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Monte Carlo approach to identification of maritime ferry operation process

Keywords

operation process, semi-Markov process, complex systems, Monte Carlo simulation

Abstract

The paper is concerned with the identification of operation processes of complex technical systems. The convenient tools suggested for analyzing these complex technical systems operation processes are semi-markov modeling and Monte Carlo simulation. The paper describes the proposed approach as well as the possibility of its practical application to identification of the operation process of a maritime ferry.

1. Introduction

If define technical system is complex (due to large numbers of components and subsystems) and if its operating process is multi gradual - prediction and optimization of its reliability, availability or safety is very difficult. The complexity of the systems' operation processes and their impact on changing in time the systems' structures and their components' reliability characteristics are very often met in real practice. Complex technical systems can be met, for instance, in piping transportation of water, gas, oil and various chemical substances. Complex technical systems are also used in electrical energy distribution, in telecommunication, in maritime transport and in shipyard and port transport systems using belt conveyers and elevators. Rope transportation systems like port elevators and ship-rope elevators used in shipyards during ship docking and undocking are model examples of such systems.
An example of such system is described in the paper [4], in which successive steps of determination of maritime ferry exploitive parameters are presented (which are probabilities of remaining in successive stages of exploitation). The core of presented method is identification of model distributions of conditional sojourn times in operational stages. The process of such identification is complex and time consuming. Therefore alternative methods are needed. Moreover currently available models/estimators of distributions can be not sufficient for particular exploitive stages. Therefore we made an attempt to automatic (computational) determination of distributions for all exploitive stages, as well as we attempted to use "Monte Carlo" computational method for finding the probabilities of remaining in successive stages of exploitation of a ferry during daily cycle of cruises.

2. Modeling of complex technical systems operation processes

We consider test λ based on Kolmogorov-Smirnov theorem [3] that can be used for testing whether two independent samples of realizations of the conditional sojourn times θ_{bl}, $b,l \in \{1,2,...,v\}$, $b \neq l$, in particular operation states of the system operation process are drawn from the population with the same distribution.
In analyzing the operation process of the complex technical system with the distinguished operation states $z_1, z_2, \ldots, z_v$, the semi-markov process [2], [5] may be used to construct its general probabilistic model [4]. To build this model the following parameters are defined:

- the vector of probabilities $[p_b(0)]_{1x\nu}$ of the system operation process initials operation states,
- the matrix of probabilities $[p_{bl}]_{\nu x\nu}$ of the system operation process transitions between the operation states,
- the matrix of conditional distribution functions $[H_{bl}(t)]_{\nu x\nu}$ of the system operation process conditional sojourn times θ_{bl} in the operation states,
- the vector $[H_b(t)]_{1x\nu}$, of the unconditional distribution functions of the sojourn times θ_b of the system operation process at the operation states,
- the vector $[M_b]_{1x\nu}$, of the mean values of the unconditional sojourn times θ_b,
- the vector $[p_b]_{1x\nu}$ of the limit values of the transient probabilities at the particular operation states,
- the vector $[\hat{M}_b]_{1x\nu}$ of the mean values of the total sojourn times $\hat{\theta}_b$ in the particular

operation states for sufficiently large operation time θ.

Operational process in the general case is described by probabilities of transitions between operation states given by following matrix:

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

where

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

In this paper the particular case of real operational process is analysed, namely operational process of a Stena Baltic ferry, that every day sails between Gdynia – Poland and Karlskrona - Sweden.

3. Operation process of a Stena Baltica ferry

Taking into account the operation process of the considered ferry we distinguish the following as its eighteen operation state:

Table 1. List of operational states.

Operation state	Activity
z_1	Loading at Gdynia port
z_2	Unmooring operations at Gdynia port
z_3	Leaving Gdynia port and navigation to “GD” buoy
z_4	Navigation at restricted waters from “GD” buoy to the end of Traffic Separation Scheme
z_5	Navigation at open waters from the end of Traffic Separation Scheme to “Angoring” buoy
z_6	Navigation at restricted waters from “Angoring” buoy to “Verko” Berth at Karlskrona
z_7	Mooring operations at Karlskrona port
z_8	Unloading at Karlskrona port
z_9	Loading at Karlskrona port
z_{10}	Unmooring operations at Karlskrona port
z_{11}	Ship turning at Karlskrona port
z_{12}	Leaving Karlskrona port and navigation at restricted waters to “Angoring” buoy
z_{13}	Navigation at open waters from “Angoring” buoy to the entering Traffic Separation Scheme
z_{14}	Navigation at restricted waters from the entering Traffic Separation Scheme to “GD” buoy
z_{15}	Navigation from “GD” buoy to turning area
z_{16}	Ship turning at Gdynia port
z_{17}	Mooring operations at Gdynia port
z_{18}	Unloading at Gdynia port

On the basis of the statistical data coming from experts it is possible to evaluate the vector of realizations

$$[p(0)] = [1, 0, 0 \ldots, 0, 0],$$

of the initial probabilities $p_b(0)$, $b = 1,2,...,18$, of the ferry operation process transients in the particular operation states z_b at the moment $t = 0$.

The ferry operation process is very regular in the sense that the operation state changes are from the particular state z_b, $b = 1,2,...,17$, to the neighboring state z_{b+1}, $b = 1,2,...,17$, and from z_{18} to z_1 only.

Therefore, the probabilities of transitions between the operation states are given by matrix (1) is simplified, and takes the following form:

$$[p_{bl}] = \begin{bmatrix} 0\,1\,0 \ldots 0\,0 \\ 0\,0\,1 \ldots 0\,0 \\ \ldots \\ 0\,0\,0 \ldots 0\,1 \\ 1\,0\,0 \ldots 0\,0 \end{bmatrix} \qquad (2)$$

4. Empirical data

Table 2. Empirical data describing exploitive process for model ferry.

Operation state	1→2	3→3	3→4	4→5	5→6	6→7	7→8	8→9	9→10	10→11	11→22	12→13	13→14	14→15	15→16	16→17	17→18	18→1
Realization	Conditional sojourn time [minutes]																	
1.	55	4	28	60	598	38	7	15	75	2	6	25	574	61	34	4	5	16
2.	52	3	31	49	635	35	9	6	59	2	5	25	427	43	35	4	3	22
3.	47	3	32	46	539	36	8	40	56	3	4	24	461	43	34	5	4	17
4.	75	2	35	57	572	39	7	28	40	3	5	23	501	46	34	4	5	8
5.	60	2	37	53	499	36	7	32	66	3	4	26	498	49	33	4	3	17
6.	60	2	48	51	507	36	5	28	47	2	5	24	490	52	33	4	5	17
7.	62	2	33	64	621	35	5	23	26	2	4	24	438	42	33	3	5	26
8.	43	3	38	51	580	39	5	15	60	2	4	23	561	63	34	4	6	26
9.	50	3	39	53	507	37	5	18	65	3	4	24	491	46	35	4	6	30
10.	61	4	43	63	511	36	5	19	25	3	6	23	513	60	36	4	10	20
11.	65	3	40	55	497	38	8	18	55	2	4	28	496	50	35	4	5	16
12.	63	2	42	53	496	37	7	24	40	2	5	24	500	50	35	4	4	17
13.	45	2	35	67	595	36	7	25	75	3	4	23	582	72	34	5	4	26
14.	45	2	36	51	495	37	8	11	77	3	4	22	491	50	35	5	5	40
15.	40	2	36	50	504	35	7	17	60	3	4	23	499	48	33	5	5	21
16.	20	2	36	62	507	38	10	31	73	3	4	26	488	50	35	4	5	34
17.	33	2	37	49	498	38	8	23	82	2	4	23	464	48	35	4	7	40
18.	50	3	35	48	483	36	8	25	118	3	4	23	484	52	34	4	6	35
19.	43	2	34	51	497	37	7	9	71	2	4	23	498	47	31	5	5	28
20.	15	2	34	52	504	36	8	25	55	2	4	22	496	53	32	5	5	22
21.	45	3	36	50	507	37	8	19	30	3	4	22	505	51	33	3	7	8
22.	57	2	36	53	503	34	8	31	24	3	4	22	595	61	46	4	5	2
23.	97	2	39	53	500	38	7	30	34	2	4	26	483	61	34	6	4	12
24.	68	3	36	54	492	40	9	35	41	5	4	22	499	48	34	6	5	13
25.	58	3	37	51	573	34	8	18	55	5	4	24	573	58	34	5	7	18
26.	35	4	36	51	498	39	7	16	55	2	4	24	497	51	35	5	7	20
27.	45	3	35	51	506	38	5	13	43	2	5	25	531	54	35	6	6	11
28.	75	3	39	49	576	39	7	3	45	2	5	24	500	47	34	5	4	10
29.	72	2	37	53	494	38	10	15	52	3	4	23	492	40	35	4	4	16
30.	62	3	36	44	505	35	9	6	48	4	5	22	496	51	34	6	7	18
31.	37	6	37	49	576	34	10	15	50	5	4	20	590	47	35	5	4	25
32.	44	3	36	62	495	40	6	17	58	6	5	33	508	47	34	5	5	18
33.	46	2	36	45	502	36	7	16	53	3	4	24	520	56	31	4	8	12
34.	78	2	37	46	574	33	7	21	30	4	5	24	562	47	33	4	7	12
35.	59	2	36	51	492	38	6	33	30	4	4	22	508	46	34	5	6	17
36.	65	2	36	47	497	38	6	34	45	2	4	22	508	42	36	4	7	14
37.	53	2	38	52	584	35	5	25	70	5	5	25	595	42	33	6	8	20
38.	25	2	37	46	504	42	7	20	35	3	4	22	506	45	32	4	10	11
39.	55	3	40	48	505	42	5	23	35	2	5	25	535	47	33	4	6	11
40.	84	2	36	65	573	44	5	27	47	3	5	25	506	46	36	5	5	10
41.	71	2	37	53	494	35	6	20	40	2	4	23	503	51	35	5	5	13
42.	67	2	34	47	495	37	6	31	50	3	4	25	503	43	33	4	6	18

5. Empirical distribution function on the basis of data coming from experts

We assume that we have the sample of non-decreasing ordered realization

$$\theta_{bl}^{k},\ k = 1,2,...,n_{bl},\ b,l \in \{1,2,...,v\},\ b \neq l, \qquad (3)$$

of the sojourn times θ_{bl} $b,l \in \{1,2,...,v\}$, $b \neq l$, respectively composed of n_{bl} realizations and we mark by

$$H_{bl}(t) = \frac{1}{n_{bl}} \#\{k : \theta_{bl}^{k} < t, k \in \{1,2,...,n_{bl}\}\},\ t \geq 0, \qquad (4)$$
$$b,l \in \{1,2,...,v\},\ b \neq l,$$

their corresponding empirical distribution functions respectively, in the following forms:

$$H_{bl}(t) = \begin{cases} \frac{n_{bl}^{1}}{n_{bl}} = 0, & t \leq \theta_{bl}^{1} \\ \frac{n_{bl}^{2}}{n_{bl}}, & \theta_{bl}^{1} < t \leq \theta_{bl}^{2} \\ \frac{n_{bl}^{3}}{n_{bl}}, & \theta_{bl}^{2} < t \leq \theta_{bl}^{3} \\ . \ . \ . & \\ \frac{n_{bl}^{k}}{n_{bl}}, & \theta_{bl}^{k-1} < t \leq \theta_{bl}^{k} \\ . \ . \ . & \\ \frac{n_{bl}^{n_{bl}}}{n_{bl}}, & \theta_{bl}^{n_{bl}-1} < t \leq \theta_{bl}^{n_{bl}} \\ \frac{n_{bl}^{n_{bl}+1}}{n_{bl}} = 1, & t \geq \theta_{bl}^{n_{bl}} \end{cases} \qquad (5)$$

where

$$n_{bl}^{1} = 0,\ n_{bl}^{n_{bl}+1} = n_{bl}, \qquad (6)$$

while

$$n_{bl}^{k} = \#\{j : \theta_{bl}^{j} < \theta_{bl}^{k},\ j \in \{1,2,...,n_{bl}\}\}, \qquad (7)$$

$$k = 2,3,...,n_{bl}^{1},$$

are the numbers of the sojourn time θ_{bl} realizations less than its realization θ_{bl}^{k}. Taking into account the data from *Table 2*, according (4)-(5), the set of empirical distributions were computed (*Figure 1*).

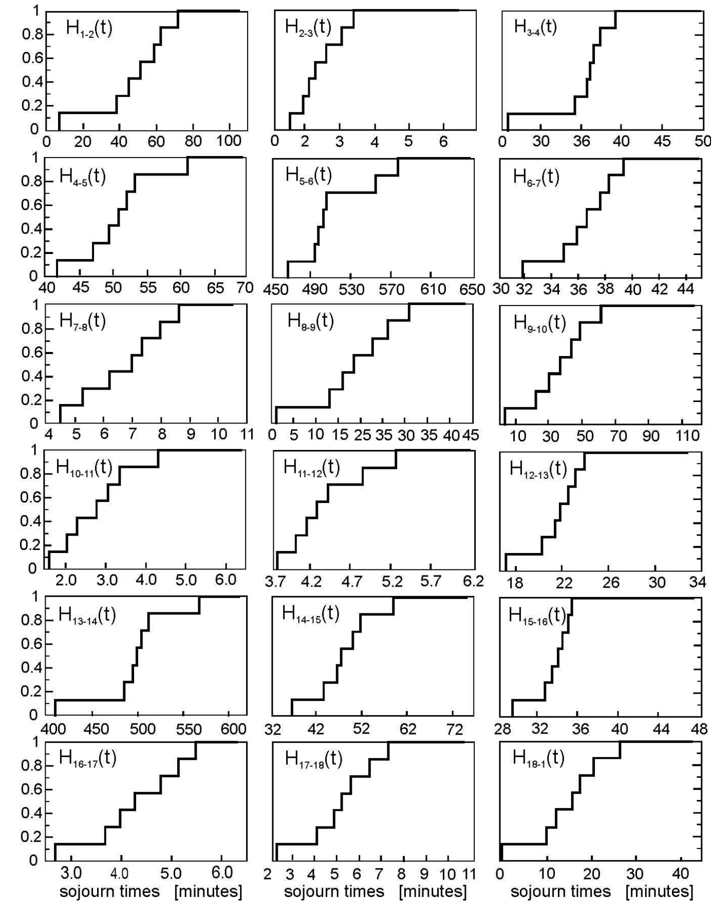

Figure 1. Empirical distributions (after data from *Table 1*)

5. "Monte Carlo" sampling method for computing of non-conditional probabilities

To determine the non-conditional probabilities of a technical device staying in subsequence states (daily cruise of a ferry Gdynia-Karskrona-Gdynia in this case), two stages of calculations were carried out. The first stage were determinations of empirical probability densities f(θ) which were prepared by conversion empirical distributions presented in *Figure 1*. In the second stage "Monte Carlo" samplings method were used for estimation of values of probability of staying in define exploitation state of a ferry. The "Monte Carlo" sampling consisted in drawings of two numbers [1], namely θ_i and f_i. The first number is a value $\theta_{min} + r \cdot (\theta_{max} - \theta_{min})$ whereas the second number is a value $r \cdot f_{max}(\theta)_i$ (where r is random number within the range from 0 to 1). If coordinates θ_i, f_i are situated beneath line of f_i then number θ_i were registered. After the great number of repeats of such process mean value M_b of θ_i were determined. Further computational process were continued using following scheme:

$$\begin{array}{ccccccccc}
M_1^1 & & M_2^1 & & \cdot\;\cdot\;\cdot & & M_{18}^1 & & \\
M_1^2 & & M_2^2 & & \cdot\;\cdot\;\cdot & & M_{18}^2 & & \\
\cdot & & \cdot & & \cdot\;\cdot\;\cdot & & \cdot & & \\
\cdot & & \cdot & & \cdot\;\cdot\;\cdot & & \cdot & & \\
\cdot & & \cdot & & \cdot\;\cdot\;\cdot & & \cdot & & \\
+\,M_1^n & & +\,M_2^n & & \cdot\;\cdot\;\cdot & & +\,M_{18}^n & & \\
\hline
S_1 & + & S_2 & + & \cdot\;\cdot\;\cdot & + & S_{18} & = & S
\end{array}$$

$$p_1 = \frac{S_1}{S} \qquad p_2 = \frac{S_2}{S} \qquad \cdot\;\cdot\;\cdot \qquad p_{18} = \frac{S_{18}}{S}$$

The number of 1000 of cycles of drawings were accepted. It was appeared that for greater number of drawings, values of M is the not . This phenomenon is displayed in *Figure 2,* in which values on M are presented as a function of a number of drawings.

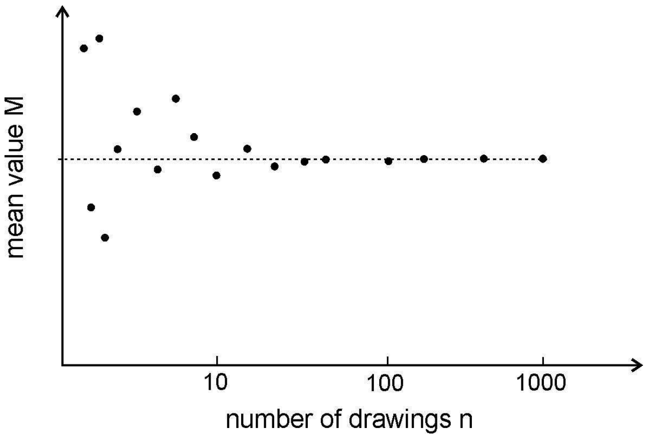

Figure 2. Convergence effect in "Monte Carlo" drawings (an example).

6. Final results and discussion

The computer code used to achieve results presented in *Table 3* allows transforming crude data (which example is in *Table 2* done) into a set of probabilities (*Table 3*) in a piece of second. It is worth to mention that those results are fully satisfying if their accuracy is considered. One can compare them with results reported by [4] – only 4 times (apart from 18) results are different, but only on third decimal place after comma.

Table 3. Computed probabilities of staying in define state ("Monte Carlo" approach).

p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}	p_{15}	p_{16}	p_{17}	p_{18}
0.038	0.002	0.025	0.036	0.364	0.026	0.005	0.015	0.037	0.002	0.003	0.017	0.352	0.035	0.024	0.003	0.004	0.013

Table 4. Probabilities of staying in define state after [4].

p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}	p_{15}	p_{16}	p_{17}	p_{18}
0.037	0.002	0.025	0.036	0.364	0.025	0.005	0.014	0.037	0.002	0.003	0.017	0.354	0.035	0.024	0.003	0.004	0.013

Presented example of operating process (activity of maritime ferry) is relatively simple (as matrix 2 informs). We assume, that "Monte Carlo" approach to identification of very complex process (in which elements of matrix of probabilities of transitions between operation states given by matrix 1 takes diverse values) will appear very suitable and useful. An example of situation close to those - a port oil pipeline transportation system – is described by [8]. The basic positive trait of proposed method is possibility of automation (computerization) of recognizing the operation process of complex technical systems.

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