Soszyńska Joanna

Kołowrocki Krzysztof

Blokus-Roszkowska Agnieszka

Guze Sambor
Maritime University, Gdynia, Poland

Prediction of complex technical systems operation processes

Keywords

system operation, semi-markov process, system operation prediction, transportation systems

Abstract

There is presented the contents of the training course addressed to industry. The curriculum of the course includes the methods, algorithms and procedures for prediction of the operation processes of the complex technical systems and their application in practice. It is based on the theoretical backgrounds concerned with the semi-markov modelling of the complex technical systems operation processes and on the methods of these processes prediction. The illustrations of the proposed methods and procedures practical application in port, shipyard and maritime transport sector and are included.

1. Introduction

The training course is concerned with the methods, algorithms and procedures of prediction of the operation processes of the complex technical systems and their application in practice and it is based on the results given in [4]. The participants of the course are provided training materials and a disk with the computer program included in [1]. Presented at the training course examples of practical applications are coming from [2]-[3] and [5]-[6].
The training course includes the following items:

- Theoretical backgrounds based on [4]: mathematical model of the complex technical system operation process and its basic parameters and characteristics;
- Methodology of description of the complex technical systems: fixing the system designation and operation conditions, fixing the system subsystems and components;
- Methodology of defining basic parameters of the system operation process based on [4]: fixing the number of disjoin operation states of the system, defining the operation states of the system, fixing the possible transitions between the system operation states;
- Procedure of defining the input parameters of the system operation process based on [4]: fixing the system operation time, fixing the number of system operation states, the probabilities of the initial states of the system operation process, fixing the probabilities of the system operation process transitions between the operation states during the operation time, fixing the mean values of distributions of the conditional sojourn time of the system operation in the particular operation states;
- Procedure of predicting the characteristics of the system operation process based on [4]: determining the mean values of the unconditional sojourn times of the system operation process in particular operation states for typical conditional distributions distinguished in [4], determining transient probabilities in particular operation states, determining mean values of the total sojourn times of the system operation process in particular operation states during the fixed operation time;
- Procedure of applying the computer program for prediction of the system operation process based on [1];

- Application of the procedures and computer program for prediction of the operation processes of real complex technical systems: prediction of the operation process of the port oil piping transportation system based on [5], prediction of the operation process of the shipyard ship-rope elevator based on [2], prediction of the operation process of the shipyard ground ship-rope transportation system based on [3], prediction of the operation process of the ferry technical system based on [6].

2. Theoretical backgrounds

Training material is given in [4].

3. Procedures of prediction of the operation process of the complex technical system

3.1. Methodology of description of the complex technical system

The description of the complex technical systems should include at least the following items:
- the system designation,
- the system operation conditions,
- the system subsystems and components.

3.2. Methodology of defining the parameters of the system operation process

To make the estimation of the unknown parameters of the system operations process the experiment delivering the necessary statistical data should be precisely planned.
Firstly, before the experiment, we should perform the following preliminary steps:

i) to analyze the system operation process;

ii) to fix or to define its following general parameters:

- the number of the operation states of the system operation process v,

- the operation states of the system operation process $z_1, z_2, \ldots, z_v$;

iii) to fix the possible transitions between the system operation states;

iv) to fix the set of the unknown parameters of the system operation process semi-markov model.

3.3. Procedure of defining the input parameters of the system operation process

To predict the basic characteristics of the system operations process, we should define its necessary following input preliminary parameters:

- the duration time of the system operation process θ,

- the number of the operation states of the system operation process v,

- the vector of probabilities of the system operation process $Z(t)$ initial operation states

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

where

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

- the matrix of probabilities of the system operation process $Z(t)$ transitions between the operation states

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

where

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

- the mean values of the conditional sojourn times θ_{bl} at the operation states z_b when its next operation state is z_l,

$$M_{bl} = E[\theta_{bl}],\ b, l = 1,2,...,v,\ b \neq l. \tag{3}$$

3.4. Procedure of predicting the characteristics of the system operation process

From the formula for total probability, it follows that the mean values of the unconditional sojourn times θ_b, $b = 1,2,...,v,$ of the system operation process at the operation states z_b, $b = 1,2,...,v,$ are given by [4]

$$M_b = E[\theta_b] = \sum_{l=1}^{v} p_{bl} M_{bl},\ b = 1,2,...,v, \tag{4}$$

where p_{bl} are the input probabilities of transitiens between the operation states defined by (2) and M_{bl} are the input conditional mean values of the conditional sojourn times θ_{bl}, defined in [7] by the formula (8) in the case of any distribution of the sojourn times θ_{bl} and determined either by the formulae (9)-(16) in [7] in the cases of the particular distributions the sojourn times θ_{bl} distinguished in [4] or determined approximately by the formula (7) in [7] or given by experts in the cases of not sufficient empirical data.
The limit values of the transient probabilities at the particular operation states $p_b(t) = P(Z(t) = z_b)$, $t \in <0,+\infty)$, $b = 1,2,...,v,$ are given by

$$p_b = \frac{\pi_b M_b}{\sum_{l=1}^{v} \pi_l M_l}, \ b = 1,2,...,v, \quad (5)$$

where M_b, $b = 1,2,...,v,$ are given by (4), while the steady probabilities π_b of the vector $[\pi_b]_{1xv}$ satisfy the system of equations

$$\begin{cases} [\pi_b] = [\pi_b][p_{bl}] \\ \sum_{l=1}^{v} \pi_l = 1. \end{cases} \quad (6)$$

Other practically interesting characteristics of the system operation process possible to obtain are its total sojourn times $\hat{\theta}_b$ in the particular operation states z_b, $b = 1,2,...,v,$ in the fixed operation time θ. It is well known [4] 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

$$E[\hat{\theta}_b] = p_b \theta, \ b = 1,2,...,v, \quad (7)$$

where p_b are given by (5).

4. Procedure of applying the computer program for prediction of the system operation process

Training material is given in [1].

5. Prediction of the operation processes of real complex technical systems – using procedures

5.1. Prediction of the port oil piping transportation system operation process

5.1.1. The port oil piping transportation system description

The considered port oil piping transportation system is the main part of the Oil Terminal in Dębogórze that is designated for the reception from ships, the storage and sending by carriages or by cars the oil products such like petrol and oil. It is also designated for receiving from carriages or cars, the storage and loading the tankers with oil products.
The considered terminal is composed of three parts *A*, *B* and *C*, linked by the piping transportation systems with the pier. The scheme of this terminal is presented in *Figure 1*.

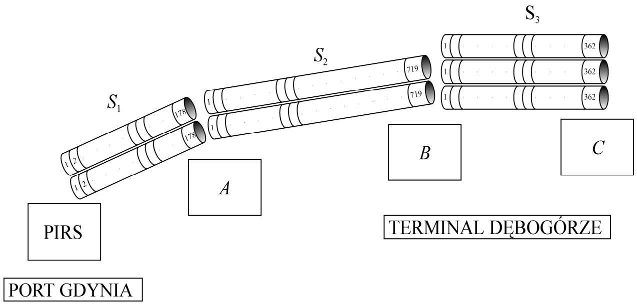

Figure 1. The scheme of the port oil piping transportation system.

The unloading of tankers is performed at the pier placed in the Port of Gdynia. The pier is connected with terminal part *A* through the transportation subsystem S_1 built of two piping lines composed of steel pipe segments with diameter of 600 mm. In the part *A* there is a supporting station fortifying tankers pumps and making possible further transport of oil by the subsystem S_2 to the terminal part *B*. The subsystem S_2 is built of two piping lines composed of steel pipe segments of the diameter 600 mm. The terminal part *B* is connected with the terminal part *C* by the subsystem S_3. The subsystem S_3 is built of one piping line composed of steel pipe segments of the diameter 500 mm and two piping lines composed of steel pipe segments of diameter 350 mm. The terminal part *C* is designated for the loading the rail cisterns with oil products and for the wagon sending to the railway station of the Port of Gdynia and further to the interior of the country.
The oil pipeline system consists three subsystems S_1, S_2, S_3:
- the subsystem S_1 composed of two identical pipelines, each composed of 178 pipe segments of length 12m and two valves,

- the subsystem S_2 composed of two identical pipelines, each composed of 717 pipe segments of length 12m and two valves,
- the subsystem S_3 composed of three different pipelines, each composed of 360 pipe segments of either 10 m or 7,5 m length and two valves.

5.1.2. Defining the parameters of the port oil piping transportation system operation process

Taking into account the expert opinion on the operation process of the considered port oil pipeline transportation system we fix:
- the number of the pipeline system operation process states $\nu = 7$
and we distinguish the following as its seven operation states:

- an operation state z_1 – transport of one kind of medium from the terminal part B to part C using two out of three pipelines in subsystem S_3,
- an operation state z_2 – transport of one kind of medium from the terminal part C (from carriages) to part B using one out of three pipelines in subsystem S_3,
- an operation state z_3 – transport of one kind of medium from the terminal part B through part A to pier using one out of two pipelines in subsystem S_2 and one out of two pipelines in subsystem S_1,
- an operation state z_4 – transport of two kinds of medium from the pier through parts A and B to part C using one out of two pipelines in subsystem S_1, one out of two pipelines in subsystem S_2 and two out of three pipelines in subsystem S_3,
- an operation state z_5 – transport of one kind of medium from the pier through part A to B using one out of two pipelines in subsystem S_1 and one out of two pipelines in subsystem S_2,
- an operation state z_6 – transport of one kind of medium from the terminal part B to C using two out of three pipelines in subsystem S_3, and simultaneously transport one kind of medium from the pier through part A to B using one out of two pipelines in parts S_1 and one out of two pipelines in subsystem S_2,
- an operation state z_7 – transport of one kind of medium from the terminal part B to C using one out of three pipelines in part S_3, and simultaneously transport second kind of medium from the terminal part C to B using one out of three pipelines in part S_3.

Moreover, we fix that there are possible the transitions between all system operation states. Thus, the unknown parameters of the system operation process semi-markov model are:

- the initial probabilities $p_b(0)$, $b = 1,2,...,7$, $b \neq l$, of the pipeline system operation process transients in the particular states z_b at the moment $t = 0$,
- the transition probabilities p_{bl}, $b,l = 1,2,...,7$, of the pipeline system operation process from the operation state z_b into the operation state z_l,
- the distributions of the conditional sojourn times θ_{bl}, $b,l = 1,2,...,7$, $b \neq l$, in the particular operation states and/or their mean values $M_{bl} = E[\theta_{bl}]$, $b,l = 1,2,...,7$, $b \neq l$.

5.1.3. Defining the input parameters of the port oil piping transportation system operation process

The input necessary parameters of the port oil piping transportation system operation process are as follows [2], [7]:

- the oil piping system operation time is $\theta = 1$ year = 365 days,

- the number of the piping system operation states is $\nu = 7$,

- the initial probabilities $p_b(0)$, $b = 1,2,...,7$, of the piping system operation process transients in the particular states z_b at the moment $t = 0$, are

$$[p(0)]_{1x7} = [0.34, 0.05, 0, 0, 0.23, 0.19, 0.19],$$

- the transition probabilities p_{bl}, $b,l = 1,2,...,7$, of the piping transportation system operation process from the operation state z_b into the operation state z_l are

$[p_{bl}]_{7x7} =$

$$\begin{bmatrix} 0 & 0.022 & 0.022 & 0 & 0.534 & 0.111 & 0.311 \\ 0.2 & 0 & 0 & 0 & 0 & 0 & 0.8 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0.488 & 0.023 & 0 & 0.023 & 0 & 0.233 & 0.233 \\ 0.095 & 0 & 0 & 0 & 0.667 & 0 & 0238 \\ 0.516 & 0.064 & 0 & 0 & 0.226 & 0.194 & 0 \end{bmatrix}$$

- the mean values of the conditional sojourn time of the system operation process in the particular operation states

$$M_{12} = 1920, \; M_{13} = 480, \; M_{15} = 1999.4,$$

$$M_{16} = 1250, \; M_{17} = 1129.6, \; M_{21} = 9960,$$

$$M_{27} = 810, \; M_{31} = 575, \; M_{47} = 380,$$

$$M_{51} = 874.7, \; M_{52} = 480, \; M_{54} = 300,$$

$$M_{56} = 436.3, \; M_{57} = 1042.5, \; M_{61} = 325,$$

$$M_{65} = 510.7, \; M_{67} = 438, \; M_{71} = 874.1,$$

$$M_{72} = 510, \; M_{75} = 2585.7, \; M_{76} = 2380.$$

As there are no realizations of conditional sojourn times θ_{14}, θ_{23}, θ_{24}, θ_{25}, θ_{26}, θ_{32}, θ_{34}, θ_{35}, θ_{36}, θ_{37}, θ_{41}, θ_{42}, θ_{43}, θ_{45}, θ_{46}, θ_{53}, θ_{62}, θ_{63}, θ_{64}, θ_{73}, and θ_{74} it is impossible to estimate their conditional mean values M_{14}, M_{23}, M_{24}, M_{25}, M_{26}, M_{32}, M_{34}, M_{35}, M_{36}, M_{37}, M_{41}, M_{42}, M_{43}, M_{45}, M_{46}, M_{53}, M_{62}, M_{63}, M_{64}, M_{73}, M_{74}.

5.1.4. Prediction of the characteristics of the port oil piping transportation system operation process

Hence, by (4), the unconditional mean sojourn times in the particular operation states are:

$$M_1 = E[\theta_1] = p_{12}M_{12} + p_{13}M_{13}$$

$$+ p_{15}M_{15} + p_{16}M_{16} + p_{17}M_{17}$$

$$= 0.022 \cdot 1920 + 0.022 \cdot 480$$

$$+ 0.534 \cdot 1999.4 + 0.111 \cdot 1250$$

$$+ 0.311 \cdot 1129.6 \cong 1610.52,$$

$$M_2 = E[\theta_2] = p_{21}M_{21} + p_{27}M_{27}$$

$$= 0.2 \cdot 9960 + 0.8 \cdot 810 \cong 2640,$$

$$M_3 = E[\theta_3] = p_{31}M_{31} = 1 \cdot 575 = 575,$$

$$M_4 = E[\theta_4] = p_{47}M_{47} = 1 \cdot 380 = 380,$$

$$M_5 = E[\theta_5] = p_{51}M_{51} + p_{52}M_{52}$$

$$+ p_{54}M_{54} + p_{56}M_{56} + p_{57}M_{57}$$

$$= 0.488 \cdot 874.7 + 0.023 \cdot 480$$

$$+ 0.023 \cdot 300 + 0.233 \cdot 436.3$$

$$+ 0.233 \cdot 1042.5 \cong 789.35,$$

$$M_6 = E[\theta_6] = p_{61}M_{61} + p_{65}M_{65} + p_{67}M_{67}$$

$$= 0.095 \cdot 325 + 0.667 \cdot 510.7$$

$$+ 0.238 \cdot 438 \cong 475.76,$$

$$M_7 = E[\theta_7] = p_{71}M_{71} + p_{72}M_{72} + p_{75}M_{75} + p_{76}M_{76}$$

$$= 0.516 \cdot 874.1 + 0.064 \cdot 510$$

$$+ 0.226 \cdot 2585.7 + 0.194 \cdot 2380 \cong 1529.76.$$

Since from the system of equations (6) given here in the form

$$\begin{cases} [\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7] \\ = [\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7][p_{bl}]_{7x7} \\ \pi_1 + \pi_2 + \pi_3 + \pi_4 + \pi_5 + \pi_6 + \pi_7 = 1, \end{cases}$$

we get

$$\pi_1 = 0.288, \; \pi_2 = 0.028, \; \pi_3 = 0.006, \; \pi_4 = 0.007,$$

$$\pi_5 = 0.302, \; \pi_6 = 0.146, \; \pi_7 = 0.223,$$

then the limit values p_b of the transient probabilities $p_b(t)$ at the operational states z_b, according to (5), are

$$p_1 = 0.389, \; p_2 = 0.062, \; p_3 = 0.003, \; p_4 = 0.002,$$

$p_5 = 0.20, \ p_6 = 0.058, \ p_7 = 0.286.$

Hence, the expected values of the total sojourn times $\hat{\theta}_b$, $b = 1,2,...,7,$ of the system operation process in particular operation states z_b, $b = 1,2,...,7,$ during the fixed operation time

$\theta = 1$ year = 365 days,

after applying (7), amount:

$E[\hat{\theta}_1]$ = 0.389 year = 142 days,

$E[\hat{\theta}_2]$ = 0.062 year = 22.6 days,

$E[\hat{\theta}_3]$ = 0.003 year = 1.1 day,

$E[\hat{\theta}_4]$ = 0.002 year = 0.7 day,

$E[\hat{\theta}_5]$ = 0.20 year = 73 days,

$E[\hat{\theta}_6]$ = 0.058 year = 21.2 days,

$E[\hat{\theta}_7]$ = 0.286 year = 104.4 days.

5.2. Prediction of the shipyard ship-rope elevator operation process

5.2.1. The shipyard ship-rope elevator description

Ship-rope elevators are used to dock and undock ships coming to shipyards for repairs. The elevator utilized in the Naval Shipyard in Gdynia, with the scheme presented in *Figure 2*, is composed of a steel platform-carriage placed in its syncline (hutch). The platform is moved vertically with 10 rope-hoisting winches fed by separate electric motors. Motors are equipped in ropes "Bridon" with the diameter 47 mm each rope having a maximum load of 300 tonnes. During ship docking the platform, with the ship settled in special supporting carriages on the platform, is raised to the wharf level (upper position). During undocking, the operation is reversed. While the ship is moving into or out of the syncline and while stopped in the upper position the platform is held on hooks and the loads in the ropes are relieved. Since the platform-carriage and electric motors are highly reliable in comparison to the ropes, which work in extremely aggressive conditions, in our further analysis we will discuss the reliability of the rope system only.

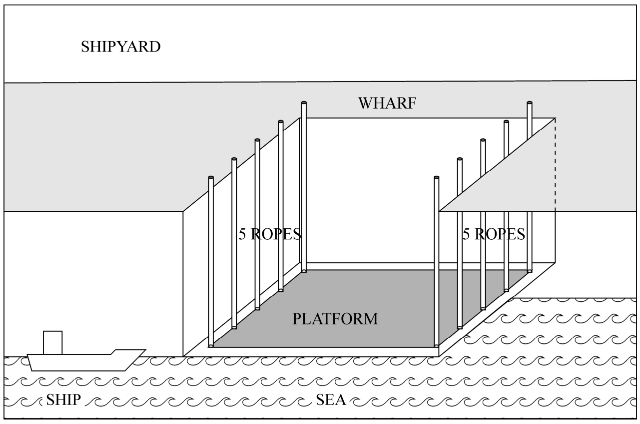

Figure 2. The scheme of the ship-rope transportation system

5.2.2. Defining the parameters of the shipyard ship-rope elevator operation process

Taking into account the expert opinion on the operation process of the considered ship-rope elevator we fix:

- the number of the ship-rope elevator operation process states $\nu = 5$
and we distinguish the following as its five operation states:

- an operation state z_1 – loading over 0 up to 500 tones,
- an operation state z_2 – loading over 500 up to 1000 tones,
- an operation state z_3 – loading over 1000 up to 1500 tones,
- an operation state z_4 – loading over 1500 up to 2000 tones,
- an operation state z_5 – loading over 2000 up to 2500 tones.

Moreover, we fix that there are possible the transitions between all system operation states. Thus, the unknown parameters of the system operation process semi-markov model are:

- the initial probabilities $p_b(0)$, $b = 1,2,...,5,$ $b \neq l,$ of the ship-rope elevator operation process transients in the particular states z_b at the moment t = 0,
- the transition probabilities p_{bl}, $b,l = 1,2,...,5,$ of the ship-rope elevator operation process from the operation state z_b into the operation state z_l,
- the distributions of the conditional sojourn times θ_{bl}, $b,l = 1,2,...,5, \ b \neq l,$ in the

particular operation states and/or their mean values $M_{bl} = E[\theta_{bl}]$, $b,l = 1,2,...,5,\ b \neq l.$

5.2.3. Defining the input parameters of the shipyard ship-rope elevator operation process

The input necessary parameters of the shipyard ship-rope elevator operation process are as follows [2], [7]:

- the ship-rope elevator operation time is $\theta = 1$ year = 365 days,

- the number of the ship-rope elevator operation states is $\nu = 5$,

- the initial probabilities $p_b(0)$, $b = 1,2,3,4,5,$ of the ship-rope elevator operation process transients in the particular states z_b at the moment $t = 0$, are

$$[p(0)]_{1x5} = [0.4211,\ 0.3684, 0.2105, 0, 0],$$

- the transition probabilities p_{bl}, $b,l = 1,2,3,4,5,$ of the ship-rope elevator operation process from the operation state z_b into the operation state z_l are

$$[p_{bl}]_{5x5} = \begin{bmatrix} 0 & 0,3158 & 0,5789 & 0,1053 & 0 \\ 0,3333 & 0 & 0,4444 & 0,1667 & 0,0556 \\ 0,3636 & 0,4546 & 0 & 0,0909 & 0,0909 \\ 0,2857 & 0,2857 & 0,2857 & 0 & 0,1429 \\ 0,5 & 0 & 0,5 & 0 & 0 \end{bmatrix},$$

- the conditional mean values of the conditional sojourn times θ_{bl}, $b,l = 1,2,...,5,\ b \neq l,$ in the particular operation states are:

$$M_{12} = 114.33,\ M_{13} = 125.45,\ M_{14} = 152.50,$$

$$M_{21} = 225.33,\ M_{23} = 171.25,\ M_{24} = 230.00,$$

$$M_{25} = 240.00,\ M_{31} = 243.75,\ M_{32} = 324.00,$$

$$M_{34} = 290.00,\ M_{35} = 270.00,\ M_{41} = 157.50,$$

$$M_{42} = 180.00,\ M_{43} = 157.50,\ M_{45} = 150.00,$$

$$M_{51} = 300.00,\ M_{52} = 0,\ M_{53} = 450.00.$$

As there are no realizations of conditional sojourn times θ_{15} and θ_{54} it is impossible to estimate their conditional mean values M_{15} and M_{54}.

5.2.4. Prediction of the characteristics of the shipyard ship-rope elevator operation process

Hence, by (4), the unconditional mean sojourn times in the particular operation states are:

$$M_1 = E[\theta_1] = 0.3158 \cdot 114.33 + 0.5789 \cdot 125.45 + 0.1053 \cdot 152.50 \cong 124.79,$$

$$M_2 = E[\theta_2] = 0.3333 \cdot 225.33 + 0.4444 \cdot 171.25 + 0.1667 \cdot 230.00 + 0.0556 \cdot 240.00 \cong 202.89,$$

$$M_3 = E[\theta_3] = 0.3636 \cdot 243.75 + 0.4546 \cdot 324.00 + 0.0909 \cdot 290.00 + 0.0909 \cdot 270.00 \cong 286.82,$$

$$M_4 = E[\theta_4] = 0.2857 \cdot 157.50 + 0.2857 \cdot 180.00 + 0.2857 \cdot 157.50 + 0.1429 \cdot 150.00 \cong 162.86,$$

$$M_5 = E[\theta_5] = 0.5 \cdot 300.00 + 0.5 \cdot 450.00 = 375.00.$$

Since from the system of equations (6) given here in the form

$$\begin{cases} [\pi_1, \pi_2, \pi_3, \pi_4, \pi_5] = [\pi_1, \pi_2, \pi_3, \pi_4, \pi_5][p_{bl}]_{5x5} \\ \pi_1 + \pi_2 + \pi_3 + \pi_4 + \pi_5 = 1, \end{cases}$$

we get

$$\pi_1 = 0.2578,\ \pi_2 = 0.2489,\ \pi_3 = 0.2659,$$

$$\pi_4 = 0.1657,\ \pi_5 = 0.0617,$$

then the limit values p_b of the transient probabilities $p_b(t)$ at the operational states z_b, according to (5), are

$$p_1 = 0.1539,\ p_2 = 0.2415,\ p_3 = 0.3648,$$

$$p_4 = 0.1291,\ p_5 = 0.1107.$$

Hence, the expected values of the total sojourn times $\hat{\theta}_b$, $b = 1,2,...,5,$ of the system operation process in particular operation states z_b, $b = 1,2,...,5$, during the fixed operation time

$\theta = 1$ year = 365 days,

after applying (7), amount:

$E[\hat{\theta}_1]$ = 0.1539 year = 56.2 days,

$E[\hat{\theta}_2]$ = 0.2415 year = 88.1 days,

$E[\hat{\theta}_3]$ = 0.3648 year = 133.2 days,

$E[\hat{\theta}_4]$ = 0.1291 year = 47.1 days,

$E[\hat{\theta}_5]$ = 0.1107 year = 40.4 days.

5.3. Prediction of the shipyard ground ship-rope transporter operation process

5.3.1. The shipyard ground ship-rope transporter description

The ground ship-rope transporter in the Naval Shipyard in Gdynia is composed of three broaching machines working independently equipped in the steel ropes "Drumet" with the diameter 30 mm. This system is used to transfer ships coming to the shipyard for repairs from platform to the repair post and back from repair post to the platform. The load of steel ropes in the broaching machines is measured as a power consumption of amperage. The maximum of power consumption of broaching machines is 100 Ampere.

First during ship docking the ship settled in special supporting carriages on the platform is raised to the wharf level and then the ship is transferred from the platform with the rope broaching machine on a traverse. Next the ship with the traverse, on which the ship is settled, is shifted in the repair post direction. Then after stretching the ropes from the ship to the broaching machine through some blocs, the ship is transferred from the traverse to the repair post. After some repair measures, the ship is transferred back to the traverse and then on the platform. Finally, during undocking the ship on the platform is moved down to the water. There are nine repair posts, denoted by symbols R1-R9. The first repair post R1 can be lengthening to the post R1/B1 for long ships. There are also available two repair depots denoted by symbols B and D. Generally all kind of repairs can be carried out in any repair post. The repair posts R1 and R2 are equipped in crane. The submarines are repaired in the depot. Additionally large vessels are transferred to the repair post R1/B1. The scheme of the plan of repair post placing is given in *Figure 3*.

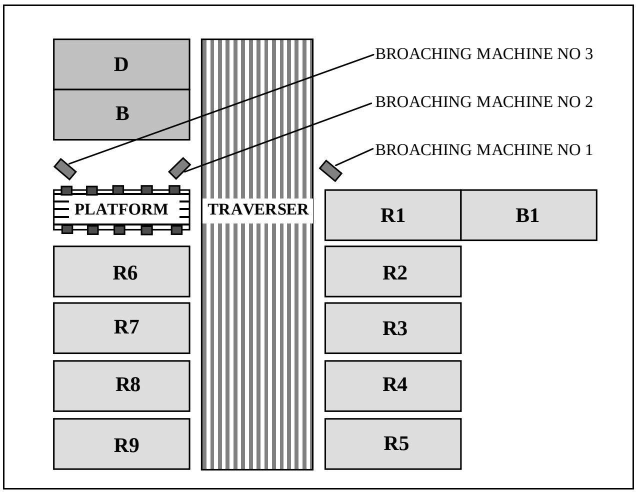

Figure 3. The scheme of the plan of repair post placing

The ground ship-rope transporter reliability depends strongly on the tonnage of transferred ships and the place where the ship should be transferred. The broaching machines in the transportation system are numbered 1, 2, 3. There is used one or there are used two or possibly three broaching machines depending on weight and length of the ship and on which repair post the ship should be transferred. All three broaching machines are working in the extreme situation when large vessel over 1800 tones is transferred.

5.3.2. Defining the parameters of the shipyard ground ship-rope transporter operation process

Taking into account the expert opinion on the operation process of the considered ground ship-rope transporter we fix:

- the number of the ground ship-rope transporter operation process states $\nu = 7$
and we distinguish the following as its seven operation states:

- an operation state z_1 – the ship with a tonnage up to 1300 tones is transferred from the platform to the traverse, from the traverse to the repair posts R1-R5 and from the repair posts R6-R9 to the traverse (the broaching machine number 1 is used (S_1)),
- an operation state z_2 – the ship with a tonnage up to 1300 tones is transferred from the traverse to the repair posts R6-R9, from

the repair posts R1-R5 to the traverse and from the traverse to the platform (the broaching machine number 3 is used (S_3)),

- an operation state z_3 – the ship with a tonnage up to 1300 tones is transferred from the repair posts R1-R5 to the traverse and the access to the broaching machine number 3 is difficult (the broaching machine number 2 is used (S_2)),
- an operation state z_4 – the ship with a tonnage over 1300 up to 1800 tones (or the ship with a tonnage up to 1300 tones after long period of renovation or after taking some special kind of measures) is transferred from the platform to the traverse, from the traverse to the repair posts R1-R5 or from the repair posts R6-R9 to the traverse (the broaching machines 1 and 3 are used (S_1, S_3)),
- an operation state z_5 – the ship with a tonnage over 1300 up to 1800 tones (or the ship with a tonnage up to 1300 tones after long period of renovation or after taking some special kind of measures) is transferred from the platform to the traverse, from the traverse to the repair posts R1-R5 or from the repair posts R6-R9 to the traverse and the access to the broaching machine number 3 is difficult (the broaching machines 1 and 2 are used (S_1, S_2)),
- an operation state z_6 – the ship with a tonnage over 1300 up to 1800 tones (or the ship with a tonnage up to 1300 tones after long period of renovation or after taking some special kind of measures) is transferred from the traverse to the repair posts R6-R9, from the repair posts R1-R5 to the traverse or from the traverse to the platform (the broaching machines 2 and 3 are used (S_2, S_3)),
- an operation state z_7 – the ship with a tonnage over 1800 tones is transferred (all broaching machines 1, 2 and 3 are used (S_1, S_2, S_3)).

Moreover, we fix that there are possible the transitions between all system operation states. Thus, the unknown parameters of the system operation process semi-markov model are:

- the initial probabilities $p_b(0)$, $b = 1,2,...,7,$ $b \neq l,$ of the ground ship-rope transporter operation process transients in the particular states z_b at the moment $t = 0$,
- the transition probabilities p_{bl}, $b,l = 1,2,...,7,$ of the ground ship-rope transporter operation process from the operation state z_b into the operation state z_l,
- the distributions of the conditional sojourn times θ_{bl}, $b,l = 1,2,...,7,$ $b \neq l,$ in the particular operation states and/or their mean values $M_{bl} = E[\theta_{bl}]$, $b,l = 1,2,...,7,$ $b \neq l.$

5.3.3. Defining the input parameters of the shipyard ground ship-rope transporter operation process

The input necessary parameters of the ground ship-rope transporter operation process are as follows [3], [7]:

- the ground ship-rope transporter operation time is $\theta = 1$ year = 365 days,

- the number of the ground ship-rope transporter operation states is $\nu = 7$,

- the initial probabilities $p_b(0)$, $b = 1,2,...,7,$ of the ship-rope elevator operation process transients in the particular states z_b at the moment $t = 0$, are

$$[p(0)]_{1x7} = [0.6315, 0.1053, 0.1579, 0, 0, 0, 0.1053],$$

- the transition probabilities p_{bl}, $b,l = 1,2,...,7,$ of the ship-rope elevator operation process from the operation state z_b into the operation state z_l are

$$[p_{bl}]_{7x7} = \begin{bmatrix} 0 & 0.7500 & 0.1667 & 0.0278 & 0 & 0.0555 & 0 \\ 0.6190 & 0 & 0.1667 & 0 & 0.0238 & 0.1191 & 0.0714 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0.5 & 0 & 0 & 0 & 0 & 0.5 & 0 \\ 0.5 & 0 & 0 & 0 & 0 & 0.5 & 0 \\ 0.6667 & 0 & 0.1111 & 0.1111 & 0 & 0 & 0.1111 \\ 0.25 & 0.5 & 0 & 0 & 0.25 & 0 & 0 \end{bmatrix}$$

- the conditional mean values of the conditional sojourn times θ_{bl}, $b,l = 1,2,...,7,$ $b \neq l,$ in the particular operation states are:

$$M_{12} = 102.04, \; M_{13} = 179.17, \; M_{14} = 145,$$

$$M_{16} = 215, \; M_{21} = 81.30, \; M_{23} = 41,$$

$M_{25} = 32,\ M_{26} = 50,\ M_{27} = 108.33,$

$M_{32} = 56.21,\ M_{41} = 150,\ M_{46} = 70,$

$M_{51} = 240,\ M_{56} = 180,\ M_{61} = 175,$

$M_{63} = 190,\ M_{64} = 190,\ M_{67} = 150,$

$M_{71} = 245,\ M_{72} = 235,\ M_{75} = 60.$

As there are no realizations of conditional sojourn times θ_{15}, θ_{17}, θ_{24}, θ_{34}, θ_{35}, θ_{36}, θ_{37}, θ_{42}, θ_{43}, θ_{45}, θ_{47}, θ_{52}, θ_{53}, θ_{54}, θ_{57}, θ_{62}, θ_{65}, θ_{73}, θ_{74} and θ_{76} it is impossible to estimate their conditional mean values M_{15}, M_{17}, M_{24}, M_{34}, M_{35}, M_{36}, M_{37}, M_{42}, M_{43}, M_{45}, M_{47}, M_{52}, M_{53}, M_{54}, M_{57}, M_{62}, M_{65}, M_{73}, M_{74} and M_{76}.

5.3.4. Prediction of the characteristics of the shipyard ground ship-rope transporter operation process

Hence, by (4), the unconditional mean sojourn times in the particular operation states are:

$$M_1 = E[\theta_1] = 0.75 \cdot 101.85 + 0.1667 \cdot 179.17$$
$$+ 0.0278 \cdot 145 + 0.0555 \cdot 215 \cong 122.22,$$

$$M_2 = E[\theta_2] = 0.6190 \cdot 81.54 + 0.1667 \cdot 41$$
$$+ 0.0238 \cdot 32 + 0.1191 \cdot 50 + 0.0714 \cdot 108.33$$
$$\cong 71.76,$$

$$M_3 = E[\theta_3] = 1 \cdot 56{,}21 = 56.21,$$

$$M_4 = E[\theta_4] = 0.5 \cdot 150 + 0.5 \cdot 70 = 110,$$

$$M_5 = E[\theta_5] = 0.5 \cdot 240 + 0.5 \cdot 180 = 210,$$

$$M_6 = E[\theta_6] = 0.6667 \cdot 175 + 0.1111 \cdot 190,$$
$$+ 0.1111 \cdot 150 \cong 175.56,$$

$$M_7 = E[\theta_7] = 0.25 \cdot 245 + 0.5 \cdot 235 + 0.25 \cdot 60$$
$$= 193.75.$$

Since from the system of equations (6) given here in the form

$$\begin{cases} [\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7] \\ = [\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7][p_{bl}]_{7x7} \\ \pi_1 + \pi_2 + \pi_3 + \pi_4 + \pi_5 + \pi_6 + \pi_7 = 1, \end{cases}$$

we get

$$\pi_1 = 0.3300,\ \pi_2 = 0.3856,\ \pi_3 = 0.1285,$$

$$\pi_4 = 0.0183,\ \pi_5 = 0.0183,\ \pi_6 = 0.0826,$$

$$\pi_7 = 0.0367,$$

then the limit values p_b of the transient probabilities $p_b(t)$ at the operational states z_b, according to (5), are given by

$$p_1 = 0.3928,\ p_2 = 0.2695,\ p_3 = 0.0703,$$

$$p_4 = 0.0196,\ p_5 = 0.0374,\ p_6 = 0.1412,$$

$$p_7 = 0.0692.$$

Hence, the expected values of the total sojourn times $\hat{\theta}_b$, $b = 1,2,...,7$, of the system operation process in particular operation states z_b, $b = 1,2,...,7$, during the fixed operation time

$\theta = 1$ year = 365 days,

after applying (7), amount:

$E[\hat{\theta}_1]$ = 0.3928 year = 143.4 days,

$E[\hat{\theta}_2]$ = 0.2695 year = 98.4 days,

$E[\hat{\theta}_3]$ = 0.0703 year = 25.7 days,

$E[\hat{\theta}_4]$ = 0.0196 year = 7.2 days,

$E[\hat{\theta}_5]$ = 0.0374 year = 13.7 days,

$E[\hat{\theta}_6]$ = 0.1412 year = 51.5 days,

$E[\hat{\theta}_7]$ = 0.0692 year = 25.3 days.

5.4. Prediction of the Stena Baltica ferry operation process

5.4.1. The Stena Baltica ferry description

The m/v Stena Baltica is a passenger Ro-Ro ship operating in Baltic Sea between Gdynia and Karlskrona ports on regular everyday line.

We assume that the ship is composed of a number of main subsystems having an essential influence on its safety. These subsystems are illustrated in *Figure 4*. On the scheme of the ship presented in *Figure 4*, there are distinguished her following subsystems:
S_1 - a navigational subsystem,
S_2 - a propulsion and controlling subsystem,
S_3 - a loading and unloading subsystem,
S_4 - a hull subsystem,
S_5 - an anchoring and mooring subsystem,
S_6 - a protection and rescue subsystem,
S_7 - a social subsystem.

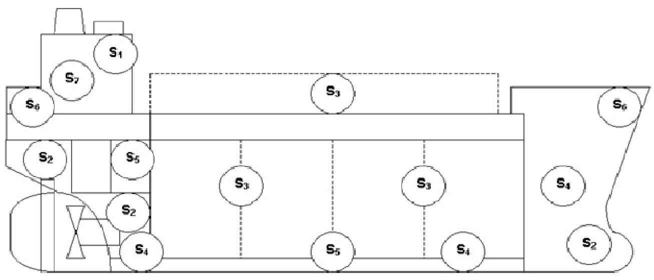

Figure 4. Subsystems having an essential influence on ship safety

5.4.2. Defining the parameters of the Stena Baltica ferry operation process

Taking into account the expert opinion on the operation process of the considered Stena Baltica ferry we fix:

- the number of the ship operation process states $\nu = 18$
and we distinguish the following as its eighteen operation states:

- an operation state z_1 – loading at Gdynia Port,
- an operation state z_2 – unmooring operations at Gdynia Port,
- an operation state z_3 – leaving Gdynia Port and navigation to "GD" buoy,
- an operation state z_4 – navigation at restricted waters from "GD" buoy to the end of Traffic Separation Scheme,
- an operation state z_5 – navigation at open waters from the end of Traffic Separation Scheme to "Angoring" buoy,
- an operation state z_6 – navigation at restricted waters from "Angoring" buoy to "Verko" Berth at Karlskrona,
- an operation state z_7 – mooring operations at Karlskrona Port,
- an operation state z_8 – unloading at Karlskrona Port,
- an operation state z_9 – loading at Karlskrona Port,
- an operation state z_{10} – unmooring operations at Karlskrona Port,
- an operation state z_{11} – ship turning at Karlskrona Port,
- an operation state z_{12} – leaving Karlskrona Port and navigation at restricted waters to "Angoring" buoy,
- an operation state z_{13} – navigation at open waters from "Angoring" buoy to the entering Traffic Separation Scheme,
- an operation state z_{14} – navigation at restricted waters from the entering Traffic Separation Scheme to "GD" buoy,
- an operation state z_{15} – navigation from "GD" buoy to turning area,
- an operation state z_{16} – ship turning at Gdynia Port,
- an operation state z_{17} – mooring operations at Gdynia Port,
- an operation state z_{18} – unloading at Gdynia Port.

Moreover, we fix that there are possible only the transitions between the neighboring system operation states, i.e., from the operation states z_b to the operation states z_{b+1}, $b = 1,2,...,17$, and from the operation state z_{18} to the operation state z_1.

Thus, the unknown parameters of the system operation process semi-markov model are:

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

- the probabilities of transitions p_{bb+1}, $b = 1,2,...,17$, and $p_{18\,1}$ of the Stena Baltica ferry operation process from the operation state z_b into the operation state z_{b+1}, $b = 1,2,...,17$, and from the operation state z_{18} into the operation state z_1,

- the distributions of the conditional sojourn times $\theta_{b\,b+1}$, $b = 1,2,...,17$, and $\theta_{18\,1}$ in the particular operation states and/or their mean values $M_{bl} = E[\theta_{bl}]$, $b = 1,2,...,17$, and $M_{bl} = E[\theta_{18\,1}]$.

5.4.3. Defining the input parameters of the Stena Baltica ferry operation process

The input necessary parameters of the Stena Baltica ferry operation process are as follows [6], [7]:

- the Stena Baltica ferry operation time is θ = 42 days,

- the number of the Stena Baltica ferry operation states is $\nu = 18$,

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

$$[p(0)]_{1x18} = [1, 0, ..., 0],$$

- the transition probabilities p_{bl}, $b,l = 1,2,...,18$, of the Stena Baltica ferry operation process from the operation state z_b into the operation state z_l are

$$[p_{bl}]_{1818} = [p_{bl}] = \begin{bmatrix} 0\,1\,0 ... 0\,0 \\ 0\,0\,1 ... 0\,0 \\ ... \\ 0\,0\,0 ... 0\,1 \\ 1\,0\,0 ... 0\,0 \end{bmatrix},$$

- the mean values of the conditional sojourn times $\theta_{b\,b+1}$, $b = 1,2,...,17$, and $\theta_{18\,1}$ in the particular operation states are:

$$M_{12} = 54.33,\ M_{23} = 2.57,\ M_{34} = 36.57,$$

$$M_{45} = 52.5,\ M_{56} = 525.95,\ M_{67} = 37.16,$$

$$M_{78} = 7.02,\ M_{89} = 21.43,\ M_{910} = 53.69,$$

$$M_{1011} = 2.93,\ M_{1112} = 4.38,\ M_{1213} = 23.86,$$

$$M_{1314} = 509.69,\ M_{1415} = 50.14,\ M_{1516} = 54.33,$$

$$M_{1617} = 4.52,\ M_{1718} = 5.62,\ M_{181} = 54.33.$$

5.4.4. Prediction of the characteristics of the Stena Baltica ferry operation process

Hence, by (4), the unconditional mean sojourn times in the particular operation states are:

$$M_1 = E[\theta_1] = p_{12}M_{12} = 1 \cdot 54.33 = 54.33,$$

$$M_2 = E[\theta_2] = p_{23}M_{23} = 1 \cdot 2.57 = 2.57,$$

$$M_3 = E[\theta_3] = p_{34}M_{34} = 1 \cdot 36.57 = 36.57,$$

$$M_4 = E[\theta_4] = p_{45}M_{45} = 1 \cdot 52.5 = 52.5,$$

$$M_5 = E[\theta_5] = p_{56}M_{56} = 1 \cdot 525.95 = 525.95,$$

$$M_6 = E[\theta_6] = p_{67}M_{67} = 1 \cdot 37.16 = 37.16,$$

$$M_7 = E[\theta_7] = p_{78}M_{78} = 1 \cdot 7.02 = 7.02,$$

$$M_8 = E[\theta_8] = p_{89}M_{89} = 1 \cdot 21.43 = 21.43,$$

$$M_9 = E[\theta_9] = p_{910}M_{910} = 1 \cdot 53.69 = 53.69,$$

$$M_{10} = E[\theta_{10}] = p_{1011}M_{1011} = 1 \cdot 2.93 = 2.93,$$

$$M_{11} = E[\theta_{11}] = p_{1112}M_{1112} = 1 \cdot 4.38 = 4.38,$$

$$M_{12} = E[\theta_{12}] = p_{1213}M_{1213} = 1 \cdot 23.86 = 23.86,$$

$$M_{13} = E[\theta_{13}] = p_{1314}M_{1314} = 1 \cdot 509.69 = 509.69,$$

$$M_{14} = E[\theta_{14}] = p_{1415}M_{1415} = 1 \cdot 50.14 = 50.14,$$

$$M_{15} = E[\theta_{15}] = p_{1516}M_{1516} = 1 \cdot 34.28 = 34.28,$$

$$M_{16} = E[\theta_{16}] = p_{1617}M_{1617} = 1 \cdot 4.52 = 4.52,$$

$$M_{17} = E[\theta_{17}] = p_{1718}M_{1718} = 1 \cdot 5.62 = 5.62,$$

$$M_{18} = E[\theta_{18}] = p_{181}M_{181} = 1 \cdot 18.74 = 18.74.$$

Since from the system of equations (6) given here in the form

$$\begin{cases} [\pi_{bl}]_{1x18} = [\pi_{bl}]_{1x18} \cdot [p_{bl}]_{18x18} \\ \sum_{b=1}^{18} \pi_b = 1, \end{cases}$$

we get

$\pi_b = 0.056, \ b = 1,2,...,18,$

then the limit values of the transient probabilities at the operational states z_b, according to (5), are

$p_1 = 0.037, \ p_2 = 0.002, \ p_3 = 0.025,$

$p_4 = 0.036, \ p_5 = 0.364, \ p_6 = 0.025,$

$p_7 = 0.005, \ p_8 = 0.014, \ p_9 = 0.037,$

$p_{10} = 0.002, \ p_{11} = 0.003, \ p_{12} = 0.017,$

$p_{13} = 0.354, \ p_{14} = 0.035, \ p_{15} = 0.024,$

$p_{16} = 0.003, \ p_{17} = 0.004, \ p_{18} = 0.013.$

Hence, the expected values of the total sojourn times $\hat{\theta}_b$, $b = 1,2,...,18,$ of the system operation process in particular operation states z_b, $b = 1,2,...,18,$ during the fixed operation time

$\theta = 1$ year = 365 days,

after applying (7), amount:

$E[\hat{\theta}_1]$ = 0.036 year = 13.1 days,

$E[\hat{\theta}_2]$ = 0.002 year = 0.7 day,

$E[\hat{\theta}_3]$ = 0.025 year = 9.1 days,

$E[\hat{\theta}_4]$ = 0.037 year = 13.5 days,

$E[\hat{\theta}_5]$ = 0.366 year = 133.6 days,

$E[\hat{\theta}_6]$ = 0.026 year = 9.5 days,

$E[\hat{\theta}_7]$ = 0.005 year = 1.8 days,

$E[\hat{\theta}_8]$ = 0.013 year = 4.7 days,

$E[\hat{\theta}_9]$ = 0.032 year = 11.7 days,

$E[\hat{\theta}_{10}]$ = 0.002 year = 0.7 day,

$E[\hat{\theta}_{11}]$ = 0.003 year = 1.1 days,

$E[\hat{\theta}_{12}]$ = 0.0117 year = 4.3 days,

$E[\hat{\theta}_{13}]$ = 0.357 year = 130.3 days,

$E[\hat{\theta}_{14}]$ = 0.036 year = 13.1days,

$E[\hat{\theta}_{15}]$ = 0.023 year = 8.4 days,

$E[\hat{\theta}_{16}]$ = 0.003 year = 1.1 days,

$E[\hat{\theta}_{17}]$ = 0.004 year = 1.5 days,

$E[\hat{\theta}_{18}]$ = 0.013 year = 4.7 days.

6. Prediction of the operation processes of real complex technical systems – using computer program

The computer program is based on on methods and algorithms for prediction of the characteristics of the complex technical systems operation processes given in [4]. The program allows to determine the mean values of the unconditional sojourn times of the system operation process at the operation states, the limit values of the transient probabilities of the system operation process at the particular operation states and the system operation process total sojourn times at the particular operation states for the fixed sufficiently large system operation time. The computer program may be used for predicting the characteristics of the operation processes of real technical systems, particularly, the operation processes of port, shipyard and maritime transportation systems [2]-[3], [5]-[6]. It may also be used to construct the integrated safety and reliability decision support systems for various maritime and coastal transport sectors. This program together with the description may also be included into these training courses addressed to industry.

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