$\theta_{12}^{1} = 120,\ \theta_{12}^{2} = 60,\ \theta_{12}^{3} = 60,\ \theta_{12}^{4} = 215,$
$\theta_{12}^{5} = 109,\ \theta_{12}^{6} = 122,$

- the variable θ_{13}, the number of realizations $n_{13} = 11$,
realizations:

$\theta_{13}^{1} = 60,\ \theta_{13}^{2} = 105,\ \theta_{13}^{3} = 100,\ \theta_{13}^{4} = 60,$
$\theta_{13}^{5} = 275,\ \theta_{13}^{6} = 70,\ \theta_{13}^{7} = 80,\ \theta_{13}^{8} = 75,\ \theta_{13}^{9} = 298,$
$\theta_{13}^{10} = 182,\ \theta_{13}^{11} = 75,$

- the variable θ_{14}, the number of realizations $n_{14} = 2$,
realizations:

$\theta_{14}^{1} = 235,\ \theta_{14}^{2} = 70,$

- the variable θ_{15}, the number of realizations $n_{15} = 0$,
realizations:

there are no realizations,

- the variable θ_{21}, the number of realizations $n_{21} = 6$,
realizations:

$\theta_{21}^{1} = 180,\ \theta_{21}^{2} = 120,\ \theta_{21}^{3} = 120,\ \theta_{21}^{4} = 200,$
$\theta_{21}^{5} = 137,\ \theta_{21}^{6} = 595,$

- the variable θ_{22}, the number of realizations $n_{22} = 0$,
realizations:

θ_{22}^{k} - these realizations are not possible,
- the variable θ_{23}, the number of realizations $n_{23} = 8$,
realizations:

$\theta_{23}^{1} = 360,\ \theta_{23}^{2} = 290,\ \theta_{23}^{3} = 60,\ \theta_{23}^{4} = 180,$
$\theta_{23}^{5} = 140,\ \theta_{23}^{6} = 60,\ \theta_{23}^{7} = 60,\ \theta_{23}^{8} = 220,$

- the variable θ_{24}, the number of realizations $n_{24} = 3$,
realizations:

$\theta_{24}^{1} = 120,\ \theta_{24}^{2} = 330,\ \theta_{24}^{3} = 240,$

- the variable θ_{25}, the number of realizations $n_{25} = 1$,
realizations:

$\theta_{25}^{1} = 240,$

- the variable θ_{31}, the number of realizations $n_{31} = 8$,
realizations:
$\theta_{31}^{1} = 60,\ \theta_{31}^{2} = 120,\ \theta_{31}^{3} = 190,\ \theta_{31}^{4} = 200,$
$\theta_{31}^{5} = 410,\ \theta_{31}^{6} = 440,\ \theta_{31}^{7} = 250,\ \theta_{31}^{8} = 280,$

- the variable θ_{32}, the number of realizations $n_{32} = 10$,
realizations:

$\theta_{32}^{1} = 180,\ \theta_{32}^{2} = 165,\ \theta_{32}^{3} = 180,\ \theta_{32}^{4} = 120,$
$\theta_{32}^{5} = 180,\ \theta_{32}^{6} = 410,\ \theta_{32}^{7} = 255,\ \theta_{32}^{8} = 150,$
$\theta_{32}^{9} = 495,\ \theta_{32}^{10} = 1105,$

- the variable θ_{33}, the number of realizations $n_{33} = 0$,
realizations:

θ_{33}^{k} - these realizations are not possible,

- the variable θ_{34}, the number of realizations $n_{34} = 2$,
realizations:

$\theta_{34}^{1} = 310,\ \theta_{34}^{2} = 270,$

- the variable θ_{35}, the number of realizations $n_{35} = 2$,
realizations:

$\theta_{35}^{1} = 180,\ \theta_{35}^{2} = 360,$

- the variable θ_{41}, the number of realizations $n_{41} = 2$,
realizations:

$\theta_{41}^{1} = 175,\ \theta_{41}^{2} = 140,$

- the variable θ_{42}, the number of realizations $n_{42} = 2$,
realizations:

$\theta_{42}^{1} = 180,\ \theta_{42}^{2} = 180,$

- the variable θ_{43}, the number of realizations $n_{43} = 2$,
realizations:

$\theta_{43}^{1} = 135,\ \theta_{43}^{2} = 180,$

- the variable θ_{44}, the number of realizations $n_{44} = 0$,
realizations:

θ_{44}^{k} - these realizations are not possible,

- the variable θ_{45}, the number of realizations $n_{45} = 1$,
realizations:

$\theta_{45}^{1} = 150,$

- the variable θ_{51}, the number of realizations $n_{51} = 2$, realizations:

$\theta_{51}^1 = 240, \ \theta_{51}^2 = 360,$

- the variable θ_{52}, the number of realizations $n_{52} = 0$, realizations:

there are no realizations,

- the variable θ_{53}, the number of realizations $n_{53} = 2$, realizations:

$\theta_{53}^1 = 180, \ \theta_{53}^2 = 720,$

- the variable θ_{54}, the number of realizations $n_{54} = 0$, realizations:

there are no realizations.

- the variable θ_{55}, the number of realizations $n_{55} = 0$, realizations:

θ_{55}^k - these realizations are not possible.

5.2.4. Evaluating the unknown parameters of the shipyard ship-rope elevator operation process

On the basis of the statistical data from Section 4.2.3, using the formulae given in Section 3.3, it is possible to evaluate

- the vector of realizations

$[p(0)] = [0.4211, 0.3684, 0.2105, 0, 0]$

of 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 $t = 0$,

- the matrix of realizations

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

of 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 during the experiment time $\Theta = 616$ days.

Until now there are too small numbers of realizations to determine, presented in Section 3.4 empirical characteristics of the realizations of the conditional sojourn time of the system operation process in the particular operation states.

5.2.5. Identifying the distributions of the conditional sojourn times in the operation states of the shipyard ship-rope elevator

The realizations of the system operation process sojourn times θ_{bl}, in the state z_b while the next transition is to the state z_l may allow us to formulate and to verify the hypotheses about their conditional distribution functions $H_{bl}(t)$. Unfortunately until now there are too small numbers of realizations to formulate any hypotheses about the distributions of the conditional sojourn times in the particular operation states.

5.2.6. Identifying the mean values of the system conditional sojourn times in operation states of the shipyard ship-rope elevator

Due to the fact pointed in Section 5.2.5, the conditional empirical mean values $M_{bl} = E[\theta_{bl}]$, $b, l = 1,2,...,5, \ b \neq l,$ of the sojourn times in the particular operation states on the basis of the realizations of the ship-rope elevator operation process conditional sojourn times θ_{bl} and after applying formula the (7) are estimated and they amount:

$$M_{12} = 114.33, \ M_{13} = 125.45, \ M_{14} = 152.50,$$
$$M_{21} = 225.33, \ M_{23} = 171.25, \ M_{24} = 230.00,$$
$$M_{25} = 240.00, \ M_{31} = 243.75, \ M_{32} = 324.00,$$
$$M_{34} = 290.00, \ M_{35} = 270.00, \ M_{41} = 157.50,$$
$$M_{42} = 180.00, \ M_{43} = 157.50, \ M_{45} = 150.00,$$
$$M_{51} = 300.00, \ M_{53} = 450.00.$$

As there are no realizations of conditional sojourn times θ_{15}, θ_{52} and θ_{54} it is impossible to estimate their conditional mean values M_{15}, M_{52} and M_{54}.

5.3. Statistical identification 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 22*.

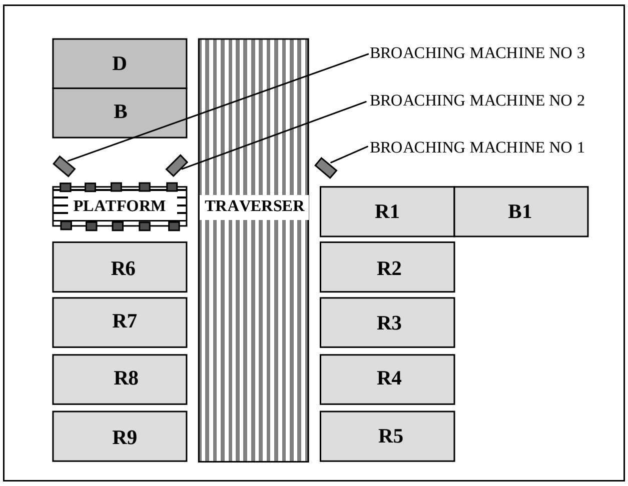

Figure 22. The scheme of the plan of repair post placing

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}, $b = 1,2,...,7,$ $b \neq l,$ 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}, $b = 1,2,...,7,$ $b \neq l,$ in the particular operation states and their mean values.

To identify all these parameters of the ground ship-rope transporter operation process the statistical data about this process is needed. The statistical data that has been collected is given in the Appendix 3A in *Tables 2-21* [4]. From data given in these Tables, on the basis of methods and procedures given in the previous sections, in further sections the ground ship-rope transporter operation process statistical data are fixed and its unknown parameters are estimated.

5.3.3. The shipyard ground ship-rope transporter operation process data collection

The collected statistical data necessary to evaluating the initial transient probabilities of the ground ship-rope transporter operation process in the particular states are:

- the ground ship-rope transporter operation process observation/experiment time $\Theta = 616$ days,

- the number of the ground ship-rope transporter operation process realizations $n(0) = 19$,

- the realization $n_b(0)$ of the number of the ground ship-rope transporter operation process transients in the particular operation states z_b at the initial moment $t = 0$

$$n_1(0) = 12,\ n_2(0) = 2,\ n_3(0) = 3,\ n_4(0) = 0,$$

$$n_5(0) = 0,\ n_6(0) = 0,\ n_7(0) = 2,$$

- the vector of realizations of the numbers of the ground ship-rope transporter operation process transitions in the particular operation states z_b at the initial moment $t = 0$

$$[n_b(0)] = [n_1(0), n_2(0), n_3(0), n_4(0), n_5(0), n_6(0), n_7(0)]$$

$$= [12,2,3,0,0,0,2].$$

The collected statistical data necessary to evaluating the transition probabilities of the ground ship-rope transporter operation process between the operation states are:

- the realization n_{bl} of the numbers of ground ship-rope transporter operation process transitions from the state z_b into the state z_l during the experiment time $\Theta = 616$ days

$$n_{12} = 27,\ n_{13} = 6,\ n_{14} = 1,\ n_{16} = 2,$$
$$n_{21} = 26,\ n_{23} = 7,\ n_{25} = 1,\ n_{26} = 5,\ n_{27} = 3,$$
$$n_{32} = 14,$$
$$n_{41} = 1,\ n_{46} = 1,$$
$$n_{51} = 1,\ n_{56} = 1,$$
$$n_{61} = 6,\ n_{63} = 1,\ n_{64} = 1,\ n_{67} = 1,$$
$$n_{71} = 1,\ n_{72} = 2,\ n_{75} = 1,$$

- the matrix of realizations n_{bl} of the numbers of the ground ship-rope transporter operation process transitions from the state z_b into the state z_l during the experiment time $\Theta = 616$ days

$$[n_{bl}] = \begin{bmatrix} 0 & 27 & 6 & 1 & 0 & 2 & 0 \\ 26 & 0 & 7 & 0 & 1 & 5 & 3 \\ 0 & 14 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 6 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 2 & 0 & 0 & 1 & 0 & 0 \end{bmatrix},$$

- the realization n_b of the total numbers of the ground ship-rope transporter operation process transitions from the operation state z_b during the experiment time $\Theta = 616$ days (the sums of the numbers of the matrix $[n_{bl}]$)

$n_1 = 36,\ n_2 = 42,\ n_3 = 14,\ n_4 = 2,\ n_5 = 2,$
$n_6 = 9,\ n_7 = 4,$

- the matrix of realizations of the total numbers of the ground ship-rope transporter operation process transitions from the operation state z_b during the experiment time $\Theta = 616$ days

$$[n_b] = [n_1, n_2, n_3, n_4, n_5, n_6, n_7] = [36,42,14,2,2,9,4].$$

The collected statistical data necessary to evaluating the unknown parameters of the distributions of the conditional sojourn times of the ground ship-rope transporter operation process in the particular operation states are as follows:

- the realizations θ_{bl}^k, k = 1,2, …, n_{bl}, of the conditional sojourn times θ_{bl} of the ground ship-rope transporter operation process at the operation state z_b when the next transition is to the operation state z_l during the observation time:

- the variable θ_{11}, the number of realizations n_{11} = 0, realizations:

θ_{11}^k - these realizations are not possible,

- the variable θ_{12}, the number of realizations $n_{12} = 27$,
realizations:

$\theta_{12}^1 = 40,\ \theta_{12}^2 = 45,\ \theta_{12}^3 = 240,\ \theta_{12}^4 = 80,$
$\theta_{12}^5 = 205, \theta_{12}^6 = 45,\ \theta_{12}^7 = 50,\ \theta_{12}^8 = 50,$
$\theta_{12}^9 = 80,\ \theta_{12}^{10} = 115,\ \theta_{12}^{11} = 60,\ \theta_{12}^{12} = 70,$
$\theta_{12}^{13} = 155,\ \theta_{12}^{14} = 125,\ \theta_{12}^{15} = 40,\ \theta_{12}^{16} = 265,$
$\theta_{12}^{17} = 145,\ \theta_{12}^{18} = 40,\ \theta_{12}^{19} = 60,\ \theta_{12}^{20} = 40,$
$\theta_{12}^{21} = 140,\ \theta_{12}^{22} = 192,\ \theta_{12}^{23} = 33,\ \theta_{12}^{24} = 15,$
$\theta_{12}^{25} = 185,\ \theta_{12}^{26} = 65,\ \theta_{12}^{27} = 170,$

- the variable θ_{13}, the number of realizations $n_{13} = 6$, realizations:

$\theta_{13}^1 = 135,\ \theta_{13}^2 = 125,\ \theta_{13}^3 = 100,\ \theta_{13}^4 = 390,$
$\theta_{13}^5 = 115,\ \theta_{13}^6 = 210,$

- the variable θ_{14}, the number of realizations $n_{14} = 1$, realizations:

$\theta_{14}^1 = 145,$

- the variable θ_{15}, the number of realizations $n_{15} = 0$, realizations:

there are no realizations,

- the variable θ_{16}, the number of realizations $n_{16} = 2$, realizations:

$\theta_{16}^1 = 250,\ \theta_{16}^2 = 180,$

- the variable θ_{17}, the number of realizations $n_{17} = 0$, realizations:
there are no realizations,

- the variable θ_{21}, the number of realizations $n_{21} = 26$,
realizations:

$\theta_{21}^1 = 45,\ \theta_{21}^2 = 55,\ \theta_{21}^3 = 35,\ \theta_{21}^4 = 40,$
$\theta_{21}^5 = 75,\ \theta_{21}^6 = 270,\ \theta_{21}^7 = 55,\ \theta_{21}^8 = 50,$
$\theta_{21}^9 = 115,\ \theta_{21}^{10} = 70,\ \theta_{21}^{11} = 35,\ \theta_{21}^{12} = 205,$
$\theta_{21}^{13} = 130,\ \theta_{21}^{14} = 240,\ \theta_{21}^{15} = 30,\ \theta_{21}^{16} = 190,$
$\theta_{21}^{17} = 60,\ \theta_{21}^{18} = 15,\ \theta_{21}^{19} = 20,\ \theta_{21}^{20} = 65,$
$\theta_{21}^{21} = 60,\ \theta_{21}^{22} = 75,\ \theta_{21}^{23} = 45,\ \theta_{21}^{24} = 60,$
$\theta_{21}^{25} = 40,\ \theta_{21}^{26} = 40,$

- the variable θ_{22}, the number of realizations $n_{22} = 0$, realizations:

θ_{22}^k - these realizations are not possible,

- the variable θ_{23}, the number of realizations $n_{23} = 7$,
realizations:

$\theta_{23}^{1} = 27,\ \theta_{23}^{2} = 20,\ \theta_{23}^{3} = 15,\ \theta_{23}^{4} = 75,$
$\theta_{23}^{5} = 40,\ \theta_{23}^{6} = 60,\ \theta_{23}^{7} = 50,$

- the variable θ_{24}, the number of realizations $n_{24} = 0$, realizations:

there are no realizations,

- the variable θ_{25}, the number of realizations $n_{25} = 1$, realizations:

$\theta_{25}^{1} = 32,$

- the variable θ_{26}, the number of realizations $n_{26} = 5$, realizations:

$\theta_{26}^{1} = 50,\ \theta_{26}^{2} = 70,\ \theta_{26}^{3} = 45,\ \theta_{26}^{4} = 45,\ \theta_{26}^{5} = 40,$

- the variable θ_{27}, the number of realizations $n_{27} = 3$, realizations:

$\theta_{27}^{1} = 90,\ \theta_{27}^{2} = 165,\ \theta_{27}^{3} = 70,$

- the variable θ_{31}, the number of realizations $n_{31} = 0$, realizations:

there are no realizations,

- the variable θ_{32}, the number of realizations $n_{32} = 14$, realizations:

$\theta_{32}^{1} = 95,\ \theta_{32}^{2} = 25,\ \theta_{32}^{3} = 20,\ \theta_{32}^{4} = 25,\ \theta_{32}^{5} = 62,$
$\theta_{32}^{6} = 60,\ \theta_{32}^{7} = 70,\ \theta_{32}^{8} = 45,\ \theta_{32}^{9} = 70,\ \theta_{32}^{10} = 50,$
$\theta_{32}^{11} = 90,\ \theta_{32}^{12} = 60,\ \theta_{32}^{13} = 55,\ \theta_{32}^{14} = 60,$

- the variable θ_{33}, the number of realizations $n_{33} = 0$, realizations:

θ_{33}^{k} - these realizations are not possible,

- the variable θ_{34}, the number of realizations $n_{34} = 0$, realizations:

there are no realizations,

- the variable θ_{35}, the number of realizations $n_{35} = 0$, realizations:

there are no realizations,

- the variable θ_{36}, the number of realizations $n_{36} = 0$, realizations:

there are no realizations,

- the variable θ_{37}, the number of realizations $n_{37} = 0$, realizations:

there are no realizations,

- the variable θ_{41}, the number of realizations $n_{41} = 1$, realizations:

$\theta_{41}^{1} = 150,$

- the variable θ_{42}, the number of realizations $n_{42} = 0$, realizations:

there are no realizations,

- the variable θ_{43}, the number of realizations $n_{43} = 0$, realizations:

there are no realizations,

- the variable θ_{44}, the number of realizations $n_{44} = 0$, realizations:

θ_{44}^{k} - these realizations are not possible,

- the variable θ_{45}, the number of realizations $n_{45} = 0$, realizations:

there are no realizations,

- the variable θ_{46}, the number of realizations $n_{46} = 1$, realizations:

$\theta_{46}^{1} = 70,$

- the variable θ_{47}, the number of realizations $n_{47} = 0$, realizations:

there are no realizations,

- the variable θ_{51}, the number of realizations $n_{51} = 1$, realizations:

$\theta_{51}^{1} = 240,$

- the variable θ_{52}, the number of realizations $n_{52} = 0$, realizations:

there are no realizations,

- the variable θ_{53}, the number of realizations $n_{53} = 0$, realizations:

there are no realizations,

- the variable θ_{54}, the number of realizations $n_{54} = 0$, realizations:

there are no realizations,

- the variable θ_{55}, the number of realizations $n_{55} = 0$, realizations:

θ_{55}^{k} - these realizations are not present,

- the variable θ_{56}, the number of realizations $n_{56} = 1$, realizations:

$\theta_{56}^{1} = 180,$

- the variable θ_{57}, the number of realizations $n_{57} = 0$, realizations:

there are no realizations,

- the variable θ_{61}, the number of realizations $n_{61} = 6$, realizations:
$\theta_{61}^{1} = 210,\ \theta_{61}^{2} = 210,\ \theta_{61}^{3} = 80,\ \theta_{61}^{4} = 180,$
$\theta_{61}^{5} = 180,\ \theta_{61}^{6} = 190,$

- the variable θ_{62}, the number of realizations $n_{62} = 0$, realizations:

there are no realizations,

- the variable θ_{63}, the number of realizations $n_{63} = 1$, realizations:

$\theta_{63}^{1} = 190,$

- the variable θ_{64}, the number of realizations $n_{64} = 1$, realizations:

$\theta_{64}^{1} = 190,$

- the variable θ_{65}, the number of realizations $n_{65} = 0$, realizations:
there are no realizations,

- the variable θ_{66}, the number of realizations $n_{66} = 0$, realizations:

θ_{66}^{k} - these realizations are not possible,

- the variable θ_{71}, the number of realizations $n_{71} = 1$, realizations:

$\theta_{71}^{1} = 245,$

- the variable θ_{72}, the number of realizations $n_{72} = 2$, realizations:

$\theta_{72}^{1} = 230,\ \theta_{72}^{2} = 240,$

- the variable θ_{73}, the number of realizations $n_{73} = 0$,
realizations:

there are no realizations,

- the variable θ_{74}, the number of realizations $n_{74} = 0$, realizations:

there are no realizations,

- the variable θ_{75}, the number of realizations $n_{75} = 1$, realizations:

$\theta_{75}^{1} = 60,$

- the variable θ_{76}, the number of realizations $n_{76} = 0$, realizations:

there are no realizations,

- the variable θ_{77}, the number of realizations $n_{77} = 0$, realizations:

θ_{77}^{k} - these realizations are not possible.

5.3.4. Evaluating the unknown parameters of the shipyard ground ship-rope transporter operation process

On the basis of the statistical data from Section 5.3.3, using the formulae given in Section 3.4, it is possible to evaluate

- the vector of realizations

$$[p(0)] = [0.6315,\ 0.1053, 0.1579, 0, 0, 0, 0.1053]$$

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

- the matrix of realizations

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

of 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 during the experiment time $\Theta = 616$ days.

On the basis of the statistical data from Section 5.3.3, using the formulae given in Section 3.4, it is possible to determine the following empirical characteristics of the realizations of the conditional sojourn time of the ground ship-rope transporter operation process in the particular operation states:

- the realizations of the mean values $\bar{\theta}_{12}$ of the conditional sojourn times θ_{12} of the ground ship-rope transporter operation process at the operation state z_1 when the next transition is to the operation state z_2

$$\bar{\theta}_{12} = \frac{1}{27}\sum_{k=1}^{27}\theta_{12}^k \cong 101.9 \quad b,l = 12,...,7 \quad b \neq l,$$

- the number $\bar{r}_{12}$ of the disjoint intervals $I_j =< a_{bl}^j, b_{bl}^j)$, $j = 1,2,...,\bar{r}_{12}$, that include the realizations θ_{12}^k, $k = 1,2,...,27$, of the conditional sojourn times θ_{12} at the operation state z_1 when the next transition is to the operation state z_2

$$\bar{r}_{12} \cong \sqrt{27} \cong 5,$$

- the length d_{12} of the intervals $I_j =< a_{bl}^j, b_{bl}^j)$, $j = 1,2,...,5$,

$$d_{12} = \frac{\bar{R}_{12}}{\bar{r}_{12} - 1} = \frac{250}{4} \cong 63$$

where

$$\bar{R}_{12} = \max_{1 \le k \le 27}\theta_{12}^k - \min_{1 \le k \le 27}\theta_{12}^k = 265 - 15 = 250,$$

- the ends a_{bl}^j, b_{bl}^j, of the intervals $I_j =< a_{bl}^j, b_{bl}^j)$, $j = 1,2,...,5$, according to the formulae

$$\min_{1 \le k \le 27}\theta_{12}^k - \frac{d_{12}}{2} = 15 - \frac{63}{2} = -16.5,$$

$$a_{12}^1 = \max\{-16.5, 0\} = 0,$$

$$b_{12}^1 = a_{12}^1 + 63 = 0 + 63 = 63,$$

$$a_{12}^2 = b_{12}^1 = 63, \quad b_{12}^2 = a_{12}^1 + 2 \cdot 63 = 0 + 126 = 126,$$

$$a_{12}^3 = b_{12}^2 = 126, \quad b_{12}^3 = a_{12}^1 + 3 \cdot 63 = 0 + 189 = 189,$$

$$a_{12}^4 = b_{12}^3 = 189, \quad b_{12}^4 = a_{12}^1 + 4 \cdot 63 = 0 + 252 = 252,$$

$$a_{12}^5 = b_{12}^4 = 252, \quad b_{12}^5 = a_{12}^1 + 5 \cdot 63 = 0 + 315 = 315,$$

- the numbers n_{12}^j of the realizations θ_{12}^k in particular intervals I_j, $j = 1,2,...,5$,

$$n_{12}^1 = 12, \; n_{12}^2 = 6, \; n_{12}^3 = 5, \; n_{12}^4 = 3, \; n_{12}^5 = 1,$$

Histogram of the conditional sojourn time θ_{12}					
$I_j =< a_{bl}^j, b_{bl}^j)$	0 – 63	63 – 126	126 – 189	189 – 252	252- 315
n_{12}^j	12	6	5	3	1
$\bar{h}_{12}(t) = n_{12}^j / n_{12}$	12/27	6/27	5/27	3/27	1/27

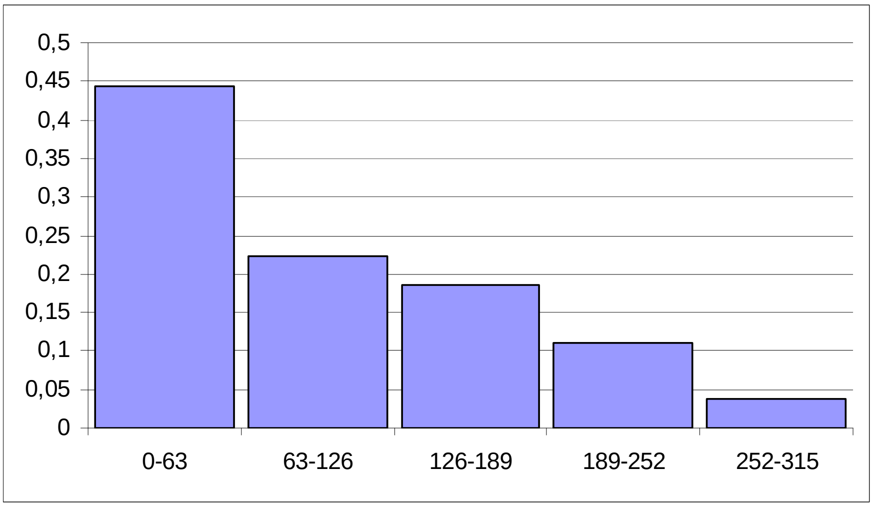

Figure 23. Histogram of the conditional sojourn time θ_{12}

- the realizations of the mean values $\bar{\theta}_{21}$ of the conditional sojourn times θ_{21} of the ground ship-rope transporter operation process at the operation state z_2 when the next transition is to the operation state z_1

$$\bar{\theta}_{21} = \frac{1}{26}\sum_{k=1}^{26}\theta_{21}^k \cong 81.5, \ b,l = 12,...,7 \ b \neq l,$$

- the number $\bar{r}_{21}$ of the disjoint intervals $I_j =< a_{bl}^j, b_{bl}^j)$, $j = 1,2,...,\bar{r}_{21}$, that include the realizations θ_{21}^k, $k = 1,2,...,26$, of the conditional sojourn times θ_{21} at the operation state z_2 when the next transition is to the operation state z_1

$$\bar{r}_{21} = \sqrt{26} \cong 5,$$

- the length d_{21} of the intervals $I_j =< a_{bl}^j, b_{bl}^j)$, $j = 1,2,...,5$,

$$d_{21} = \frac{\bar{R}_{12}}{\bar{r}_{21} - 1} = \frac{255}{4} \cong 64$$

where

$$\bar{R}_{21} = \max_{1\le k\le 26}\theta_{21}^k - \min_{1\le k\le 26}\theta_{21}^k = 270 - 15 = 255,$$

- the ends a_{bl}^j, b_{bl}^j, of the intervals $I_j =< a_{bl}^j, b_{bl}^j)$, $j = 1,2,...,5$, according to the formulae

$$\min_{1\le k\le 26}\theta_{21}^k - \frac{d_{21}}{2} = 15 - \frac{64}{2} = -17,$$

$$a_{21}^1 = \max\{-17, 0\} = 0, \ b_{21}^1 = a_{21}^1 + 64 = 0 + 64 = 64,$$

$$a_{21}^2 = b_{21}^1 = 64, \ b_{21}^2 = a_{21}^1 + 2\cdot 64 = 0 + 128 = 128,$$

$$a_{21}^3 = b_{21}^2 = 128, \ b_{21}^3 = a_{21}^1 + 3\cdot 64 = 0 + 192 = 192,$$

$$a_{21}^4 = b_{21}^3 = 192, \ b_{21}^4 = a_{21}^1 + 4\cdot 64 = 0 + 256 = 256,$$

$$a_{21}^5 = b_{21}^4 = 256, \ b_{21}^5 = a_{21}^1 + 5\cdot 64 = 0 + 320 = 320,$$

- the numbers n_{21}^j of the realizations θ_{21}^k in particular intervals I_j, $j = 1,2,...,5$,

$$n_{21}^1 = 16, \ n_{21}^2 = 5, \ n_{21}^3 = 2, \ n_{21}^4 = 2, \ n_{21}^5 = 1.$$

Histogram of the conditional sojourn time θ_{21}					
$I_j =< a_{bl}^j, b_{bl}^j)$	0 – 64	64 – 128	128 – 192	192 – 256	256- 320
n_{21}^j	16	5	2	2	1
$\bar{h}_{21}(t) = n_{21}^j / n_{21}$	16/26	5/26	2/26	2/26	1/26

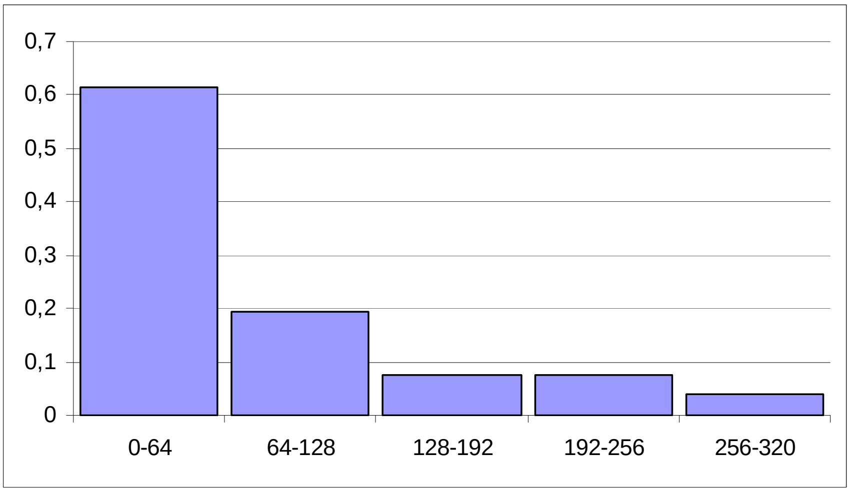

Figure 24. Histogram of the conditional sojourn time θ_{21}

5.3.5. Identifying the distributions of the conditional sojourn times in the operation states of the shipyard ground ship-rope transporter

Using the procedure given in Section 3.5 we may verify hypotheses on the distributions of the conditional sojourn times θ_{bl}, $b, l = 1,2,...,7,\ b \neq l,$ in the particular operation states. At the moment, because of the lack of statistical data coming from experiment it was possible to verify only two hypotheses on the distributions of the sojourn times. Namely, we have the following results:

- the conditional sojourn time θ_{12} has an exponential distribution with the density function

$$h_{12}(t) = \begin{cases} 0, & t < 0, \\ 0.0098\exp[-0.0098t], & t \geq 0, \end{cases}$$

- the conditional sojourn time θ_{21} has an exponential distribution with the density function

$$h_{21}(t) = \begin{cases} 0, & t < 0, \\ 0.0123\exp[-0.0123t], & t \geq 0. \end{cases}$$

5.3.6. Identifying the mean values of the system conditional sojourn times in operation states of the shipyard ground ship-rope transporter

For the above distributions identified in Section 5.3.5, using either the formulae (8) or (13), we can find the following mean values of the conditional sojourn times in the particular operation states:

$$M_{12} = 102.04,\ M_{21} = 81.30.$$

In the remaining cases not identified in Section 5.3.5 distributions, using formula (7), it is possible to find only the approximate values of the empirical mean values $M_{bl} = E[\theta_{bl}]$ of the conditional sojourn times in the particular operation states that are as follows:

$$M_{13} = 179.17,\ M_{14} = 145,\ M_{16} = 215,$$
$$M_{23} = 41,\ M_{25} = 32,\ M_{26} = 50,\ M_{27} = 108.33,$$
$$M_{32} = 56.21,$$
$$M_{41} = 150,\ M_{46} = 70,$$
$$M_{51} = 240,\ M_{56} = 180,$$
$$M_{61} = 175,\ M_{63} = 190,\ M_{64} = 190,\ M_{67} = 150,$$
$$M_{71} = 245,\ M_{72} = 235,\ M_{75} = 60.$$

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}.

5.4. Statistical identification 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. Her owner is Stena Line Scandinavia AB. She was build in Gdańsk Shipyard in 2005. She is characterized by the following parameters: the length of 164.41m, the breadth moulded of 27.60 m, the summer load draft of 6.313 m, DWT of 4456, the displacement of 16618 tons, the cargo capacity of 466 cars, the total numbers of passengers and crew capacity of 1200 + 96 = 1296. The number of cabins is 379 with the number of beds 949 and total number of seats on a board is 981. The main engines are 4 of the kind MAN 4840 kW, the propellers are 2 of the kind Ka Me Wa with diameter 4800 mm, the BOW thrusters are 2 of the kind 1275 kW and 735 kW and the aft thruster is 1 of the kind 735 kW. The navigation and communication equipments are according to SOLAS Convention. The ferry speed is 19.5 knots (calm water) (RPM – 178). The service restriction are: maximum of 350 NM from land and wave height of 3.1 m, according to the Stockholm Agreement.

We assume that the ferry is composed of a number of main subsystems having an essential influence on its safety. These subsystems are illustrated in *Figure 25*. On the scheme of the ferry presented in *Figure 25*, there are distinguished its 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.

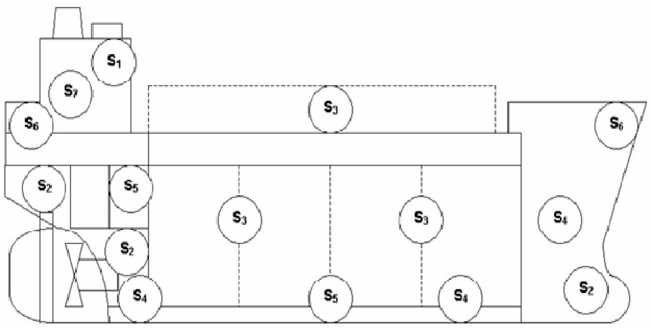

Figure 25. Subsystems having an essential influence on ferry safety

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

- the transition probabilities p_{bb+1}, $b = 1,2,...,17$, and p_{181} of the Stena Baltica ferry operation process from the operation state z_b into the operation state z_{b+1} 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 θ_{181} in the particular operation states and their mean values.

To identify all these parameters of the Stena Baltica ferry operation process the statistical data about this process is needed. The statistical data that has been collected during spring is given in the Appendix 4A in *Tables 1-7* [7].
From data given in these Tables, on the basis of methods and procedures given in the previous section, in further sections the Stena Baltica ferry operation process statistical data is fixed and its unknown parameters are estimated.

5.4.3. The Stena Baltica ferry operation process data collection

The collected statistical data necessary to evaluating the initial transient probabilities of the Stena Baltica ferry operation process in the particular states are:

- the ship operation process observation/experiment time $\Theta = 42$ days,

- the number of the ship operation process realizations $n(0) = 42$,

- the numbers $n_b(0)$ of the system operation process transients in the particular operation states z_b at the initial moment $t = 0$

$$n_1(0) = 42,\ n_2(0) = 0,\ \ldots,\ n_{18}(0) = 0,$$

where

$$n_1(0) + n_2(0) + \ldots + n_\nu(0) = 42,$$

- the vector of realizations of the numbers of the system operation process transients in the particular operation states z_b at the initial moment $t = 0$

$$[n_b(0)] = [n_1(0), n_2(0), ..., n_\nu(0)] = [42,0,...,0].$$

The collected statistical data necessary to evaluating the transition probabilities of the Stena Baltica ferry operation process between the operation states are:

- the realization n_{bl} of the numbers of the ship operation process transitions from the state z_b into the state z_l during the experiment time $\Theta = 42$ days

$$n_{11} = 0,\ n_{12} = 42,\ n_{13} = 0, ...,\ n_{117} = 0,\ n_{118} = 0,$$
$$n_{21} = 0,\ n_{22} = 0,\ n_{23} = 42,\ \ldots,\ n_{217} = 0,\ n_{218} = 0,$$
$$\ldots$$
$$n_{171} = 0,\ n_{172} = 0,\ n_{173} = 0,\ \ldots,\ n_{1717} = 0,\ n_{1718} = 42,$$

$$n_{181} = 42,\ n_{182} = 0,\ n_{183} = 0,\ \ldots,\ n_{1817} = 0,\ n_{1818} = 0,$$

- the matrix of realizations n_{bl} of the numbers of the ferry operation process transitions from the state z_b into the state z_l during the experiment time $\Theta = 42$ days

$$[n_{bl}] = \begin{bmatrix} 0 & 42 & 0 \ldots 0 & 0 \\ 0 & 0 & 42 \ldots 0 & 0 \\ \ldots & & & \\ 0 & 0 & 0 \ldots 0 & 42 \\ 42 & 0 & 0 \ldots 0 & 0 \end{bmatrix},$$

- the realization n_b of the total numbers of the ship operation process transitions from the operation state z_b during the experiment time $\Theta = 42$ days (the sums of the numbers of the matrix $[n_{bl}]$)

$$n_1 = n_{11} + n_{12} + \ldots + n_{118} = 42,$$
$$n_2 = n_{21} + n_{22} + \ldots + n_{218} = 42,$$
$$\ldots$$
$$n_{17} = n_{171} + n_{172} + \ldots + n_{1718} = 42,$$
$$n_{18} = n_{181} + n_{182} + \ldots + n_{1818} = 42,$$

- the matrix of realizations of the total numbers of the ship operation process transitions from the operation state z_b during the experiment time $\Theta = 42$ days

$$[n_b] = [n_1, n_2, ..., n_\nu] = [42,42,...,42].$$

The collected statistical data necessary to evaluating the unknown parameters of the distributions of the conditional sojourn times of the Stena Baltica ferry operation process in the particular operation states are as follows:

- the realizations θ_{bl}^{k}, $k = 1,2, \ldots, n_{bl}$, of the conditional sojourn times θ_{bl} of the Stena Baltica ferry operation process at the operation state z_b when the next transition is to the operation state z_l during the observation time are given in the *Tables 1-7*. In the *Tables 1-7* there are given realizations of the conditional sojourn times in particular operation states on the basis of a sample composed of $n = 42$ realizations of the Stena Baltica ferry operation process. It is assumed that one voyage from Gdynia to Karlskrone and back to Gdynia of the ferry is a single realization of its operation process. The conditional sojourn times in particular operation states of each single realization of the ferry operation process are given in minutes in separate columns. The operation process is very regular in the sense that the operation state changes are from the particular state z_b, $b = 1,2,\ldots,17$, to the neighbouring state z_{b+1}, $b = 1,2,\ldots,17$, only and from z_{18} to z_1. Therefore, the realizations of the conditional sojourn times θ_{bb+1}^{j}, $b = 1,2,\ldots,17$, $j = 1,2,\ldots,42$, are given in the Tables b-th row and the realizations of the conditional sojourn time $\theta_{18\,1}^{j}$, $b = 1,2,\ldots,17$, are given in the Tables 18-th row.

Table 1. Realization of conditional sojourn times θ_{bl} at operations states

Operation state z_b	θ_{bb+1}^{1}	θ_{bb+1}^{2}	θ_{bb+1}^{3}	θ_{bb+1}^{4}	θ_{bb+1}^{5}	θ_{bb+1}^{6}
z_1	55	52	47	75	60	60
z_2	4	3	3	2	2	2
z_3	28	31	32	35	37	48
z_4	52	46	48	65	53	47
z_5	598	635	539	572	499	507
z_6	35	42	42	44	35	37
z_7	7	9	8	7	7	5
z_8	25	20	23	27	20	31
z_9	75	59	56	40	66	47
z_{10}	5	3	2	3	2	3
z_{11}	6	5	4	5	4	5
z_{12}	25	22	25	25	23	25
z_{13}	574	427	461	501	498	490
z_{14}	61	43	43	46	49	52
z_{15}	33	32	33	36	35	33
z_{16}	4	4	5	4	4	4
z_{17}	8	10	6	5	5	6
z_{18}	26	26	30	20	16	17

Table 2. Realization of conditional sojourn times θ_{bl} at operations states

Operation state z_b	θ_{bb+1}^{7}	θ_{bb+1}^{8}	θ_{bb+1}^{9}	θ_{bb+1}^{10}	θ_{bb+1}^{11}	θ_{bb+1}^{12}
z_1	62	43	50	61	65	63
z_2	2	3	3	4	3	2
z_3	33	38	39	43	40	42
z_4	49	62	45	46	51	47
z_5	621	580	507	511	497	496
z_6	34	40	36	33	38	38
z_7	5	5	5	5	8	7
z_8	15	17	16	21	33	34
z_9	26	60	65	25	55	40
z_{10}	5	6	3	4	4	2
z_{11}	4	4	4	6	4	5
z_{12}	20	33	24	24	22	22
z_{13}	438	561	491	513	496	500
z_{14}	42	63	46	60	50	50
z_{15}	35	34	31	33	34	36
z_{16}	3	4	4	4	4	4
z_{17}	4	5	8	7	6	7
z_{18}	16	22	17	8	17	17

Table 3. Realization of conditional sojourn times θ_{bl} at operations states

Operation state z_b	θ_{bb+1}^{13}	θ_{bb+1}^{14}	θ_{bb+1}^{15}	θ_{bb+1}^{16}	θ_{bb+1}^{17}	θ_{bb+1}^{18}
z_1	45	45	40	20	33	50
z_2	2	2	2	2	2	3
z_3	35	36	36	36	37	35
z_4	51	51	51	49	53	44
z_5	595	495	504	507	498	483
z_6	34	39	38	39	38	35
z_7	7	8	7	10	8	8
z_8	18	16	13	3	15	6
z_9	75	77	60	73	82	118
z_{10}	5	2	2	2	3	4

z_{11}	4	4	4	4	4	4
z_{12}	24	24	25	24	23	22
z_{13}	582	491	499	488	464	484
z_{14}	72	50	48	50	48	52
z_{15}	34	35	35	34	35	34
z_{16}	5	5	5	4	4	4
z_{17}	7	7	6	4	4	7
z_{18}	26	40	21	34	40	35

Table 4. Realization of conditional sojourn times θ_{bl} at operations states

Operation state z_b	θ^{19}_{bb+1}	θ^{20}_{bb+1}	θ^{21}_{bb+1}	θ^{22}_{bb+1}	θ^{23}_{bb+1}	θ^{24}_{bb+1}
z_1	43	15	45	57	97	68
z_2	2	2	3	2	2	3
z_3	34	34	36	36	39	36
z_4	51	52	50	53	53	54
z_5	497	504	507	503	500	492
z_6	37	36	37	34	38	40
z_7	7	8	8	8	7	9
z_8	9	25	19	31	30	35
z_9	71	55	30	24	34	41
z_{10}	2	2	3	3	2	5
z_{11}	4	4	4	4	4	4
z_{12}	23	22	22	22	26	22
z_{13}	498	496	505	595	493	499
z_{14}	47	53	51	61	61	48
z_{15}	31	32	33	46	34	34
z_{16}	5	5	3	4	6	6
z_{17}	5	5	7	5	4	5
z_{18}	28	22	8	2	12	13

Table 5. Realization of conditional sojourn times θ_{bl} at operations states

Operation state z_b	θ^{25}_{bb+1}	θ^{26}_{bb+1}	θ^{27}_{bb+1}	θ^{28}_{bb+1}	θ^{29}_{bb+1}	θ^{30}_{bb+1}
z_1	58	35	45	75	72	62
z_2	3	4	3	3	2	3
z_3	37	36	35	39	37	36
z_4	67	51	50	62	49	48
z_5	573	498	506	576	494	505
z_6	36	37	35	38	38	36
z_7	8	7	5	7	10	9
z_8	25	11	17	31	23	25
z_9	55	55	43	45	52	48
z_{10}	3	3	3	3	2	3
z_{11}	4	4	5	5	4	5
z_{12}	23	22	23	26	23	23
z_{13}	573	497	531	500	492	496
z_{14}	58	51	54	47	40	51
z_{15}	34	35	33	35	35	34
z_{16}	5	5	6	5	4	6
z_{17}	4	5	5	5	7	6
z_{18}	18	20	11	10	16	18

Table 6. Realization of conditional sojourn times θ_{bl} at operations states

Operation state z_b	θ^{31}_{bb+1}	θ^{32}_{bb+1}	θ^{33}_{bb+1}	θ^{54}_{bb+1}	θ^{35}_{bb+1}	θ^{36}_{bb+1}
z_1	37	44	46	78	59	65
z_2	6	3	2	2	2	2
z_3	37	36	36	37	36	36
z_4	64	51	53	63	55	53
z_5	576	495	502	574	492	497
z_6	35	39	37	36	38	37
z_7	10	6	7	7	6	6
z_8	23	15	18	19	18	24
z_9	50	58	53	30	30	45
z_{10}	2	2	3	3	2	2
z_{11}	4	5	4	5	4	4
z_{12}	24	23	24	23	28	24
z_{13}	590	508	520	502	508	508
z_{14}	47	47	56	47	46	42
z_{15}	33	34	35	36	35	35
z_{16}	5	5	4	4	5	4
z_{17}	5	6	6	10	5	4
z_{18}	25	18	12	12	17	14

Table 7. Realization of conditional sojourn times θ_{bl} at operations states

Operation state z_b	θ_{bb+1}^{37}	θ_{bb+1}^{38}	θ_{bb+1}^{39}	θ_{bb+1}^{40}	θ_{bb+1}^{41}	θ_{bb+1}^{42}
z_1	53	25	55	84	71	67
z_2	2	2	3	2	2	2
z_3	38	37	40	36	37	34
z_4	60	49	46	57	53	51
z_5	584	504	505	573	494	495
z_6	38	35	36	39	36	36
z_7	5	7	5	5	6	6
z_8	15	6	40	28	32	28
z_9	70	35	35	47	40	50
z_{10}	2	2	3	3	3	2
z_{11}	5	4	5	5	4	4
z_{12}	25	25	24	23	26	24
z_{13}	595	506	535	506	503	503
z_{14}	42	45	47	46	51	43
z_{15}	34	35	34	34	33	33
z_{16}	6	4	4	5	5	4
z_{17}	5	3	4	5	3	5
z_{18}	20	11	11	10	13	18

5.4.4. Evaluating the unknown parameters of the Stena Baltica ferry operation process

On the basis of the statistical data from Section 5.4.3, using the formulae given in Section 3.4, it is possible to evaluate

- the vector of realizations

$$[p(0)] = [1,0,0,...,0,0]$$

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

- the matrix of realizations

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

of the transition probabilities $p_{bl},\ b,l = 1,2,...,18,$ of the system operation process from the operation state z_b into the operation state z_l during the experiment time $\Theta = 42$ days.

On the basis of the statistical data from Section 5.4.3, using the formulae given in Section 3.4, it is possible to determine the following empirical characteristics of the realizations of the conditional sojourn time of the Stena Baltica ferry operation process in the particular operation states:

- the realizations of the mean values $\bar{\theta}_{12}$ of the conditional sojourn times θ_{12} of the Stena Baltia ferry operation process at the operation state z_1 when the next transition is to the operation state z_2

$$\bar{\theta}_{12} = \frac{1}{42}\sum_{k=1}^{42}\theta_{12}^{k} = 54.3,\ \ b,l = 12,...,18\ \ b \neq l,$$

- the number $\bar{r}_{12}$ of the disjoint intervals $I_j = < a_{bl}^j, b_{bl}^j),\ j = 1,2,...,\bar{r}_{12},$ that include the realizations $\theta_{12}^k,\ k = 1,2,...,42,$ of the conditional sojourn times θ_{12} at the operation state z_1 when the next transition is to the operation state z_2

$$\bar{r}_{12} = \sqrt{n_{bl}} = \sqrt{42} \cong 6,$$

- the length d_{12} of the intervals $I_j = < a_{bl}^j, b_{bl}^j),\ j = 1,2,...6,$

$$d_{12} = \frac{\bar{R}}{\bar{r}_{12} - 1} = \frac{82}{5} \cong 16,$$

where

$$\bar{R}_{12} = \max_{1\le k\le 42}\theta_{12}^k - \min_{1\le k\le 42}\theta_{12}^k = 97 - 15 = 82,$$

- the ends $a_{bl}^j,\ b_{bl}^j,$ of the intervals $I_j = < a_{bl}^j, b_{bl}^j),$ $j = 1,2,...6,$ according to the formulae

$$\min_{1\le k\le 42}\theta_{12}^k - \frac{d_{12}}{2} = 15 - \frac{16}{2} = 15 - 8 = 7,$$

$$a_{12}^1 = \max\{7, 0\} = 7,$$

$$b_{12}^1 = a_{12}^1 + d = 7 + 16 = 23,$$

$$a_{12}^2 = b_{12}^1 = 23,\ \ b_{12}^2 = a_{12}^1 + 2\cdot 16 = 7 + 32 = 39,$$

$a_{12}^{3} = b_{12}^{2} = 39, \ b_{12}^{3} = a_{12}^{1} + 3 \cdot 16 = 7 + 48 = 55,$

$a_{12}^{4} = b_{12}^{3} = 55, \ b_{12}^{4} = a_{12}^{1} + 4 \cdot 16 = 7 + 64 = 71,$

$a_{12}^{5} = b_{12}^{4} = 71, \ b_{12}^{5} = a_{12}^{1} + 5 \cdot 16 = 7 + 80 = 87,$

$a_{12}^{6} = b_{12}^{5} = 87, \ b_{12}^{6} = a_{12}^{1} + 6 \cdot 16 = 7 + 96 = 103,$

- the numbers n_{12}^{j} of the realizations θ_{12}^{42} in particular intervals I_j, $j = 1,2,...6,$

$n_{12}^{1} = 2, \ n_{12}^{2} = 4, \ n_{13}^{3} = 15, \ n_{12}^{4} = 14, \ n_{12}^{5} = 6, \ n_{12}^{6} = 1,$

Histogram of the conditional sojourn time θ_{12}						
$I_j = < a_{bl}^{j}, b_{bl}^{j})$	7 – 23	23 – 39	39 – 55	55 - 71	71 - 87	87 – 103
n_{12}^{j}	2	4	15	14	6	1
$\bar{h}_{12}(t) = n_{12}^{j} / n_{12}$	2/42	4/42	15/42	14/42	6/42	1/42

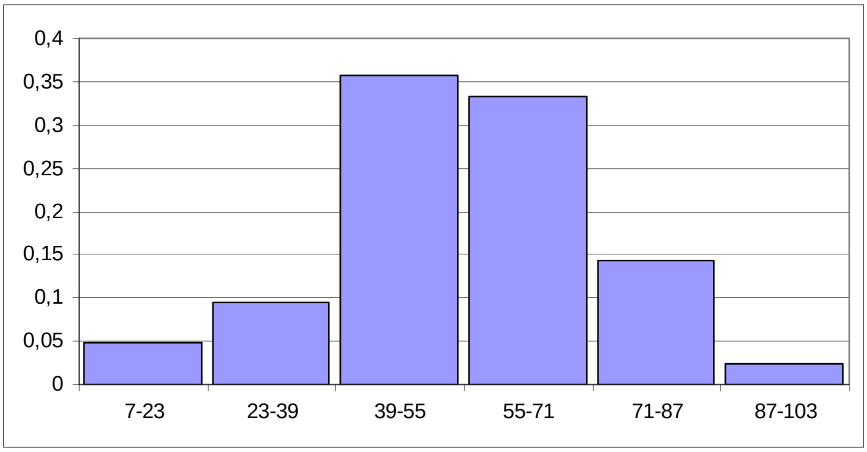

Figure 26. Histogram of the conditional sojourn time θ_{12}

- the realizations of the mean values $\bar{\theta}_{23}$ of the conditional sojourn times θ_{23} of the Stena Baltia ferry operation process at the operation state z_2 when the next transition is to the operation state z_3

$$\bar{\theta}_{23} = \frac{1}{42} \sum_{k=1}^{42} \theta_{23}^{k} = 2.6, \ b,l = 1,2,...,18, \ b \neq l,$$

- the number $\bar{r}_{23}$ of the disjoint intervals $I_j = < a_{bl}^{j}, b_{bl}^{j}),$ $j = 1,2,...,\bar{r}_{23}$, that include the realizations θ_{23}^{k}, $k = 1,2,...,42,$ of the conditional sojourn times θ_{23} at the operation state z_2 when the next transition is to the operation state z_3

$$\bar{r}_{12} = \sqrt{n_{bl}} = \sqrt{42} \cong 6,$$

- the length d_{23} of the intervals $I_j = < a_{bl}^{j}, b_{bl}^{j}),$ $j = 1,2,...6,$

$$d_{23} = \frac{\bar{R}_{23}}{\bar{r}_{23} - 1} = \frac{82}{5} \cong 16,$$

where

$$\bar{R}_{12} = \max_{1 \le k \le 42} \theta_{12}^{k} - \min_{1 \le k \le 42} \theta_{12}^{k} = 97 - 15 = 82,$$

- the ends a_{bl}^{j}, b_{bl}^{j}, of the intervals $I_j = < a_{bl}^{j}, b_{bl}^{j}),$ $I_j = < a_{bl}^{j}, b_{bl}^{j}),$ according to the formulae

$$\min_{1 \le k \le 42} \theta_{23}^{k} - \frac{d_{23}}{2} = 2 - \frac{0.8}{2} = 2 - 0.4 = 1.6,$$

$a_{23}^1 = \max\{1.6, 0\} = 1.6,$

$b_{23}^1 = a_{23}^1 + 0.8 = 1.6 + 0.8 = 2.4,$

$a_{23}^2 = b_{23}^1 = 2.4, \ b_{23}^2 = a_{23}^1 + 2 \cdot 0.8 = 1.6 + 1.6 = 3.2,$

$a_{23}^3 = b_{23}^2 = 3.2, \ b_{23}^3 = a_{23}^1 + 3 \cdot 0.8 = 1.6 + 2.4 = 4.0,$

$a_{23}^4 = b_{23}^3 = 4.0, \ b_{23}^4 = a_{23}^1 + 4 \cdot 0.8 = 1.6 + 3.2 = 4.8,$

$a_{23}^5 = b_{23}^4 = 4.8, \ b_{23}^5 = a_{23}^5 + 5 \cdot 0.8 = 1.6 + 4.0 = 5.6,$

$a_{23}^6 = b_{23}^5 = 5.6, \ b_{23}^6 = a_{23}^6 + 6 \cdot 0.8 = 1.6 + 4.8 = 6.4,$

- the numbers n_{23}^j of the realizations θ_{23}^{42} in particular intervals I_j, $j = 1,2,...6,$

$n_{12}^1 = 24, \ n_{12}^2 = 14, \ n_{13}^3 = 0, \ n_{12}^4 = 3, \ n_{12}^5 = 0, \ n_{12}^6 = 1.$

Histogram of the conditional sojourn time θ_{23}						
$I_j =< a_{bl}^j, b_{bl}^j)$	1.6 – 2.4	2.4 – 3.2	3.2 – 4.0	4.0 – 4.8	4.8 – 5.6	5.6 – 6.4
n_{23}^j	24	14	0	3	0	1
$\bar{h}_{23}(t) = n_{23}^j / n_{23}$	24/42	14/42	0/42	3/42	0/42	1/42

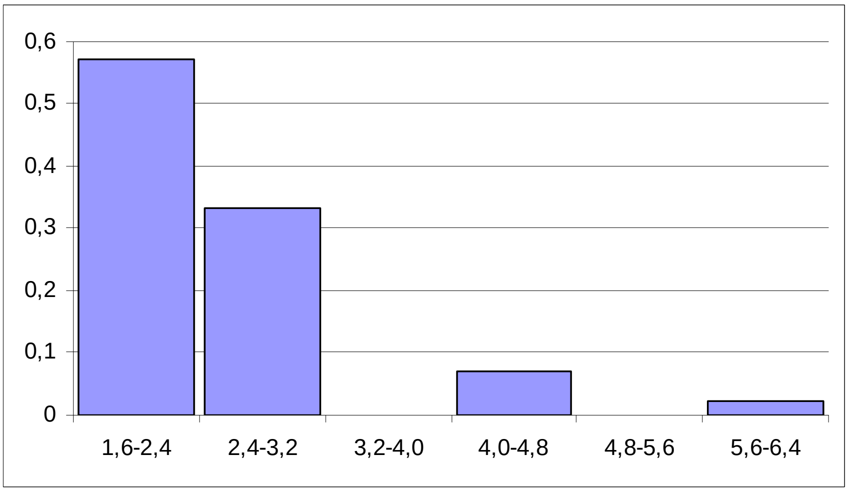

Figure 27. Histogram of the conditional sojourn time θ_{23}

At the remaining cases we are proceeding afterwards in an analogous way.

5.4.5. Identifying the distributions of the conditional sojourn times in the operation states of the Stena Baltica

Using the procedure given in Section 3.5 we may verify the hypotheses on the distributions of the conditional sojourn times θ_{bl}, $b, l = 1,2,...,18$, $b \neq l$, in the particular operation states and we have the following results:

- the conditional sojourn time θ_{12} has a triangular distribution with the density function

$$h_{12}(t) = \begin{cases} 0, & t < 7, \\ \frac{2}{103-7}\frac{t-7}{54-7} = \frac{1}{48}\frac{t-7}{47}, & 7 \le t < 54, \\ \frac{2}{103-7}\frac{103-t}{103-54} = \frac{1}{48}\frac{103-t}{49}, & 54 \le t < 103, \\ 0, & t \ge 103, \end{cases}$$

- the conditional sojourn time θ_{23} has an exponential distribution with the density function

$$h_{23}(t) = \begin{cases} 0, & t < 1.6, \\ 1.03\exp[-1.03(t-1.6)], & t \ge 1.6, \end{cases}$$

- the conditional sojourn time θ_{34} has a chimney distribution with the density function

$$h_{34}(t) = \begin{cases} 0, & t < 29, \\ 0.0278, & 29 \le t < 35, \\ 0.1984, & 35 \le t < 38, \\ 0.0266, & 38 \le t < 47, \\ 0, & t \ge 47; \end{cases}$$

- the conditional sojourn time θ_{45} has a chimney distribution with the density function

$$h_{45}(t) = \begin{cases} 0, & t < 41, \\ 0.0095, & 41 \le t < 46, \\ 0.0762, & 46 \le t < 56, \\ 0.0127, & 56 \le t < 71, \\ 0, & t \ge 71; \end{cases}$$

- the conditional sojourn time θ_{56} has a double trapezium distribution with the density function

$$h_{56}(t) = \begin{cases} 0, & t < 467.8, \\ -0.00004t + 0.0277, & 467.8 \le t \le 525.95, \\ -0.00006t + 0.0397, & 525.95 \le t \le 650.2, \\ 0, & t < 650.2; \end{cases}$$

- the conditional sojourn time θ_{67} has a double trapezium distribution with the density function

$$h_{67}(t) = \begin{cases} 0, & t < 31.9, \\ 0.0067t - 0.1747, & 31.9 \le t \le 37.17, \\ 0.0031t - 0.0395, & 37.17 \le t \le 45.1, \\ 0, & t > 45.1; \end{cases}$$

- the conditional sojourn time θ_{78} has a double trapezium distribution with the density function

$$h_{78}(t) = \begin{cases} 0, & t < 4.5, \\ -0.0183t + 0.2922, & 4.5 \le t \le 7.02, \\ -0.0069t + 0.2122, & 7.02 \le t \le 10.5, \\ 0, & t > 10.5; \end{cases}$$

- the conditional sojourn time θ_{89} has a triangular distribution with the density function

$$h_{89}(t) = \begin{cases} 0, & t < 0, \\ 0.0021t, & 0 \le t \le 21.4 \\ -0.002t + 0.087, & 21.4 \le t \le 44.4, \\ 0, & t > 44.4; \end{cases}$$

- the conditional sojourn time θ_{910} has a double trapezium distribution with the density function

$$h_{910}(t) = \begin{cases} 0, & t < 14.6, \\ 0.0001t + 0.0109, & 14.6 \le t \le 52.26, \\ 0.0062, & 52.2 \le t \le 127.4, \\ 0, & t > 127.4; \end{cases}$$

- the conditional sojourn time θ_{1011} has a chimney distribution with the density function

$$h_{1011}(t) = \begin{cases} 0, & t < 1.6, \\ 0.506, & 1.6 \le t \le 3.2, \\ 0.0595, & 3.2 \le t \le 6.4, \\ 0, & t > 6.4; \end{cases}$$

- the conditional sojourn time θ_{1112} has a chimney distribution with the density function

$$h_{1112}(t) = \begin{cases} 0, & t < 3.8, \\ 1.6667, & 3.8 \le t \le 4.2, \\ 0.1667, & 4.2 \le t \le 6.2, \\ 0, & t > 6.2; \end{cases}$$

- the conditional sojourn time θ_{1213} has a chimney distribution with the density function

$$h_{1213}(t) = \begin{cases} 0, & t < 18.7, \\ 0.0092, & 18.7 \le t \le 21.3, \\ 0.1786, & 21.3 \le t < 26.5, \\ 0.0061, & 26.5 \le t < 34.3, \\ 0, & t > 34.3; \end{cases}$$

- the conditional sojourn time θ_{1314} has a chimney distribution with the density function

$$h_{1314}(t) = \begin{cases} 0, & t < 410.2, \\ 0.0014, & 410.2 \le t < 477.4, \\ 0.0184, & 477.4 \le t < 511, \\ 0.0028, & 511 \le t < 611.4, \\ 0, & t \ge 611.4; \end{cases}$$

- the conditional sojourn time θ_{1415} has a Weibull's distribution with the density function

$$h_{1415}(t) = \begin{cases} 0, & t < 36.8, \\ 0.1415(t-36.8)^{1.1403} \exp[-0.0661(t-36.8)^{2.1403}], & t > 36.8; \end{cases}$$

- the conditional sojourn time θ_{1516} has a chimney distribution with the density function

$$h_{1516}(t) = \begin{cases} 0, & t < 30, \\ 0.0317, & 30 \le t < 33, \\ 0.2698, & 33 \le t < 36, \\ 0.0084, & 36 \le t < 48, \\ 0, & t \ge 48; \end{cases}$$

- the conditional sojourn time θ_{1617} has a triangular distribution with the density function

$$h_{1617}(t) = \begin{cases} 0, & t < 2.7, \\ 0.305t - 0.823, & 2.7 \le t \le 4.52, \\ -0.313t + 1.9719, & 4.52 \le t \le 6.3, \\ 0, & t > 6.3; \end{cases}$$

- the conditional sojourn time θ_{1718} has a double trapezium distribution with the density function

$$h_{1718}(t) = \begin{cases} 0, & t < 2.3, \\ -0.1134t + 0.6707, & 2.3 \le t \le 5.62, \\ 0.0071t - 0.0063, & 5.62 \le t \le 10.7, \\ 0, & t > 10.7; \end{cases}$$

- the conditional sojourn time θ_{181} has a Weibull's distribution with the density function

$$h_{181}(t) = \begin{cases} 0, & t < 0, \\ 0.1113t^{1.3519} \exp[-0.0473t^{2.3519}], & t \ge 0. \end{cases}$$

5.4.6. Identifying the mean values of the system conditional sojourn times in operation states of the Stena Baltica ferry

For the distributions identified in Section 5.4.5, according to either the formulae (8) or (9)-(16), the mean values $M_{bl} = E[\theta_{bl}]$, $b,l = 1,2,...,18$, $b \ne l$, of the system operation process *Z*(*t*) conditional sojourn times in particular operation states ware determined and they amount:

$$M_{12} = 54.33,\ M_{23} = 2.57,\ M_{34} = 36.57,$$
$$M_{45} = 52.5,\ M_{56} = 525.95,\ M_{67} = 37.16,$$
$$M_{78} = 7.02,\ M_{89} = 21.43,\ M_{910} = 53.69,$$
$$M_{1011} = 2.93,\ M_{1112} = 4.38,\ M_{1213} = 23.86,$$
$$M_{1314} = 509.69,\ M_{1415} = 50.14,\ M_{1516} = 34.28,$$
$$M_{1617} = 4.52,\ M_{1718} = 5.62,\ M_{181} = 18.74.$$

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

The computer program allows to identify of the unknown basic parameters of the system operation processes and to verify the hypotheses concerning the unknown forms of the distribution functions of the conditional sojourn times in the particular operation states on the basis of empirical data coming from the operation processes of complex technical systems. The program is based on the methods and algorithms for the estimating unknown parameters of the operations process included in [1]. Particularly, the computer program is useful in determining the probabilities of the initial operation states of the system operation process and the probabilities of the system operation process transitions between the operation states. The computer program allows to estimate the unknown parameters of the distributions of the conditional sojourn times of the system operation process in the particular operation states distinguished in [5] as the suitable for these variables uniform, triangular, double trapezium, quasi-trapezium, exponential, Weibull, normal and chimney distributions. Next, the program allows for testifying the hypotheses about the fitting empirical distributions with the distinguished distributions. Moreover, in the cases of the hypotheses acceptance, the computer program allows to determine the theoretical mean values of the sojourn times of the system operation process in the particular operation states. If the hypotheses are rejected, the program allows to find the empirical values of the mean values of these variables.

The computer program may be used for unknown parameters identification of the operation processes of real technical systems, particularly, the operation processes of port, shipyard and maritime transportation systems [3]-[4], [6]-[7] . 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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References

[1] Blokus-Roszkowska A., Guze S., Kołowrocki K., Jurdziński M., Kwiatuszewska-Sarnecka B., Milczek B., Soszyńska J., Salahuddin Habibullah M. & Fu X. (2009). Integrated package of solutions for complex industrial systems and processes safety and reliability optimization. WP 7 – Task 7.3. Methods of unknown parameters of complex technical systems operation, reliability, availability, safety models evaluation. Report. Poland-Singapore Joint Project.

[2] Blokus-Roszkowska, A., Guze, S., Kołowrocki, K. & Soszyńska, J. (2010). Packages of Tools for Complex Industrial Systems and Processes Safety and Reliability Optimization. WP8 - Task 8.1. The computer program for identification of the operation processes of complex technical systems. Report. Poland-Singapore Joint Project.

[3] Blokus-Roszkowska, A., Kołowrocki, K. & Namysłowski, M. (2010). Applications and Testing of Packages of Tools in Complex Maritime Transportation Systems and Processes Safety and Reliability Optimization. WP9 – Task 9.2. Shipyard ship-rope elevator operation, reliability, risk, availability and cost identification, prediction and optimization. Report. Poland-Singapore Joint Project.

[4] Blokus-Roszkowska, A., Kołowrocki, K. & Namysłowski, M. (2010). Applications and Testing of Packages of Tools in Complex Maritime Transportation Systems and Processes Safety and Reliability Optimization. WP9 – Task 9.3. Shipyard ground ship-rope transporter operation, reliability, risk, availability and cost identification, prediction and optimization. Report. Poland-Singapore Joint Project.

[5] Kołowrocki K. & Soszyńska J. (2009). Integrated package of solutions for complex industrial systems and processes safety and reliability optimization. WP 7 – Task 7.1. Methods of complex technical systems operation processes modeling. Report. Poland-Singapore Joint Project.

[6] Kołowrocki, K., Soszyńska, J. & Baranowski, Z. (2010). Applications and Testing of Packages of Tools in Complex Maritime Transportation Systems and Processes Safety and Reliability Optimization. WP9 – Task 9.1. Port oil piping transportation system operation, reliability, risk, availability and cost identification, prediction and optimization. Report. Poland-Singapore Joint Project.

[7] Kołowrocki, K., Soszyńska, J. & Kamiński, P. (2010). Applications and Testing of Packages of Tools in Complex Maritime Transportation Systems and Processes Safety and Reliability Optimization. WP9 – Task 9.4. Stena Baltica ferry technical system operation, safety, risk and cost identification, prediction and optimization. Report. Poland-Singapore Joint Project.