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Modelling port piping transport and shipping critical infrastructures operation processes including operating environment threats

Keywords

port piping transport, shipping, critical infrastructure, operation process, operating environment threats

Abstract

In the paper, the traditional semi-Markov approach to a complex technical system operation process modeling is proposed to modelling a critical infrastructure operation process including operating environment threats. Next the model is applied to real critical infrastructures such as the port oil piping transportation system and the maritime ferry technical system.

1. Introduction

The operation process of a critical infrastructure is very complex and often it is difficult to analyze these critical infrastructure safety with respect to changing in time its operation process states and operating environment conditions that are essential in this analysis. The complexity of the critical infrastructure operation process and its influence on changing in time the critical infrastructure structure and its components' safety parameters are essential in critical infrastructure safety analysis and protection. Usually, the critical infrastructure environment have either an explicit or an implicit strong influence on the critical infrastructure operation process. As a rule, some of the environmental events together with the infrastructure operation conditions define a set of different operation states of the critical infrastructure in which the critical infrastructure change its safety structure and its components safety parameters. In this report, we propose a convenient tool for analyzing this problem applying the semi-Markov model [13]-[15], [17], [23]-[24] of the critical infrastructure operation process, both without including critical infrastructure environment threats and with including them into this model.

2. Operation process of port oil piping transportation system

2.1. Port oil piping transportation system description

The considered oil piping transportation system is operating at one of the Baltic Oil Terminals that is designated for the reception from ships, the storage and sending by carriages or cars the oil products. It is also designated for receiving from carriages or cars, the storage and loading the tankers with oil products such like petrol and oil. The considered terminal is composed of three parts *A*, *B* and *C*, linked by the piping transportation system with the pier [22].
The unloading of tankers is performed at the pier placed in the port. 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 and further to the interior of the country.

Thus, the port oil pipeline transportation system consists of three subsystems:

- the subsystem S_1 composed of two pipelines, each composed of 178 pipe segments and 2 valves,
- the subsystem S_2 composed of two pipelines, each composed of 717 pipe segments and 2 valves,
- the subsystem S_3 composed of three pipelines, each composed of 360 pipe segments and 2 valves.

2.2. Semi-Markov model of port oil piping transportation system operation process

Taking into account expert opinions on the varying in time operation process of the considered piping system, we distinguish the following as its eight 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 of the subsystem S_3,
- an operation state $z_2 -$ transport of one kind of medium from the terminal part C to part B using one out of three pipelines of the 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 of the subsystem S_1 and one out of two pipelines of the subsystem S_2,
- an operation state $z_4 -$ transport of one kind of medium from the pier through parts A and B to part C using one out of two pipelines of the subsystem S_1, one out of two pipelines in subsystem S_2 and two out of three pipelines of the 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 of the subsystem S_1 and one out of two pipelines of the 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 of the subsystem S_3, and simultaneously transport one kind of medium from the pier through part A to B using one out of two pipelines of the subsystem S_1 and one out of two pipelines of the 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 of the subsystem S_3, and simultaneously transport second kind of medium from the terminal part C to B using one out of three pipelines of the subsystem S_3.

Further, using semi-Markov model introduced in [24], we can define the port oil piping transportation system operation process $Z(t)$ not related to its operating environment threats, by:

- the vector $[p_b(0)]_{1x7}$ of the initial probabilities $p_b(0) = P(Z(0) = z_b)$, $b = 1,2,...,7,$ of the port oil piping transportation systemoperation process $Z(t)$ staying at particular operation states at the moment $t = 0$;
- the matrix $[p_{bl}]_{7x7}$ of probabilities p_{bl}, $b, l = 1,2,...,7,$ of the port oil piping transportation systemoperation process $Z(t)$ transitions between the operation states z_b and z_l;
- the matrix $[H_{bl}(t)]_{7x7}$ of conditional distribution functions $H_{bl}(t) = P(\theta_{bl} < t)$, $b, l = 1,2,...,7,$ of the port oil piping transportation systemoperation process $Z(t)$ conditional sojourn times θ_{bl} at the operation states.

2.3. Operation process of port oil piping transportation system including operating environment threats

We consider the port oil piping transportation system described in Section 2.1 with the scheme presented in *Figure 8* in [3]. We assume that its system safety structure and its subsystems and components safety depend on its changing in time operation states z_1, z_2, …, z_7, defined in Section 2.2. Additionally, we assume that the port oil transportation system operation process and safety may depend on its operating environment threats and we distinguished the following 3unnatural threats:

ut_1 – a human error,
ut_2 – a terrorist attack,
ut_3 – an act of vandalizm and/ortheft.

In this case, according to (3.3) in [3], the maximum value of the number of operation states ν' of the port oil piping transportation system operation process $Z'(t)$ related to its operating environment threats is

$$7 \cdot [\binom{3}{0} + \binom{3}{1} + \binom{3}{2} + \binom{3}{3}] = 7 \cdot 2^3 = 56.$$

Taking into account expert opinions on the varying in time operation process $Z'(t)$ of the considered piping system, definitions (1)-(2) in [24] and assuming that the threats are disjoint, according to (4)-(11) in [24], we distinguish the following as its 28 operation states:

- the operation states z_i, $i=1,2,...,7$, without including operating environment threats ut_1, ut_2, ut_3, marked by

$$z_i^{'} = z_i,\ i=1,2,...,7; \quad (1)$$

- the operation states z_i, $i=1,2,...,7$, including the threat ut_1, respectively marked by

$$z_i^{'},\ i=8,9,...,14; \quad (2)$$

- the operation states z_i, $i=1,2,...,7$, including the threat ut_2, respectively marked by

$$z_i^{'},\ i=15,16,...,21; \quad (3)$$

- the operation states z_i, $i=1,2,...,7$, including the threat ut_3, respectively marked by

$$z_i^{'},\ i=22,23,...,28. \quad (4)$$

Practically more comfortable is to numerate the new states, according to (1)-(3), as follows:

- the operation states z_i, $i=1,2,...,7$, without including operating environment threats ut_1, ut_2, ut_3, marked by

$$z_i^{'} = z_1 \text{ for } i=1,\ z_i^{'} = z_2 \text{ for } i=5,\ \ldots,\ z_i^{'} = z_7 \text{ for } i=25; \quad (5)$$

- the operation states including state z_1 and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i=2,3,4; \quad (6)$$

- the operation states including state z_2 and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i=6,7,8; \quad (7)$$

- the operation states including state z_3 and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i=10,11,12; \quad (8)$$

- the operation states including state z_4 and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i=14,15,16; \quad (9)$$

- the operation states including state z_5 and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i=18,19,20; \quad (10)$$

- the operation states including state z_6 and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i=22,23,24; \quad (11)$$

- the operation states including state z_7 and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i=26,27,28. \quad (12)$$

The influence of the above system operation states changing on the changes of the pipeline system safety structure is similar to that described in Section 2.2.

For the new operation states numeration (5)-(12) we have:

- at the system operation states $z_1^{'}$, $z_8^{'}$, $z_{15}^{'}$, $z_{22}^{'}$ and $z_7^{'}$, $z_{14}^{'}$, $z_{21}^{'}$, $z_{28}^{'}$, the system is composed of the subsystem S_3, that is a series-”2 out of 3” system containing three series subsystems with the scheme showed in *Figure 10* [3];
- at the system operation state $z_2^{'}$, $z_9^{'}$, $z_{16}^{'}$, $z_{23}^{'}$, the system is composed of a series-parallel subsystem S_3, which contains three pipelines with the scheme showed in *Figure 11* [3];
- at the system operation states $z_3^{'}$, $z_{10}^{'}$, $z_{17}^{'}$, $z_{24}^{'}$ and $z_5^{'}$, $z_{12}^{'}$, $z_{19}^{'}$, $z_{26}^{'}$, the system is series and composed of two series-parallel subsystems S_1, S_2 each containing two pipelines with the scheme showed in *Figure 12* [3];
- at the operation states $z_4^{'}$, $z_{11}^{'}$, $z_{18}^{'}$, $z_{25}^{'}$ and $z_6^{'}$, $z_{13}^{'}$, $z_{20}^{'}$, $z_{27}^{'}$, the system is series and composed of two series-parallel subsystems S_1, S_2 each containing two pipelines and one series-“2 out of 3” subsystem S_3 with the scheme showed in *Figure 13* [3].

For the new operation states numeration (5)-(12) we have:

- at the system operation states z'_1, z'_2, z'_3, z'_4 and z'_{25}, z'_{26}, z'_{27}, z'_{28}, the system is composed of the subsystem S_3, that is a series-”2 out of 3” system containing three series subsystems with the scheme showed in *Figure 10* [3];
- at the system operation state z'_5, z'_6, z'_7, z'_8, the system is composed of a series-parallel subsystem S_3, which contains three pipelines with the scheme showed in *Figure 11* [3];
- at the system operation states z'_9, z'_{10}, z'_{11}, z'_{12} and z'_{17}, z'_{18}, z'_{19}, z'_{20}, the system is series and composed of two series-parallel subsystems S_1, S_2, each containing two pipelines with the scheme showed in *Figure 12* [3];
- at the operation states z'_{13}, z'_{14}, z'_{15}, z'_{16} and z'_{21}, z'_{22}, z'_{23}, z'_{24}, the system is series and composed of two series-parallel subsystems S_1, S_2, each containing two pipelines and one series-“2 out of 3” subsystem S_3 with the scheme showed in *Figure 13* [3].

Further, using semi-Markov model introduced in Section 3.1 [24], we can define the port oil piping transportation system operation process $Z'(t)$ related to its operating environment threats, by:

- the vector $[p'_b(0)]_{1x28}$ of the initial probabilities $p'_b(0) = P(Z'(0) = z'_b),\ b = 1,2,...,28,$ of the port oil piping transportation system operation process $Z'(t)$ staying at particular operation states at the moment $t = 0$;
- the matrix $[p'_{bl}]_{28vx28}$ of probabilities p'_{bl}, $b, l = 1,2,...,28,$ of the port oil piping transportation system operation process $Z'(t)$ transitions between the operation states z'_b and z'_l;
- the matrix $[H'_{bl}(t)]_{28x28}$ of conditional distribution functions $H'_{bl}(t) = P(\theta'_{bl} < t)$, $b, l = 1,2,...,28,$ of the port oil piping transportation systemoperation process $Z'(t)$ conditional sojourn times θ'_{bl} at the operation states.

3. Operation process of maritime ferry

3.1. Maritime ferry technical system description

The considered maritime ferry is a passenger Ro-Ro ship operating at the Baltic Sea between Gdynia and Karlskrona ports on regular everyday line. We assume that the ferry is composed of a number of main subsystems having an essential influence on its safety [22]. 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 stability control subsystem,
S_5 - an anchoring and mooring subsystem,
S_6 - a protection and rescue subsystem,
S_7 - a social subsystem.

In the safety analysis of the ferry, we omit the protection and rescue subsystem S_6 and the social subsystem S_7 and we consider its strictly technical subsystems S_1, S_2, S_3, S_4 and S_5 only, further called the ferry technical system.

The navigational subsystem S_1 is composed of one general component $E_{11}^{(1)}$, that is equipped with GPS, AIS, speed log, gyrocompass, magnetic compass, echo sounding system, paper and electronic charts, radar, ARPA, communication system and other subsystems.

The propulsion and controlling subsystem S_2 is composed of:

- the subsystem S_{21} which consist of 4 main engines $E_{11}^{(2)}$, $E_{12}^{(2)}$, $E_{13}^{(2)}$, $E_{14}^{(2)}$;
- the subsystem S_{22} which consist of 3 thrusters $E_{21}^{(2)}$, $E_{22}^{(2)}$, $E_{31}^{(2)}$;
- the subsystem S_{23} which consist of twin pitch propellers $E_{41}^{(2)}$, $E_{51}^{(2)}$;
- the subsystem S_{24} which consist of twin directional rudders $E_{61}^{(2)}$, $E_{71}^{(2)}$.

The loading and unloading subsystem S_3 is composed of:

- the subsystem S_{31} which consist of 2 remote upper trailer decks to main deck $E_{11}^{(3)}$, $E_{21}^{(3)}$;
- the subsystem S_{32} which consist of 1 remote fore car deck to main deck $E_{31}^{(3)}$;
- the subsystem S_{33} which consist of passenger gangway to Gdynia Terminal $E_{41}^{(3)}$;
- the subsystem S_{34} which consist of passenger gangway to Karlskrona Terminal $E_{51}^{(3)}$.

The stability control subsystem S_4 is composed of :

- the subsystem S_{41} which consist of an anti-heeling system $E_{11}^{(4)}$, which is used in port during loading operations;

- the subsystem S_{42} which consist of an anti-heeling system $E_{21}^{(4)}$, which is used at sea to stabilizing ships rolling.

The anchoring and mooring subsystem S_5 is composed of :
- the subsystem S_{51} which consist of aft mooring winches $E_{11}^{(5)}$;
- the subsystem S_{52} which consist of fore mooring and anchor winches $E_{21}^{(5)}$;
- the subsystem S_{53} which consist of fore mooring winches $E_{31}^{(5)}$.

3.2. Semi-Markov model of maritime ferry operation process

Taking into account expert opinions on the varying in time operation process of the considered ferry technical system, 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} – ferry 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} – ferry turning at Gdynia Port,
- an operation state z_{17} – mooring operations at Gdynia Port,
- an operation state z_{18} – unloading at Gdynia Port.

Further, using semi-Markov model introduced in Section 2 [24] we can define the maritime ferry technical system operation process $Z(t)$ not related to its operating environment threats, by:
- the vector $[p_b(0)]_{1x18}$ of the initial probabilities $p_b(0) = P(Z(0) = z_b)$, $b = 1,2,...,18$, of the maritime ferry technical systemoperation process $Z(t)$ staying at particular operation states at the moment $t = 0$;
- the matrix $[p_{bl}]_{18x18}$ of probabilities p_{bl}, $b, l = 1,2,...,18$, of the maritime ferry technical system operation process $Z(t)$ transitions between the operation states z_b and z_l;
- the matrix $[H_{bl}(t)]_{18x18}$ of conditional distribution functions $H_{bl}(t) = P(\theta_{bl} < t)$, $b, l = 1,2,...,18$, of the maritime ferry technical system operation process $Z(t)$ conditional sojourn times θ_{bl} at the operation states.

3.3. Operation process of maritime ferry technical system including operating environment threats

We consider the maritime ferry in Section 2.3 in [3] with the scheme presented in *Figures 14-16* [3]. We assume that its system safety structure and its subsystems and components safety depend on its changing in time operation states z_1, z_2, …, z_{18}, defined in Section 3.2. Additionally, we assume that the maritime ferry operation process and safety may depend on its operating environment threats and we distinguished the following 3 unnatural threats:

ut_1 – a human error,

ut_2 – a terrorist attack,

ut_3 – a heavy sea traffic.

In this case, according to (3) [24], the maximum value of the number of operation states ν' of the maritime ferry technical system operation process $Z'(t)$ related to its operating environment threats is

$$18 \cdot [\binom{3}{0} + \binom{3}{1} + \binom{3}{2} + \binom{3}{3}] = 18 \cdot 2^3 = 144.$$

Taking into account expert opinions on the varying in time operation process $Z'(t)$ of the considered maritime ferry, definitions (1)-(2) [24] and assuming that the threats are disjoint, according to (4)-(11) [24] we distinguish the following as its 72 operation states:

- the operation states z_i, $i = 1,2,...,18$, without including operating environment threats ut_1, ut_2, ut_3, marked by

$$z_i^{'} = z_i,\ i = 1,2,...,18; \tag{13}$$

- the operation states z_i, $i = 1,2,...,18$, including the threat ut_1, respectively marked by

$$z_i^{'},\ i = 19,20,...,36; \tag{14}$$

- the operation states z_i, $i = 1,2,...,18$ including the threat ut_2, respectively marked by

$$z_i^{'},\ i = 37,38,...,54; \tag{15}$$

- the operation states z_i, $i = 1,2,...,18$, including the threat ut_3, respectively marked by

$$z_i^{'},\ i = 55,56,...,72. \tag{16}$$

Practically more comfortable is to numerate the new states, according to (12)-(15) [24], as follows:

- the operation states z_i, $i = 1,2,...,18$, without including operating environment threats ut_1, ut_2, ut_3, marked by

$$z_i^{'} = z_1 \text{ for } i = 1,\ z_i^{'} = z_2 \text{ for } i = 5,\ \ldots,\ z_i^{'} = z_{18} \text{ for } i = 69; \tag{17}$$

- the operation states including state z_1 and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i = 2,3,4; \tag{18}$$

- the operation states including state z_2 and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i = 6,7,8; \tag{19}$$

- the operation states including state z_3 and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i = 10,11,12; \tag{20}$$

- the operation states including state z_4 and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i = 14,15,16; \tag{21}$$

- the operation states including state z_5 and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i = 18,19,20; \tag{22}$$

- the operation states including state z_6 and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i = 22,23,24; \tag{23}$$

. . .;

- the operation states including state z_{18} and successively the threats ut_1, ut_2, ut_3, respectively marked by

$$z_i^{'},\ i = 70,71,72. \tag{24}$$

The influence of the above system operation states changing on the changes of the maritime ferry technical system safety structure is similar to that described in Section 3.2.

For the new operation states numeration (17)-(24) we have:

- at the operation states $z_1^{'}$, $z_{19}^{'}$, $z_{37}^{'}$, $z_{55}^{'}$ and $z_{18}^{'}$, $z_{36}^{'}$, $z_{54}^{'}$, $z_{72}^{'}$, the ferry technical system is composed of two subsystems S_3 and S_4 forming a series structure shown in *Figure 17* [3];
- at the operation states $z_2^{'}$, $z_{20}^{'}$, $z_{38}^{'}$, $z_{56}^{'}$ and $z_7^{'}$, $z_{25}^{'}$, $z_{43}^{'}$, $z_{61}^{'}$ and $z_{10}^{'}$, $z_{28}^{'}$, $z_{46}^{'}$, $z_{64}^{'}$ and $z_{17}^{'}$, $z_{35}^{'}$, $z_{53}^{'}$, $z_{71}^{'}$, the ferry technical system is composed of three subsystems S_1, S_2 and S_5 forming a series structure shown in *Figure 18* [3];
- at the operation states $z_3^{'}$, $z_{21}^{'}$, $z_{39}^{'}$, $z_{57}^{'}$ and $z_{11}^{'}$, $z_{29}^{'}$, $z_{47}^{'}$, $z_{65}^{'}$ and $z_{15}^{'}$, $z_{33}^{'}$, $z_{51}^{'}$, $z_{69}^{'}$ and $z_{16}^{'}$, $z_{34}^{'}$, $z_{52}^{'}$, $z_{70}^{'}$, the ferry technical system is composed of two

subsystems S_1 and S_2 forming a series structure shown in *Figure 19* [3];

- at the operation states z'_4, z'_{22}, z'_{40}, z'_{58} and z'_5, z'_{23}, z'_{41}, z'_{59} and z'_{12}, z'_{30}, z'_{48}, z'_{66} and z'_{13} z'_{31}, z'_{49}, z'_{67} and z'_{14}, z'_{32}, z'_{50}, z'_{68}, the ferry technical system is composed of three subsystems S_1, S_2 and S_4 forming a series structure shown in *Figure 20* [3];
- at the operation state z'_6, z'_{24}, z'_{42}, z'_{60}, the ferry technical system is composed of three subsystems S_1, S_2 and S_4 forming a series structure shown in *Figure 21*[3];
- at the operation state z'_8, z'_{26}, z'_{44}, z'_{62} and z'_9, z'_{27}, z'_{45}, z'_{63}, the ferry technical system is composed of two subsystems S_3 and S_4 forming a series structure shown in *Figure 22* [3].

For the new operation states numeration (17)-(24) we have:

-at the operation states z'_1, z'_2, z'_3, z'_4 and z'_{69}, z'_{70}, z'_{71}, z'_{72}, the ferry technical system is composed of two subsystems S_3 and S_4 forming a series structure shown in *Figure 17* [3];

- at the operation states z'_5, z'_6, z'_7, z'_8 and z'_{25}, z'_{26}, z'_{27}, z'_{28} and z'_{37}, z'_{38}, z'_{39}, z'_{40} and z'_{65}, z'_{66}, z'_{67}, z'_{68}, the ferry technical system is composed of three subsystems S_1, S_2 and S_5 forming a series structure shown in *Figure 18* [3];
- at the operation states z'_9, z'_{10}, z'_{11}, z'_{12} and z'_{45}, z'_{46}, z'_{47}, z'_{48} and z'_{57}, z'_{58}, z'_{59}, z'_{60} and z'_{61}, z'_{62}, z'_{63}, z'_{64}, the ferry technical system is composed of two subsystems S_1 and S_2 forming a series structure shown in *Figure 19* [3];
- at the operation states z'_{13}, z'_{14}, z'_{15}, z'_{16} and z'_{17}, z'_{18}, z'_{19}, z'_{20} and z'_{45}, z'_{46}, z'_{47}, z'_{48} and z'_{49} z'_{50}, z'_{51}, z'_{52} and z'_{53}, z'_{54}, z'_{55}, z'_{56}, the ferry technical system is composed of three subsystems S_1, S_2 and S_4 forming a series structure shown in *Figure 20* [3];
- at the operation state z'_{21}, z'_{22}, z'_{23}, z'_{24}, the ferry technical system is composed of three subsystems S_1, S_2 and S_4 forming a series structure shown in *Figure 21* [3];
- at the operation state z'_{29}, z'_{30}, z'_{31}, z'_{32} and z'_{33}, z'_{34}, z'_{35}, z'_{36}, the ferry technical system is composed of two subsystems S_3 and S_4 forming a series structure shown in *Figure 22* [3].

Further, using semi-Markov model introduced in Section 3 [24], we can define the maritime ferry technical system operation process $Z'(t)$ related to its operating environment threats, by:

- the vector $[p'_b(0)]_{1x72}$ of the initial probabilities $p'_b(0) = P(Z'(0) = z'_b),\ b = 1,2,...,72,$ of the maritime ferry technical system operation process $Z'(t)$ staying at particular operation states at the moment $t = 0$;
- the matrix $[p'_{bl}]_{72x72}$ of probabilities p'_{bl}, $b, l = 1,2,...,72,$ of the maritime ferry technical systemoperation process $Z'(t)$ transitions between the operation states z'_b and z'_l;
- the matrix $[H'_{bl}(t)]_{72x72}$ of conditional distribution functions $H'_{bl}(t) = P(\theta'_{bl} < t)$, $b, l = 1,2,...,72,$ of the maritime ferry technical system operation process $Z'(t)$ conditional sojourn times θ'_{bl} at the operation states.

4. Conclusion

In the paper there is presented the probabilistic model of the critical infrastructure operation process. Presented model is the basis for further considerations in particular tasks of the EU-CIRCLE project. Next this model will be used to construct the integrated general safety probabilistic model of the critical infrastructure related to its operation process and climate-weather process [3]. The model will be applied to real critical infrastructures such as the port oil piping transportation system and the maritime ferry technical system. The model further development will be done in the following EU-CIRCLE project reports: [4]-[6], [9]-[12].

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