upon entering this state.

Random variable denoting duration time of state $i \in S$, with distribution defined by distribution function $F_{ia}(t)$, is denoted as T_{ia} .

In order to evaluate economic aspects involved in the modeled operation process it is necessary to additionally determine appropriate values of economic categories connected with the manner of the process states entering and staying in them.

Moreover, it has been assumed that the model of changes of the maintenance states of the set n of homogenous, from the point of view of the purpose of the bus investigations, are independent processes $\{X_t, t \in T\}$. The random vector $\mathbf{X}(t) = [X_1(t), X_2(t), \dots, X_n(t)]$ describes the process of changes of the maintenance states of the bus set [2, 3].

A computer program has been developed that facilitates simulation of execution of the stochastic process described that way. When executing the simulation, values of the selected sets of indicators enabling to analyse the modelled process of changes of states of the objects are determined.

3. Investigation object

The paper analyses a real maintenance system of buses in an urban transport system in a selected urban agglomeration. The essential purpose of the operation of the analysed system is performance of the effective (in terms of technical and economic criteria) and safe passenger

transports by the operated and maintained means of transport in the determined quantitative and territorial scope.

The scope of the performed repair of a bus is decisive for directing the bus to a diagnostic stand in order to perform post-repair diagnostics. The post-repair diagnostics are particularly performed after repairing the following systems and assemblies of a bus [8, 10, 12]:

- Steering system,
- Braking system,
- Engine,
- Truss,
- Front axle suspension.

If the inspection result is negative, the bus is directed again to the current repairs stand.

The following dependencies have been ascertained in the process of identification of the maintenance system of buses in an urban transport system and the bus maintenance process being performed in it, as well as on the basis of the analysis of the maintenance study results:

- Distribution of the random variable describing duration of the renewal state on the type of the damaged bus subsystem,
- Distribution of the random variable describing duration of the diagnostics state on the type of the damaged bus subsystem,
- Repair cost on the type of the damaged bus subsystem,
- Diagnostics costs on the type of the damaged bus subsystem,
- Sequence of the next maintenance states on the type of the damaged bus subsystem.

The type of the damaged bus subsystem has a significant influence on the course of the maintenance process. Moreover, the applied methods of proceeding and sequences of actions aimed at restoring serviceability of technical object as well as the measures to perform them depend on the type of the damaged subsystem of that object.

The model describes, among others, influence of damages of the powertrain, being a compression-ignition internal combustion piston engine, of the analyzed object on the operation process of that object.

An assumption, that the identified set of technical objects, used in the analyzed system of operation, can be divided into n separate subsets of objects, homogeneous in terms of the research purpose, has been accepted. So classified subsets of technical objects are called: categories of objects [11]. In practice, a given technical object (bus) is assigned to a given category on the basis of the following criteria [8, 10, 12]:

- type of object (make and type of bus),
- operational potential,
- operation time,
- others.

Further, in this paper, one category of objects is discussed.

In result of identification of a real urban bus transportation system and its operation process, three finite sets of states and operation-related events significant for an analysis of the system [6, 8, 10], have been distinguished. In the computing model, selected subsets of these states and events are analyzed.

4. Computing model

In order to illustrate the discussion, the following operation states of a bus have been analyzed:

- S_1 -state connected with provision of transport services, that is a state in which a bus and its operator perform the transport task;
- S_2 - state of corrective servicing (restoring serviceability state);
- S_3 -state of waiting for performance of transport tasks, that is standby of vehicles on the territory of a bus depot while not being in operation;

S_4 -state of post-repair servicing, that is a state in which the object, after being repaired undergoes control of the object condition (the so called post-repair diagnosing) and quality of performed corrective servicing of the damaged subsystems.

In order to illustrate the discussion, influence of the type of bus subassembly damage on the change of probability of transition between states and duration times of the states as well as costs connected with the vehicle being in a particular state, has been modeled as well. An example of a vehicle system, in the research object, the damage of which affects the sequence of the successive operation states and their features is the powertrain. Damages to the engine fuel injection system requiring adjustment of the injection pump occur with relatively high frequency. The procedure of carrying out corrective servicing for that system, being applied in the enterprise under analysis, provides for the necessity to perform post-repair diagnostics. The following major assumptions have been accepted:

- After completion of corrective servicing of the vehicle subassemblies it is necessary to control the object state, that is, state S_4 is possible to reach only after a repair of the vehicle identified damage;
- If in result of control of the object state (state S_4), it is still found to be unable to perform its transport tasks or carrying out the working process would be ineffective (e.g. excessive fuel consumption due to incorrect adjustment of the fuel injection system) it is a subject to repeated corrective servicing processes performed at the station where control of its state was performed (it remains in state S_4);
- The repair cost per time unit (state S_2) is connected with the type of failure;
- The repair duration time (state S_2) depends on the type of the damaged vehicle subassembly;
- Duration time of post-repair object (state S_4) depends of the bus state control result, that is whether the vehicle is allowed to perform its transport tasks or needs to undergo another repair;
- The cost per time unit related to post-repair servicing (state S_4) of the vehicle is related to the result of the control of the vehicle condition;

Buses used in the research objects were decomposed into systems. For the needs of the simplified computing model the vehicle systems (their elements damage) were divided into the following subsets:

- Systems (their elements damage) characterized by low repair labor consumption, the repair time is relatively short (frequently the process of repair is performed outside a bus depot by units of the so called standby service) denoted by code U_1 ,
- Systems (their elements damage) which need post-repair service denoted by code U_2 ,
- Systems (their elements damage) which do not need post-repair service characterized by high labor consumption, whose average time of repair is relatively long (multiple of system denoted by U_1 code), denoted by code U_3 ,
- Engine fuel injection system (damages to the engine fuel injection system requiring adjustment of the injection pump) for which post-repair servicing denoted by code U_4 must be performed.

The data obtained by analysing results of preliminary tests performed in the considered enterprise are used in the computing model.

In the analyzed example states $i \in S$ of process $\{X_t, t \in T\}$ correspond to the identified operation states S_i , $i = 1, 2, 3, 4$. States $i = 1, 3$ of process $\{X_t, t \in T\}$ are non-decision states, that is, subsets of alternatives A_1 i A_3 are one-element subsets. In the same states, alternatives are of only formal character (maintaining the notation consistence) and they have no influence on the analyzed process $\{X_t, D_t\}$, $t \geq 0$ course. In state $i = 2$ of alternatives $a \in A_2$ of $\{D_t, t \in T\}$ process correspond to the codes of the bus distinguished damaged systems and represent their failures (elements). Set A_2 contains the following elements $A_2 = \{a_{2,1}, a_{2,2}, a_{2,3}, a_{2,4}\}$. Interpretation of entrance to state $i = 2$ of process $\{X_t, t \in T\}$, in time t and occurrence of alternative $a_{2,3}$ of process $\{D_t, t \in T\}$ is as follows; a bus failure occurred and its repair, and the damaged system is the system denoted by code U_3 . In state $i = 4$ alternatives $a \in A_4$ of process $\{D_t, t \in T\}$ correspond to

the codes of the vehicle state control results. Set A_4 contains the following elements $A_4 = \{a_{4,1}, a_{4,2}\}$. $a_{4,1}$ and $a_{4,2}$ were used to denote respectively the control which finished with admitting the vehicle to perform transport tasks and recommending a post repair.

The rule for choice of alternatives a in state i is determined by distribution of probability of the analyzed alternatives occurrence. It was assumed that q_{ik} , $i \in S, k \in N$ means probability of alternative a_{ik} occurrence upon entering state i .

Expression

$$q_i = [q_{i1}, q_{i2}, \dots, q_{ik}], \quad q_{ik} \geq 0, \quad i \in S, k \in N, \quad (11)$$

is used for denotation of vector of alternatives occurrence distribution in state i . Elements of vector q_i meet the condition:

$$\sum_{i \in S, k \in N} q_{ik} = 1. \quad (12)$$

In the considered example, elements of this vector for $i = 2$ denote probabilities of a given system failure occurrence.

	Dec 1	Dec 2	Dec 3	Dec 4
Stan 1	166,840	0,004		
Stan 2	1,000	0,021	4,551	0,023
Stan 3	49,453	0,004	4,096	0,043
Stan 4	3,130	0,006	4,767	0,023
Stan 1	w dniach EX= 0,645833 alfa= 166,84028 D^2X= 0,0025 lambda= 258,33333 lambda= 0,003871 O.ST 0,05		Stan 2 w dniach EX= 0,020833 alfa= 1 D^2X= 0,000434 lambda= 48 lambda= 0,020833 O.ST 0,020833	
Stan 3	w dniach EX= 0,181667 alfa= 49,45265 D^2X= 0,000667 lambda= 272,2164 lambda= 0,003674 O.ST 0,025833		Stan 4 w dniach EX= 0,019167 alfa= 3,130178 D^2X= 0,000117 lambda= 163,3136 lambda= 0,006123 O.ST 0,010833	
Stan 1	w dniach EX= 0,106667 alfa= 4,551111 D^2X= 0,0025 lambda= 42,66667 lambda= 0,023438 O.ST 0,05		w dniach EX= 0,177083 alfa= 4,096805 D^2X= 0,007656 lambda= 23,12925 lambda= 0,043235 O.ST 0,0875	
Stan 2	w dniach EX= 0,052083 alfa= 1,929012 D^2X= 0,001406 lambda= 37,03704 lambda= 0,027 O.ST 0,0375		w dniach EX= 0,109167 alfa= 4,766944 D^2X= 0,0025 lambda= 43,66667 lambda= 0,022901 O.ST 0,05	

Fig. 1. Window used to enter the data for simulation – parameter values of state duration times depending on the selected alternative

For the discussed assumptions, simulation of the process of a single technical object operation involves simulating the described stochastic decision process, being a model of the process of operation state changes of vehicles used in the analyzed research object.

A program enabling simulation of the stochastic decision process has been developed.

In order to perform the simulation it is necessary to use data indispensable for determination of the described process $\{X_t, D_t\} t \geq 0$.

Simulation experiments have been performed to illustrate of the discussion.

The Fig. 1 shows one of the windows used to enter the data required to perform simulation experiments.

The assumption that random variables T_{ia} for $i \in S, a \in A$ have gamma distributions with different parameters, and their being in the process states is connected with gaining profits (state 1) and bearing costs by the operation system, has been accepted for the needs of the simulations. The values defining conditional probability of stochastic matrix $P^{(i,a)}$, $i, j \in S, a \in A$ transition p_{ij}^a , have been estimated on the basis of initial experimental tests.

Values of probabilities q_{ik} , $i=2$, $k=1, 2, 3, 4$ of alternative a_{ik} occurrence have been determined basing on data concerning the bus failures. For the description simplification, alternatives a_{2k} are further denoted by code k .

The remaining values of parameters used for simulation experiments have been estimated on the basis of results of initial tests performed in the research object.

It is necessary to accept that the parameters values of random variables T_{ia} $i \in S$, $a \in A$, used in the model, are of hypothetical character. The parameters values were estimated basing on a small size data set.

Calculations for one category of objects consisting of 100 vehicles were performed, over a period of 100 days. Selected calculation results are presented in the Figures 2 to 5.

irm	Stan	Decyzja	Tau	wynik	Numer	Strategia	Stan0	Stan1	Stan2	Stan3
3,74431244851118E-03	1	0	3,74431244851118E-03	-8,98634987642683	75	0	97	3	0	0
6,06272258946172E-03	1	0	6,06272258946172E-03	-14,5505342147081	64	0	98	2	0	0
1,81944003485887E-02	1	0	1,81944003485887E-02	-43,666508366129	60	0	99	1	0	0
0,163350823933411	2	0	0,145156423584823	-54,1178233347201	60	0	99	0	1	0
0,50494810558771	0	0	0,50494810558771	169,662563477471	40	0	100	0	0	0
0,509601102005909	1	0	4,65299641819886E-03	158,495372073793	40	0	99	1	0	0
0,536444731476713	0	0	0,536444731476713	180,245429776175	84	0	100	0	0	0
0,555295200303951	0	0	0,555295200303951	186,579187302128	12	0	99	0	1	0
0,56255116785428	0	0	0,56255116785428	189,017192399038	99	0	98	0	2	0
0,566479043457721	0	0	0,566479043457721	190,336958601794	69	0	97	0	3	0
0,566549766103521	0	0	0,566549766103521	190,360721410783	71	0	96	0	4	0
0,568244824920476	0	0	0,568244824920476	190,93026117328	62	0	95	1	4	0
0,569405069045371	0	0	0,569405069045371	191,320103199245	98	0	94	1	5	0
0,570478182899378	0	0	0,570478182899378	191,680669454191	82	0	93	1	6	0
0,572777733100371	0	0	0,572777733100371	192,453318321725	53	0	92	2	6	0
0,582647798692339	0	0	0,576585076102877	179,182051355859	64	0	91	2	7	0
0,583956104160767	0	0	0,583956104160767	196,209250998018	51	0	90	2	8	0
0,585103053404446	0	0	0,585103053404446	196,594626615894	1	0	89	2	9	0
0,586218566568227	0	0	0,586218566568227	196,969438366924	91	0	88	2	10	0
0,586997861688719	0	0	0,586997861688719	197,231281527409	25	0	87	2	11	0
0,589006556813062	0	0	0,589006556813062	197,906203089189	27	0	86	3	11	0
0,591427431809154	0	0	0,591427431809154	198,719617087876	37	0	85	3	12	0
0,59152320781308	0	0	0,59152320781308	198,751797825195	57	0	84	3	13	0
0,592322539795586	1	0	5,32467810686735E-03	184,452054070928	25	0	83	3	14	0
0,592413850307584	1	3	2,58640842040628E-02	146,909059947958	71	0	84	2	14	0
0,592971034531525	0	0	0,592971034531525	199,238267602592	79	0	84	1	14	1
0,594474745701243	0	0	0,594474745701243	199,743514555618	61	0	83	1	15	1
0,596296360853663	0	0	0,596296360853663	200,35557246831	96	0	82	1	16	1
0,598947514049259	0	0	0,598947514049259	201,246364720551	26	0	81	1	17	1
0,599142732541773	0	0	0,599142732541773	201,311958134036	5	0	80	1	18	1
0,600551338848982	0	0	0,600551338848982	201,785249832528	54	0	79	2	18	1
0,602711886696861	0	0	0,602711886696861	202,511193930145	47	0	78	2	19	1
0,605252398793843	0	0	0,605252398793843	203,364805994731	30	0	77	2	20	1
0,606305734162844	0	0	0,606305734162844	203,718728667875	43	0	76	2	21	1
0,608206463278289	0	0	0,608206463278289	204,357371661505	77	0	75	2	22	1
0,609473235719824	0	0	0,609473235719824	204,738007201861	35	0	74	2	23	1
0,609664773813178	0	0	0,609664773813178	204,847364001228	74	0	73	2	24	1
0,610008546498096	0	0	0,610008546498096	204,96287162336	8	0	72	3	24	1
0,610472565528711	0	0	0,610472565528711	205,118782017647	33	0	71	4	24	1
0,610616813018804	3	0	1,82029627112201E-02	120,696793643801	71	0	70	4	25	1
0,611116761144442	0	0	0,611116761144442	205,335231744533	18	0	70	4	26	0
0,613132452316005	0	0	0,613132452316005	206,012503978178	89	0	69	4	27	0
0,613352550106446	1	0	3,68777629326755E-03	195,996700897386	74	0	68	4	28	0

Fig. 2. A part of a text file generated during simulation containing selected experiment results

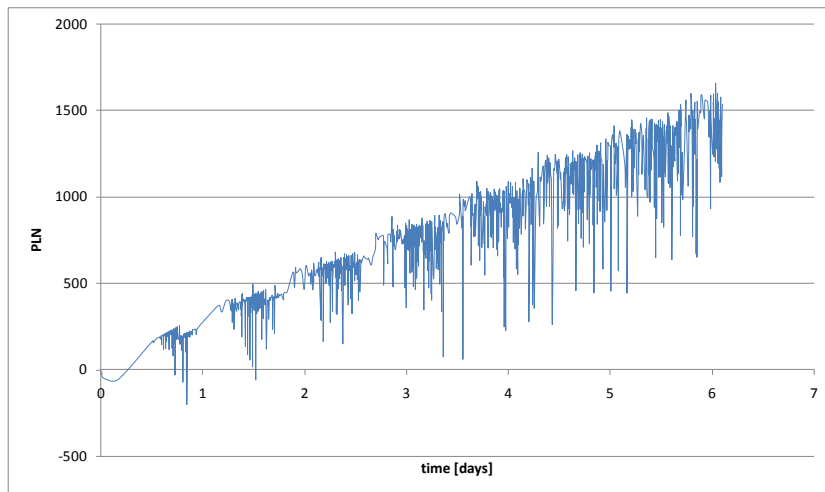


Fig. 3. An example of simulating the financial result obtained by the enterprise during the consecutive days of carrying out the transport tasks

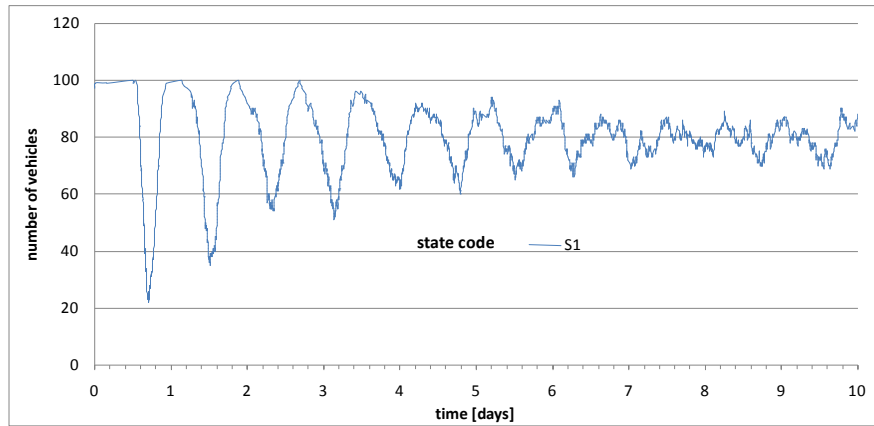


Fig. 4. Relationship between the number of the technical objects (vehicles) in the state S_1 and the time

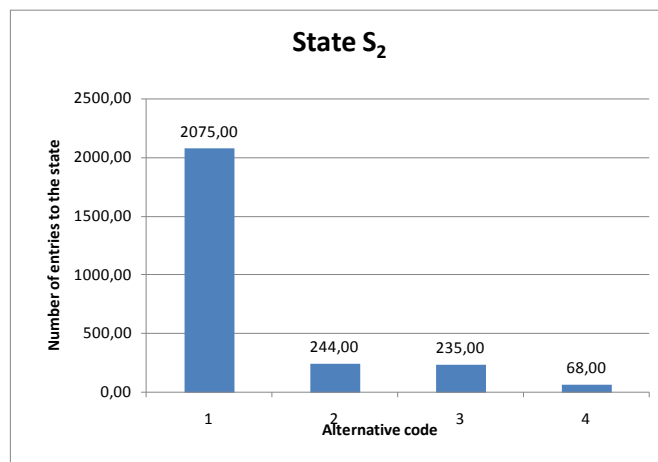


Fig. 5. Number of entries to the state S_2

5. Conclusions

Presentation of the complete set of the input data required for simulating the analysed stochastic process and the method to estimate the parameter values on the basis of the results of the real operational data goes beyond the scope of this paper. Due to the nature of the paper and extensive scope of the results generated only selected research results are presented for your reference.

The purpose of the considerations was, among other things, to present possibilities of applying the Markov decision processes for mathematical modelling of the system and process of vehicle maintenance. A possibility of using models of this type to analyse a transport system and support decision makers in that system, e.g. by forecasting behaviour of the vehicle maintenance system after changing the control requests has been presented.

The results of the simulation experiments performed let us state that the model is susceptible to a change of the value of its input parameters.

The analysis of the results of the simulation experiments shows a significant stability of the calculation results obtained (for the same data).

Mathematical models of the maintenance processes, performed in complex systems, are intrinsically a significant simplification of the real processes. The consequence of the above is a necessity to carefully formulate conclusions resulting from investigations of those models [5, 11]. However, it seems that the analysis of the results of the investigations of those models, for

the values of the model parameters, determined on the basis of the maintenance studies performed in a real transport system, makes it possible to formulate both qualitative and (to the limited extent) quantitative conclusions and opinions.

The set of the indices that may be determined includes subsets of the indices concerning: readiness, repair times, effectiveness of performance of the transport tasks, costs and others.

Performance of the research experiments for various categories of objects makes it also possible to evaluate the selected technical and economic aspects of replacing objects with new ones and evaluation of usefulness of various types of objects in the specific maintenance system.

References

- [1] Bernaciak K., *Zastosowanie decyzyjnych procesów semimarkowskich do optymalizacji eksploatacji pewnego urządzenia*, Zagadnienia Eksploatacji Maszyn, Zeszyt 3 (75), 1988.
- [2] Buslenko, N., Kałasznikow, W., Kowalenko, I., *Theory of complex systems*, PWN, Warsaw 1979.
- [3] Chrzan P., *Łącuchy decyzyjne Markowa i ich zastosowania w ekonomii*, Akademia ekonomiczna, Katowice 1990.
- [4] Kowalenko I. N., Kuzniecowa N. J., Szurienkowi W. M., *Stochastic processes, Guide*, PWN, Warsaw 1989.
- [5] Landowski B., *Applying the Markov decision processes to model changes to the maintenance states of an object*, Journal of KONES Vol. 17, No. 3, 2010.
- [6] Landowski B., *Example of applying Markov decision process to model vehicle maintenance process*, Journal of KONES Powertrain and Transport, Vol. 20, No. 4, 2013, European Science Society of Powertrain and Transport Publication, Warsaw 2013.
- [7] Landowski B., *Example of Markov decision process use for modelling of operation and maintenance process*. Interdisciplinary Integration of Science in Technology, Education and Economy. Monograph: edited by Shalapko J. and Żółtowski B., Khmelnytsky – Jaremche 2013, ISBN 978-617-70-94-07-3.
- [8] Landowski B., *Method of determination values of the chosen decision variables to control rationally the operation and maintenance process in the transport system*, Doctoral thesis, Academy of Technology and Agriculture, Bydgoszcz 1999.
- [9] Landowski B., *Simulation model of the means of transport maintenance process*, Journal of KONES Vol. 17, No. 4, 2010.
- [10] Landowski B., Woropay M., Neubauer A., *Controlling reliability in the transport systems*, Library of Maintenance Problems, Maintenance Technology Institute, Bydgoszcz-Radom 2004.
- [11] Woropay M., Grabski F., Landowski B., *Semi-Markov model of the vehicle maintenance processes in an urban transport system*, Scientific Publishers of the Polish Scientific Association of Automotive Engineering, Archives of Automotive Engineering Vol. 7, No 3, 2004.
- [12] Woropay M., Knopik L., Landowski B., *Modelling maintenance processes in a transport system*, Library of Maintenance Problems, Publishers and Printing Department of the Institute of Technology and Maintenance, Bydgoszcz – Radom 2001.
- [13] Woropay M., Landowski B., Neubauer A., *Applying semi-Markov decision processes to model and simulate the bus operation and maintenance processes*, Scientific Publishers of the Polish Scientific Association of Automotive Engineering, Archives of Automotive Engineering Vol. 7, No. 1, 2004.
- [14] Woropay M., Landowski B., Neubauer A., *Simulation of the method to optimise the operation and maintenance process of the buses in an urban transport system*, International Scientific Conference "Transport of the 21st Century ", section 5, Warsaw 2004.