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Modelling Safety of Baltic Port and Shipping Critical Infrastructure Network

Keywords

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Abstract

In the paper, the three critical infrastructure networks are introduced, i.e. port, shipping, and ship traffic and port operation information. For every of them the main safety paremeters are defined. Furthermore, the multistate system component and the multistate system main safety characteristics, i.e. their mean values of the lifetimes and in the safety state subsets and in the particular safety states and standard deviations and the moment when the system risk function exceeds a fixed permitted level are determined. Finally, the Baltic Port and Shipping Critical Infrastructure Network is defined and described in the same way.

1. Introduction

The report is devoted to safety modeling and prediction of the joint network of the port, shipping and ship traffic and port operation information critical infrastructure networks defined as complex systems. Firstly, the three critical infrastructure networks: port, shipping and ship traffic and port operation information, are described in details. Every chapter about the single critical infrastructure network consists of the definitions of this network, its input safety parameters and the prediction of its safety characteristics. Furthermore, the joint network is introduced. The input safety parameters are defined and safety characteristics are predicted. Some conclusions are mentioned.

In maritime transport, it can be distinguished several areas of activity. One is the operations of the port; the second relates to the exploitation of the fleet, and the third are the ICT systems. Every of these mentioned parts is important for the whole process of maritime transport. Thus, lack of proper functioning one of them causes the repercussions for its surroundings. This is the reason why we define the various elements as the critical infrastructure network. In earlier reports, the port critical infrastructure network, shipping critical infrastructure network, finally, the ship traffic and port operation information critical infrastructure network was introduced. In the other hand, as it was mentioned before, these critical infrastructure networks are parts of the maritime transport. Therefore, they should be considered as a whole. In the earlier reports, the port, shipping and ship traffic and port operation information critical infrastructure joint network was defined [EU-CIRCLE Report D1.4-GMU2].

Because of complexity of this joint network we consider only the multi-state approach to safety analysis [Amari, 1997], [Aven, 1985, 1999, 1993], [Barlow, Wu, 1978], [Brunelle, Kapur, 1999], [Hudson, Kapur, 1982, 1985], [Lisnianski, Levitin, 2003], [Natvig, 1982], [Ohio, Nishida, 1984], [Xue, 1985], [Xue, Yang, 1995a,b], [Yu et al 1994], [Kołowrocki, Soszyńska-Budny, 2011]. The additional assumption that the systems are composed of multi-state components with safety states degrading in time [Guze, Kołowrocki, 2008], [Kołowrocki, 2004, 2014], [Kołowrocki, Soszyńska-Budny, 2011], [Xue, 1985], [Xue, Yang 1995 a, b] gives the possibility for more precise analysis of their safety and operational processes' effectiveness. This assumption allows us to distinguish a system safety critical state to exceed which is either dangerous for the environment or does not assure the necessary level of its operation process effectiveness. Then, an important system safety characteristic is the time to the moment of exceeding the system safety critical state and its distribution, which is called the system risk function. This distribution is strictly related to the system safety function that are basic characteristics of the multi-state system.

In the report, the three critical infrastructure networks are introduced, i.e. port, shipping, and ship traffic and port operation information. For every of them the main safety paremeters are defined. Moreover, the multistate system component and the multistate system main safety characteristics, i.e. their mean values of the lifetimes and in the safety state subsets and in the particular safety states and standard deviations and the moment when the system risk function exceeds a fixed permitted level are determined. Finally, the joint network of the port, shipping, and ship traffic and port operation information critical infratsrucutre network is defined and described in the same way.

The theoretical background is done by theory constructed in [EU-CIRCLE Report D3.3-GMU3].

2. Safety and Risk prediction of Port Critical Infrastructure Network

2.1. Port Critial infrastructure Network Description

We take into account the complex technical system S_1 composed of 18 Baltic core ports and called the Baltic Port Critical Infrastructure Network with the following subsystems:

- the subsystem S_{11} which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{11}^{(1)}$, $E_{12}^{(1)}$, $E_{13}^{(1)}$;
- the subsystem S_{12} which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{21}^{(1)}$, $E_{22}^{(1)}$, $E_{23}^{(1)}$;
- the subsystem S_{13} which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{31}^{(1)}$, $E_{32}^{(1)}$, $E_{33}^{(1)}$;
- the subsystem S_{14} which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{41}^{(1)}$, $E_{42}^{(1)}$, $E_{43}^{(1)}$;
- the subsystem S_{15} which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{51}^{(1)}$, $E_{52}^{(1)}$, $E_{53}^{(1)}$;
- the subsystem S_{16} which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{61}^{(1)}$, $E_{62}^{(1)}$, $E_{63}^{(1)}$;
- the subsystem S_{17} which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{71}^{(1)}$, $E_{72}^{(1)}$, $E_{73}^{(1)}$;
- the subsystem S_{18} which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{81}^{(1)}$, $E_{82}^{(1)}$, $E_{83}^{(1)}$;
- the subsystem S_{19} which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{91}^{(1)}$, $E_{92}^{(1)}$, $E_{93}^{(1)}$;
- the subsystem $S_{1,10}$ which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{10,1}^{(1)}$, $E_{10,2}^{(1)}$, $E_{10,3}^{(1)}$;
- the subsystem $S_{1,11}$ which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{11,1}^{(1)}$, $E_{11,2}^{(1)}$, $E_{11,3}^{(1)}$;
- the subsystem $S_{1,12}$ which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{12,1}^{(1)}$, $E_{12,2}^{(1)}$, $E_{12,3}^{(1)}$;
- the subsystem $S_{1,13}$ which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{13,1}^{(1)}$, $E_{13,2}^{(1)}$, $E_{13,3}^{(1)}$;
- the subsystem $S_{1,14}$ which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{14,1}^{(1)}$, $E_{14,2}^{(1)}$, $E_{14,3}^{(1)}$;

- the subsystem $S_{1,15}$ which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{15,1}^{(1)}$, $E_{15,2}^{(1)}$, $E_{15,3}^{(1)}$;
- the subsystem $S_{1,16}$ which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{16,1}^{(1)}$, $E_{16,2}^{(1)}$, $E_{16,3}^{(1)}$;
- the subsystem $S_{1,17}$ which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{17,1}^{(1)}$, $E_{17,2}^{(1)}$, $E_{17,3}^{(1)}$;
- the subsystem $S_{1,18}$ which consist of technical loading/unloading equipment, hydrotechnical infrastructure and transport infrastructure $E_{18,1}^{(1)}$, $E_{18,2}^{(1)}$, $E_{18,3}^{(1)}$.

2.2. Defining the Parameters of the Port Critial Infrastructure Network Safety Model

According to the effectiveness and safety aspects of the operation of the Baltic Port Critical Infrastructure Network, we fix:

- the number of port critical infrastructure network safety states $(z = 4)$ and we distinguish the following five safety states:
  - a safety state 4 – BPCIN operations are fully safe,
  - a safety state 3 – BPCIN operations are less safe and more dangerous because of the possibility of damage of the land loading/unloading equipment without the environmental pollution,
  - a safety state 2 – BPCIN operations are less safe and more dangerous because of the possibility of collisions or groundings of ships in port area without the environmental pollution,
  - a safety state 1 – BPCIN operations are less safe and very dangerous because of the possibility of collisions or groundings in port area and environmental pollution,
  - a safety state 0 – BPCIN is destroyed,

Moreover, by the expert opinions, we assume that there are possible the transitions between the components safety states only from better to worse ones;

- the safety structure of the system and subsystems.

We consider the three cases of the port critical infrastructure network safety strucutres as follows:

Case 1. It is a complex series system composed of 18 series subsystems S_{11}, S_{12}, …, $S_{1,18}$, each containing four components as it was mentioned above.

Case 2. It is a complex "m out of n" system composed of 18 series subsystems S_{11}, S_{12}, …, $S_{1,18}$, each containing four components as it was mentioned above.

Case 3. It is a complex consecutive "m out of n:F" system composed of 18 series subsystems S_{11}, S_{12}, …, $S_{1,18}$, each containing four components as it was mentioned above.

The unknown parameters of the multistate ageing system safety model are:

- the number of safety states of the system and components *z*,
- the critical safety state of the system *r*,
- the system risk permitted level δ,
- the parameters of a system and subsystems safety structure.

2.3. Defining the Input Parameters of the Port Critical Infrastructure Network Safety Model

According to expert opinions, the input necessary parameters of the port critical infrastructure network safety models are as follows [EU-CIRCLE Report D3.3-GMU1, 2016], [EU-CIRCLE Report D2.2-GMU1] :

- the number of safety states of the system and components z=4,

- the critical safety state of the system $r = 2$,

- the system risk permitted level $\delta = 0.05$,

- the parameters of a system safety structure:

- Case 1 - series system
  - the number of components (subsystem) *n*, n=18
- Case 2 – "m out of n" system
  - the number of components (subsystem) *n*, n=18

  - the threshold number of subsystems m, m = 3
- Case 3 – consecutive "m out of n: F" system
  - the number of components (subsystem) *n*, *n*=18
  - the threshold number of subsystems m=2
  - the parameters of the subsystems S_{11}, …, $S_{1,18}$ safety structures
    - series system:
      – the number of components *k*,

      k=3.

- the intensities of components departure from the safety states subset {1,2,3,4}, {2,3,4}, {3,4}, {4}, are as follows:
  - for subsystems S_{1i}, $i = 1,2,3,...,18$

$$[\lambda_{ij}^{(1)}(1)],\ [\lambda_{ij}^{(1)}(2)],\ [\lambda_{ij}^{(1)}(3)],\ [\lambda_{ij}^{(1)}(4)],$$

$$i = 1,2,3,...,18,\ j = 1,2,3\ .$$

2.4. Prediction of the Characteristics of the Port Critical Infrastructure Network Safety Model

We assume that the system is composed of components having multistate exponential safety functions.

The subsystems S_1, consist of k = 18 technical systems, each composed of 3 components $E_{ij}^{(1)}$, $i = 1,2,3,...,18$, $j = 1,2,3$ with the exponential safety functions given below.

In particular port technical systems there are *3* components with the multistate safety functions co-ordinates

$$S_{ij}^{(1)}(t,1) = \exp[-\lambda_{ij}^{(1)}(1)\,t],\ S_{ij}^{(1)}(t,2) = \exp[-\lambda_{ij}^{(1)}(2)\,t],$$
$$S_{ij}^{(1)}(t,3) = \exp[-\lambda_{ij}^{(1)}(3)\,t],\ S_{ij}^{(1)}(t,4) = \exp[-\lambda_{ij}^{(1)}(4)\,t],$$

$$i = 1,2,3,...,18,\ \ j = 1,2,3\ .$$

Considering the safety model parameters from Section 2 in [EU-CIRCLE Report D3.3-GMU3] concerned with the fixed system safety structures and their shape parameters and with the assumed the exponential models of the safety functions of the system components and the results of the evaluations of the system components intensities of departures from the safety state subsets we may to perform the prediction of the Baltic Port Critical Infrstructure safety characteristics.

The subsystems S_{1i}, $i = 1,2,3,...,18$, are the five-state series systems and according to (2.22)-(2.23) in [EU-CIRCLE Report D3.3-GMU3] their five-state safety function is given by

$$\boldsymbol{S}^{(1)}(t,\cdot) = [1,\ \boldsymbol{S}^{(1)}(t,1),\ \boldsymbol{S}^{(1)}(t,2),\ \boldsymbol{S}^{(1)}(t,3),$$
$$\boldsymbol{S}^{(1)}(t,4)\ ],\ t \geq 0, \qquad (1)$$

where according to the formulae (2.22)-(2.23) and (2.58)-(2.59) in [EU-CIRCLE Report D3.3-GMU3],we have

$$\boldsymbol{S}^{(1)}(t,\ u) = \prod_{i=1}^{18} S_{ij}^{(1)}(t,u) =$$
$$S_{1j}^{(1)}(t,u) \cdot S_{2j}^{(1)}(t,u) \cdot ... \cdot S_{18,j}^{(1)}(t,u), \qquad (2)$$

for $t \in <0,\infty)$, $u = 1,2,3,4$, $j = 1,2,3$,

and particularly

$$\boldsymbol{S}^{(1)}(t,\ 1) = S_{1j}^{(1)}(t,1) \cdot S_{2j}^{(1)}(t,1) \cdot ... \cdot S_{18j}^{(1)}(t,1) = \exp[-$$
$$\lambda_{1j}^{(1)}(1)\,t]\ \exp[-\lambda_{2j}^{(1)}(1)\,t]\ ...\exp[-\lambda_{18,j}^{(1)}(1)\,t], \qquad (3)$$

$$\boldsymbol{S}^{(1)}(t,2) = S_{1j}^{(1)}(t,2) \cdot S_{2j}^{(1)}(t,2) \cdot ... \cdot S_{18j}^{(1)}(t,2) = \exp[-$$
$$\lambda_{1j}^{(1)}(2)\,t]\ \exp[-\lambda_{2j}^{(1)}(2)\,t]\ ...\exp[-\lambda_{18,j}^{(1)}(2)\,t], \qquad (4)$$

$$\boldsymbol{S}^{(1)}(t,3) = S_{1j}^{(1)}(t,3) \cdot S_{2j}^{(1)}(t,3) \cdot ... \cdot S_{18j}^{(1)}(t,3) = \exp[-$$
$$\lambda_{1j}^{(1)}(3)\,t]\ \exp[-\lambda_{2j}^{(1)}(3)\,t]\ ...\exp[-\lambda_{18,j}^{(1)}(3)\,t], \qquad (5)$$

$$\boldsymbol{S}^{(1)}(t,4) = S_{1j}^{(1)}(t,4) \cdot S_{2j}^{(1)}(t,4) \cdot ... \cdot S_{18j}^{(1)}(t,4) = \exp[-$$
$$\lambda_{1j}^{(1)}(4)\,t]\ \exp[-\lambda_{2j}^{(1)}(4)\,t]\ ...\exp[-\lambda_{18,j}^{(1)}(4)\,t]. \qquad (6)$$

Considering that the Baltic Port Critical Infrastructure Network is a five-state system with three cases of the safety structure, after applying (2.24)-(2.25) in [EU-CIRCLE Report D3.3-GMU3], its safety function is given by

$$\boldsymbol{S}(t,\cdot) = [1,\ \boldsymbol{S}(t,1),\ \boldsymbol{S}(t,2),\ \boldsymbol{S}(t,3),\ \boldsymbol{S}(t,4)\ ],$$
$$t \geq 0, \qquad (7)$$

where according to [EU-CIRCLE Report D3.3-GMU3], we have:

Case 1. Series system with cooridantes given by

$$\boldsymbol{S}(t,u) = \ddot{\boldsymbol{S}}_{18}(t,u) =$$

$$\boldsymbol{S}^{(1)}(t,u)\cdot\boldsymbol{S}^{(2)}(t,u)\cdot\ldots\cdot\boldsymbol{S}^{(18)}(t,u)$$
$$\text{for } u = 1,2,3,4, \qquad (8)$$

and particularly

$$\boldsymbol{S}^{(1)}(t,1) = \prod_{i=1}^{18}\exp[-\lambda_{ij}^{(1)}(1)t],\ j = 1,2,3,\ \text{for } t \ge 0, \quad (9)$$

$$\boldsymbol{S}^{(1)}(t,2) = \prod_{i=1}^{18}\exp[-\lambda_{ij}^{(1)}(2)],\ j = 1,2,3,\ \text{for } t \ge 0, \quad (10)$$

$$\boldsymbol{S}^{(1)}(t,3) = \prod_{i=1}^{18}\exp[-\lambda_{ij}^{(1)}(3)],\ j = 1,2,3,\ \text{for } t \ge 0, \quad (11)$$

$$\boldsymbol{S}^{(1)}(t,4) = \prod_{i=1}^{18}\exp[-\lambda_{ij}^{(1)}(4)],\ j = 1,2,3,\text{for } t \ge 0. \quad (12)$$

The expected values and standard deviations of the port critical infrastructure network lifetimes in the safety state subsets calculated from the results given by (9) – (12), according to the formulae (2.15)-(2.17) in [EU-CIRCLE Report D3.3-GMU3] respectively are:

$$\mu^{(1)}(1),\ \mu^{(1)}(2),\ \mu^{(1)}(3),\ \mu^{(1)}(4)$$

and

$$\sigma^{(1)}(1),\ \sigma^{(1)}(2),\ \sigma^{(1)}(3),\ \sigma^{(1)}(4),$$

and further, using above results , from (2.19) in [EU-CIRCLE Report D3.3-GMU3], the mean values of the port critical infrastructure network conditional lifetimes in the particular safety states are:

$$\bar{\mu}^{(1)}(1),\ \bar{\mu}^{(1)}(2),\ \bar{\mu}^{(1)}(3),\ \bar{\mu}^{(1)}(4).$$

As the critical safety state is r =2, then the port critical infrastructure network risk function, according to (2.20) in [EU-CIRCLE Report D3.3-GMU3], is given by

$$\boldsymbol{r}(\mathrm{t}) = 1-\boldsymbol{S}(t,2) = 1- \prod_{i=1}^{18}\exp[-\lambda_{ij}^{(1)}(2)],$$
$$j = 1,2,3,\ \text{for } t \ge 0. \qquad (13)$$

Case 2. series -“3 out of 18” system with coordinates given by

$$\boldsymbol{S}(t,u) = \ddot{\boldsymbol{S}}_{18}(t,u) = 1-$$
$$\sum_{\substack{r_1,r_2,\ldots,r_{18}=0\\ r_1+r_2+\ldots+r_{18}\le 2}}^{1}\ \prod_{i=1}^{18}[\prod_{j=1}^{3} S_{ij}^{(1)}(t,u)]^{r_i}[1-\prod_{j=1}^{3} S_{ij}^{(1)}(t,u)]^{1-r_i}, \quad (14)$$

for $t \in< 0,\infty)$, $u = 1,2,\ldots,4$.

The expected values and standard deviations of the port critical infrastructure network lifetimes in the safety state subsets calculated from the results given by (14), according to the formulae (2.15)-(2.17) in [EU-CIRCLE Report D3.3-GMU3] respectively are:

$$\mu^{(1)}(1),\ \mu^{(1)}(2),\ \mu^{(1)}(3),\ \mu^{(1)}(4)$$

and

$$\sigma^{(1)}(1),\ \sigma^{(1)}(2),\ \sigma^{(1)}(3),\ \sigma^{(1)}(4),$$

and further, using above results , from (2.19) in [EU-CIRCLE Report D3.3-GMU3], the mean values of the port critical infrastructure network conditional lifetimes in the particular safety states are:

$$\bar{\mu}^{(1)}(1),\ \bar{\mu}^{(1)}(2),\ \bar{\mu}^{(1)}(3),\ \bar{\mu}^{(1)}(4).$$

As the critical safety state is r =2, then the port critical infrastructure network isk function, according to (2.20) in [EU-CIRCLE Report D3.3-GMU3], is given by

$$\boldsymbol{r}(\mathrm{t}) = 1-\boldsymbol{S}(t,2) =$$
$$\sum_{\substack{r_1,r_2,\ldots,r_{18}=0\\ r_1+r_2+\ldots+r_{18}\le 2}}^{1}\ \prod_{i=1}^{18}[\prod_{j=1}^{3} S_{ij}^{(1)}(t,2)]^{r_i}[1-\prod_{j=1}^{3} S_{ij}^{(1)}(t,2)]^{1-r_i},,$$
$$i = 1,2,3,\ \text{for } t \ge 0. \qquad (15)$$

Case 3. series-consecutive “2 out of 18:F” system with the coordinates given by the following recurrent formula

$$\boldsymbol{S}(t,u) = \ddot{\boldsymbol{S}}_{18}(t,u) = \boldsymbol{S}_{\boldsymbol{k}}(t,u) =$$
$$\begin{cases} 1 & \text{for } k < m,\\ 1-\prod_{i=1}^{k}[1-\prod_{j=1}^{3}S_{ij}(t,u)] & \text{for } k = m,\\ [\prod_{j=1}^{3}S_{kj}(t,u)]\boldsymbol{S}_{k-1}(t,u) & \\ +\sum_{j=1}^{m-1}[\prod_{v=1}^{3-j}S_{k-j,v}(t,u)]\boldsymbol{S}_{k-j-1}(t,u)\cdot & \\ \prod_{\mathrm{i=k-j+1}}^{\mathrm{k}}[1-\prod_{\mathrm{v=1}}^{3}S_{\mathrm{iv}}(t,u)] & \text{for } k > m, \end{cases} \qquad (16)$$

for $t \ge 0$, $u = 1,2,3,4$.

The expected values and standard deviations of the port critical infrastructure network lifetimes in the safety state subsets calculated from the results given by (16), according to the formulae (2.15)-(2.17) in [EU-CIRCLE Report D3.3-GMU3] respectively are:

$$\mu^{(1)}(1),\ \mu^{(1)}(2),\ \mu^{(1)}(3),\ \mu^{(1)}(4)$$

and

$$\sigma^{(1)}(1),\ \sigma^{(1)}(2),\ \sigma^{(1)}(3),\ \sigma^{(1)}(4),$$

and further, using above results , from (2.19) in [EU-CIRCLE Report D3.3-GMU3], the mean values of the port critical infrastructure network conditional lifetimes in the particular safety states are:

$$\bar{\mu}^{(1)}(1),\ \bar{\mu}^{(1)}(2),\ \bar{\mu}^{(1)}(3),\ \bar{\mu}^{(1)}(4).$$

As the critical safety state is r =2, then the port critical infrastructure network risk function, according to (2.20) in [EU-CIRCLE Report D3.3-GMU3], is given by

$$\boldsymbol{r}(\mathrm{t}) = 1-\boldsymbol{S}(t,2) = 1-\boldsymbol{S}_k(t,2) = 1-$$

$$\begin{cases} 1 & \text{for } k<m, \\ 1-\prod_{i=1}^{k}[1-\prod_{j=1}^{3}S_{ij}(t,2)] & \text{for } k=m, \\ [\prod_{j=1}^{3}S_{kj}(t,2)]\boldsymbol{S}_{k-1}(t,2) & \\ +\sum_{j=1}^{m-1}[\prod_{v=1}^{3-j}S_{k-j,v}(t,2)]\boldsymbol{S}_{k-j-1}(t,2) & \\ \cdot\prod_{\mathrm{i=k-j+1}}^{\mathrm{k}}[1-\prod_{\mathrm{v=1}}^{3}S_{\mathrm{iv}}(t,2)] & \text{for } k>m, \end{cases} \quad , \qquad (17)$$

for $t \geq 0$.

3. Safety and Risk prediction of Shipping Critical Infrastructure Network

3.1. Shipping Critial infrastructure Network Description

We take into account the complex Baltic Shipping Critical Infrastructure Network S_2 composed of numbers of ships (n_{cd}) into regions D_{cd}, $c=1,2,...,m,\ d=1,2,...,n,\ m,n \in N$.

3.2. Defining the Parameters of the Shipping Critial Infrastructure Network Safety Model

According to the effectiveness and safety aspects of the operation of the Baltic Shipping Critical Infrastructure Network, we fix:

- the number of shipping critical infrastructure network safety states $(z = 4)$ and we distinguish the following five safety states:
  - a safety state 4 – BSCIN operations are fully safe,
  - a safety state 3 – BSCIN operations are less safe and more dangerous because of the possibility of damage of the ships without the environmental pollution in regions area,
  - a safety state 2 – BSCIN operations are less safe and more dangerous because of the possibility of collisions or groundings of ships without the environmental pollution in regions area,
  - a safety state 1 – BSCIN operations are less safe and very dangerous because of the possibility of collisions or groundings and environmental pollution in regions area,
  - a safety state 0 – BSCIN is destroyed,

Moreover, by the expert opinions, we assume that there are possible the transitions between the components safety states only from better to worse ones;

- the safety structure of the system and subsystems

The shipping critical infrastructure network is a complex series system composed of $c \cdot d$ series subsystems S_{2i}, $i=1,...,d,d+1,...,2d,2d+1,..., 3d,...,(c-1)d,(c-1)d+1,...,cd$ each containing numbers of ships as the components.

The unknown parameters of the multistate ageing system safety model are:

- the number of safety states of the system and components z,

- the critical safety state of the system r,

- the system risk permitted level δ,

- the parameters of a system and subsystems safety structure.

3.3. Defining the Input Parameters of the Shipping Critical Infrastructure Network Safety Model

The input necessary parameters of the shipping critical infrastructure network safety models are as follows [EU-CIRCLE Report D3.3-GMU1, 2016], [EU-CIRCLE Report D2.2-GMU1] :

- the number of safety states of the system and components z=4,

- the critical safety state of the system $r = 2$,

- the system risk permitted level $\delta = 0.05$,

- the parameters of a system safety structure:

- Case 1 - series system
  - the number of components (subsystem) $n = c \cdot d$
- Case 2 – "l out of k" system
  - the number of components (subsystem) k, $k = c \cdot d$
  - *the tresholds* number of subsystems l, $l = 0.5 \cdot c \cdot d$
- Case 1 – consecutive "l out of k:F" system
  - the number of components (subsystem) $k, k = c \cdot d$
  - *the tresholds* number of subsystems l,

    $l = 0.25 \cdot c \cdot d$
  - the parameters of the subsystems S_{2i}, $i = 1,\ldots,d,d+1,\ldots,(c-1)d,(c-1)d+1,\ldots,cd$ safety structures
- series system:
  - the number of components $k = \sum_{D_{cd}} n_{cd}$, where n_{cd} is the number of ships in area D_{cd};

- the intensities of components departure from the safety states subset {1,2,3,4}, {2,3,4}, {3,4}, {4}, are as follows:

- for subsystems S_{2i}, $i = 1,\ldots,d,d+1,\ldots,$ $(c-1)d$, $(c-1)d+1,\ldots,cd$,

$$[\lambda_{ij}^{(2)}(1)],\ [\lambda_{ij}^{(2)}(2)],\ [\lambda_{ij}^{(2)}(3)],\ [\lambda_{ij}^{(2)}(4)],$$

$i = 1,\ldots,d,d+1,\ldots,(c-1)d,(c-1)d+1,\ldots,cd$
$j = 1,2,..,n_{cd}$.

3.4. Prediction of the Characteristics of the Shipping Critical Infrastructure Network Safety Model

We assume that the system is composed of components having multistate exponential safety functions.
The subsystems S_{2i}, $i = 1,\ldots,d,d+1,\ldots,(c-1)d$, $(c-1)d+1,\ldots,cd$, consist of $k = \sum_{D_{cd}} n_{cd}$ ship dynamic technical systems, each composed of n_{cd} components $E_{ij}^{(2)}$, $i = 1,\ldots,d,d+1,\ldots,(c-1)d$, $(c-1)d+1,\ldots,cd$, $j = 1,2,..,n_{cd}$, with the exponential safety functions given below.

In particular shipping dynamic technical systems there are:

- $\sum_{D_{cd}} n_{cd}$ components with the multistate safety functions co-ordinates

$$S_{ij}^{(2)}(t,1) = \exp[-\lambda_{ij}^{(2)}(1)\, t],$$

$$S_{ij}^{(2)}(t,2) = \exp[-\lambda_{ij}^{(2)}(2)\, t],$$

$$S_{ij}^{(2)}(t,3) = \exp[-\lambda_{ij}^{(2)}(3)\, t],$$

$$S_{ij}^{(2)}(t,4) = \exp[-\lambda_{ij}^{(2)}(4)\, t],$$

$i = 1,\ldots,d,d+1,\ldots,(c-1)d,(c-1)d+1,\ldots,cd$,
$j = 1,2,..,n_{cd}$.

Taking into account the safety model parameters from Section 2 in [EU-CIRCLE Report D3.3-GMU3] and Section 3.2.1 concerned with the fixed system safety structures and their shape parameters and with the assumed the exponential models of the safety functions of the system components and the results of the evaluations of the system components intensities of departures from the safety state subsets we may to perform the prediction of the Baltic Shipping Critical Infrstructure safety characteristics.
The subsystems S_{2i}, $i = 1,\ldots,d,d+1,\ldots,(c-1)d$, $(c-1)d+1,\ldots,cd$, are the five-state series systems and according to (2.22)-(2.23) in [EU-CIRCLE Report D3.3-GMU3] their five-state safety function is given by

$$\boldsymbol{S}^{(2)}(t,\cdot) = [1,\ \boldsymbol{S}^{(2)}(t,1),\ \boldsymbol{S}^{(2)}(t,2),\ \boldsymbol{S}^{(2)}(t,3),\ \boldsymbol{S}^{(2)}(t,4)\ ],\ t \ge 0, \quad (18)$$

where according to the formulae (2.22)-(2.23) and (2.58)-(2.59) in [EU-CIRCLE Report D3.3-GMU3],we have

$$\boldsymbol{S}^{(2)}(t,u) = \prod_{j=1}^{n_{ab}} S_{ij}^{(2)}(t,u), \qquad (19)$$

for $t \in <0,\infty)$, $u = 1,2,3,4$,
$i = 1,...,d, d+1,...,(c-1)d,(c-1)d+1,...,cd$

and particularly

$$\boldsymbol{S}^{(\upsilon)}(t,1) = S_{1j}^{(\upsilon)}(t,1)\cdot S_{2j}^{(\upsilon)}(t,1)\cdot\ldots\cdot S_{n_{ab}j}^{(\upsilon)}(t,1) = \exp[-\lambda_{1j}^{(\upsilon)}(1)\,t]\exp[-\lambda_{2j}^{(\upsilon)}(1)\,t]\ldots\exp[-\lambda_{n_{ab}j}^{(\upsilon)}(1)\,t], \qquad (20)$$

$$\boldsymbol{S}^{(\upsilon)}(t,2) = S_{1j}^{(\upsilon)}(t,2)\cdot S_{2j}^{(\upsilon)}(t,2)\cdot\ldots\cdot S_{n_{ab}j}^{(\upsilon)}(t,2) = \exp[-\lambda_{1j}^{(\upsilon)}(2)\,t]\exp[-\lambda_{2j}^{(\upsilon)}(2)\,t]\ldots\exp[-\lambda_{n_{ab}j}^{(\upsilon)}(2)\,t], \qquad (21)$$

$$\boldsymbol{S}^{(\upsilon)}(t,3) = S_{1j}^{(\upsilon)}(t,3)\cdot S_{2j}^{(\upsilon)}(t,3)\cdot\ldots\cdot S_{n_{ab}j}^{(\upsilon)}(t,3) = \exp[-\lambda_{1j}^{(\upsilon)}(3)\,t]\exp[-\lambda_{2j}^{(\upsilon)}(3)\,t]\ldots\exp[-\lambda_{n_{ab}j}^{(\upsilon)}(3)\,t], \qquad (22)$$

$$\boldsymbol{S}^{(\upsilon)}(t,4) = S_{1j}^{(\upsilon)}(t,4)\cdot S_{2j}^{(\upsilon)}(t,4)\cdot\ldots\cdot S_{n_{ab}j}^{(\upsilon)}(t,4) = \exp[-\lambda_{1j}^{(\upsilon)}(4)\,t]\exp[-\lambda_{2j}^{(\upsilon)}(4)\,t]\ldots\exp[-\lambda_{n_{ab}j}^{(\upsilon)}(4)\,t]. \qquad (23)$$

We consider the Baltic Shipping Critical Infrastructure Network as a five-state system with three cases of its safety structure., after applying (2.24)-(2.25) in [EU-CIRCLE Report D3.3-GMU3], its safety function is given by

$$\boldsymbol{S}(t,\cdot) = [1, \boldsymbol{S}(t,1), \boldsymbol{S}(t,2), \boldsymbol{S}(t,3), \boldsymbol{S}(t,4)], \quad t \geq 0, \qquad (24)$$

where we have

Case 1. Series system with cooridnantes given by

$$\boldsymbol{S}(t,u) = \ddot{\boldsymbol{S}}_{ab}(t,u) = \boldsymbol{S}^{(1)}(t,u)\cdot\boldsymbol{S}^{(2)}(t,u)\cdot\ldots\cdot\boldsymbol{S}^{(c\cdot d)}(t,u) \qquad (25)$$

for $u = 1,2,3,4$,

and particularly

$$\boldsymbol{S}^{(2)}(t,1) = \prod_{i=1}^{a\cdot b}\exp[-\lambda_{ij}^{(2)}(1)t], \qquad (26)$$

$$\boldsymbol{S}^{(2)}(t,2) = \prod_{i=1}^{a\cdot b}\exp[-\lambda_{ij}^{(2)}(2)t], \qquad (27)$$

$$\boldsymbol{S}^{(2)}(t,3) = \prod_{i=1}^{a\cdot b}\exp[-\lambda_{ij}^{(2)}(3)t], \qquad (28)$$

$$\boldsymbol{S}^{(2)}(t,4) = \prod_{i=1}^{a\cdot b}\exp[-\lambda_{ij}^{(2)}(4)t], \qquad (29)$$

where $j = 1,2,...,n_{cd}$, for $t \geq 0$.

The expected values and standard deviations of the shipping critical infrastructure network lifetimes in the safety state subsets calculated from the results given by (25)-(28), according to the formulae (2.15)-(2.17) in [EU-CIRCLE Report D3.3-GMU3] respectively are:

$$\mu^{(2)}(1),\ \mu^{(2)}(2),\ \mu^{(2)}(3),\ \mu^{(2)}(4)$$

and

$$\sigma^{(2)}(1),\ \sigma^{(2)}(2),\ \sigma^{(2)}(3),\ \sigma^{(2)}(4),$$

and further, using above results , from (2.19) in [EU-CIRCLE Report D3.3-GMU3], the mean values of the shipping critical infrastructure network conditional lifetimes in the particular safety states are:

$$\bar{\mu}^{(2)}(1),\ \bar{\mu}^{(2)}(2),\ \bar{\mu}^{(2)}(3),\ \bar{\mu}^{(2)}(4).$$

As the critical safety state is $r = 2$, then the Baltic Shipping Critical Infrastrtucture Network risk function, according to (2.20) in [EU-CIRCLE Report D3.3-GMU3], is given by

$$\boldsymbol{r}(\mathrm{t}) = 1 - \boldsymbol{S}(t,2) = 1 - \prod_{i=1}^{a\cdot b}\exp[-\lambda_{ij}^{(2)}(2)t], \qquad (30)$$

for $j = 1,2,...,n_{ab}$, for $t \geq 0$.

Case 2. series -"$\lceil 0.5\cdot c\cdot d\rceil$ out of $c\cdot d$" system with coordinates given by

$$\boldsymbol{S}(t,u) = \ddot{\boldsymbol{S}}_{c\cdot d}(t,u) = 1 - \sum_{\substack{r_1,r_2,...,r_{a\cdot b}=0 \\ r_1+r_2+...+r_{a\cdot b}\leq\lceil 0.5\cdot c\cdot d\rceil-1}}^{1} \prod_{i=1}^{cd}[\prod_{j=1}^{l_i} S_{ij}(t,u)]^{r_i}[1-\prod_{j=1}^{l_i} S_{ij}(t,u)]^{1-r_i},$$

for $t \in <0,\infty)$, (31)

where
u=1,2,3,4,
$l_1 = n_{11}, l_2 = n_{12}, \ldots, l_b = n_{1d}, l_{d+1} = n_{21}, \ldots, l_{c \cdot d} = n_{cd}$.

The expected values and standard deviations of the shipping critical infrastructure network lifetimes in the safety state subsets calculated from the results given by (3.14), according to the formulae (2.15)-(2.17) in [EU-CIRCLE Report D3.3-GMU3] respectively are:

$$\mu^{(2)}(1),\ \mu^{(2)}(2),\ \mu^{(2)}(3),\ \mu^{(2)}(4)$$

and

$$\sigma^{(2)}(1),\ \sigma^{(2)}(2),\ \sigma^{(2)}(3),\ \sigma^{(2)}(4),$$

and further, using above results , from (2.19) in [EU-CIRCLE Report D3.3-GMU3], the mean values of the shipping critical infrastructure network conditional lifetimes in the particular safety states are:

$$\bar{\mu}^{(2)}(1),\ \bar{\mu}^{(2)}(2),\ \bar{\mu}^{(2)}(3),\ \bar{\mu}^{(2)}(4).$$

As the critical safety state is r =2, then the Baltic Shipping Critical Infrastructure Network risk function, according to (2.20) in [EU-CIRCLE Report D3.3-GMU3], is given by

$$\boldsymbol{r}(\mathrm{t}) = 1 - \boldsymbol{S}(t,2) = \sum_{\substack{r_1, r_2, \ldots, r_{a \cdot b} = 0 \\ r_1 + r_2 + \ldots + r_{a \cdot b} \le \lceil 0.5 \cdot c \cdot d \rceil - 1}}^{1} \prod_{i=1}^{cd} [\prod_{j=1}^{l_i} S_{ij}(t,2)]^{r_i} [1 - \prod_{j=1}^{l_i} S_{ij}(t,2)]^{1-r_i},$$

for $t \in < 0, \infty)$, (32)

where
$l_1 = n_{11}, l_2 = n_{12}, \ldots, l_d = n_{1d}, l_{d+1} = n_{21}, \ldots, l_{c \cdot d} = n_{cd}$.

Case 3. series-consecutive "$\lfloor 0.25 \cdot c \cdot d \rfloor$ out of $c \cdot d$: F" system with the coordinates given by the following recurrent formula

$$\boldsymbol{S}(t,u) = \ddot{\boldsymbol{S}}_{c \cdot d}(t,u) = \boldsymbol{S}_{\boldsymbol{k}}(t,u) =$$

$$\begin{cases} 1 & \text{for } k < m, \\ 1 - \prod_{i=1}^{k} [1 - \prod_{j=1}^{l_i} S_{ij}(t,u)] & \text{for } k = m, \\ [\prod_{j=1}^{l_k} S_{kj}(t,u)] \boldsymbol{S}_{k-1}(t,u) & \\ + \sum_{j=1}^{m-1} [\prod_{v=1}^{l_{k-j}} S_{k-j,v}(t,u)] \boldsymbol{S}_{k-j-1}(t,u) \cdot & \\ \prod_{\mathrm{i=k-j+1}}^{\mathrm{k}} [1 - \prod_{\mathrm{v=1}}^{\mathrm{l_i}} S_{\mathrm{iv}}(t,u)] & \text{for } k > m, \end{cases} \qquad (33)$$

for $t \ge 0$,
$k = 1, \ldots, d, d+1, \ldots, 2d, 2d+1, \ldots, 3d, \ldots, (c-1)d,$
$(c-1)d + 1, \ldots, cd$, u = 1,2,3,4, $l_1 = n_{11}, l_2 = n_{12}, \ldots,$.
$l_d = n_{1d}, l_{d+1} = n_{21}, \ldots, l_{c \cdot d} = n_{cd}$.

The expected values and standard deviations of the shipping critical infrastructure network lifetimes in the safety state subsets calculated from the results given by (33), according to the formulae (2.15)-(2.17) in [EU-CIRCLE Report D3.3-GMU3] respectively are:

$$\mu^{(2)}(1),\ \mu^{(2)}(2),\ \mu^{(2)}(3),\ \mu^{(2)}(4)$$

and

$$\sigma^{(2)}(1),\ \sigma^{(2)}(2),\ \sigma^{(2)}(3),\ \sigma^{(2)}(4),$$

and further, using above results , from (2.19) in [EU-CIRCLE Report D3.3-GMU3], the mean values of the shipping critical infrastructure network conditional lifetimes in the particular safety states are:

$$\bar{\mu}^{(2)}(1),\ \bar{\mu}^{(2)}(2),\ \bar{\mu}^{(2)}(3),\ \bar{\mu}^{(2)}(4).$$

As the critical safety state is r =2, then the Baltic Shipping Critical Infrastructure Network risk function, according to (2.20) in [EU-CIRCLE Report D3.3-GMU3], is given by

$$\boldsymbol{r}(\mathrm{t}) = 1 - \boldsymbol{S}(t,2) = 1 - \boldsymbol{S}_{\boldsymbol{k}}(t,2) = 1 -$$

$$\begin{cases} 1 & \text{for } k < m \\ 1 - \prod_{i=1}^{k}[1 - \prod_{j=1}^{l_i} S_{ij}(t,2)] & \text{for } k = m \\ [\prod_{j=1}^{l_k} S_{kj}(t,2)]\mathbf{S}_{k-1}(t,2) + & \\ \sum_{j=1}^{m-1}[\prod_{v=1}^{l_{k-j}} S_{k-j,v}(t,2)]\mathbf{S}_{k-j-1}(t,2) \cdot & \text{for } k > m \\ \prod_{\mathrm{i=k-j+1}}^{\mathrm{k}} [1 - \prod_{\mathrm{v=1}}^{\mathrm{l_i}} S_{\mathrm{iv}}(t,2)] & \end{cases} \quad (34)$$

where
$j = 1,2,...,l_i$, $i = 1,2,3$, for $t \geq 0$, u=1,2,3,4,
$k = 1,...,d, d+1,(c-1)d,(c-1)d+1,...,cd$,
$l_1 = n_{11}, l_2 = n_{12},..., l_d = n_{1d}, l_{d+1} = n_{21},..., l_{c \cdot d} = n_{cd}$.

4. Safety and Risk prediction of Ship Traffic and Port Operation Information Critical Infrastructure Network

4.1. Ship Traffic and Port Operation Information Critial infrastructure Network Description

We take into account the complex technical ship traffic and port operation information critical infrastructure network S_3 composed of :

- the subsystem S_{31} which consist of 121 AIS base stations and 25 DGPS stations $E_{11}^{(3)}$, $E_{21}^{(3)}$, …, $E_{146,1}^{(3)}$;
- the subsystem S_{32} which consist of at least 18 port operation information systems $E_{21}^{(3)}$, …, $E_{2,18}^{(3)}$.

4.2. Defining the Parameters of the Ship Traffic and Port Operation Information Critial Infrastructure Network Safety Model

According to the effectiveness and safety aspects of the operation of the Baltic Port Critical Infrastructure Network, we fix:

- the number of port critical infrastructure network safety states $(z = 4)$ and we distinguish the following five safety states:
  - a safety state 4 – port operation information subsystem is less safe and more dangerous because of the possibility of environment pollution and and causing small accidents,
  - a safety state 3 – ship traffic information subsystem is less safe and more dangerous because of the possibility of environment pollution and causing big accidents,
  - a safety state 2 – port operation information subsystem is less safe and more dangerous because of the possibility of environment pollution and and causing big accidents,
  - a safety state 1 – both subsystems are less safe and more dangerous because of the possibility of environment pollution and and causing accidents,
  - a safety state 0 – STPOICIN is destroyed,

Moreover, by the expert opinions, we assume that there are possible the transitions between the components safety states only from better to worse ones;

- the safety structure of the system and subsystems

We consider the ship traffic and port operation information critical infrastructure network as a series safety strucutres.

The unknown parameters of the multistate ageing system safety model are:

- the number of safety states of the system and components z,

- the critical safety state of the system r,

- the system risk permitted level δ,

- the parameters of a system and subsystems safety structure.

4.3. Defining the Input Parameters of the Ship Traffic and Port Operation Information Critical Infrastructure Network Safety Model

The input necessary parameters of the port critical infrastructure network safety models are as follows [EU-CIRCLE Report D3.3-GMU1, 2016], [EU-CIRCLE Report D2.2-GMU1] :

- the number of safety states of the system and components z=5,

- the critical safety state of the system $r = 2$,

- the system risk permitted level $\delta = 0.05$,

- the parameters of a system safety structure:

- series system
    - the number of components (subsystem) *n*, *n*=2
    - the parameters of the subsystem S_{31} safety structures
        - Case 1 - series system
            - the number of components (subsystem) *n*, *n*=146
        - Case 2 – "m out of n" system
            - the number of components (subsystem) *n*, *n*=146
            - the threshold number of subsystems m, m = 73
        - Case 3 – consecutive "m out of n: F" system
            - the number of components (subsystem) *n*, *n*=146
            - the threshold number of subsystems m, m = 2.
    - the parameters of the subsystem S_{32} safety structures
        - Case 1 - series system
            - the number of components (subsystem) *n*, *n*=18
        - Case 2 – "m out of n" system
            - the number of components (subsystem) *n*, *n*=18
            - the threshold number of subsystems m, m = 3
        - Case 3 – consecutive "m out of n: F" system
            - the number of components (subsystem) *n*, *n*=18
            - the threshold number of subsystems m, m = 2.

- the intensities of components departure from the safety states subset {1,2,3,4}, {2,3,4}, {3,4}, {4}, are as follows:

- for subsystems $S_{3\upsilon}$, $\upsilon = 1,2$

$$[\lambda_{ij}^{(3)}(1)],\ [\lambda_{ij}^{(3)}(2)],\ [\lambda_{ij}^{(3)}(3)],\ [\lambda_{ij}^{(3)}(4)],$$
$$i = 1,2,\ j = 1,2,..,l_i.$$

4.4. Prediction of the Characteristics of the Ship Traffic and Port Operation Information Critical Infrastructure Network Safety Model

We assume that the system is composed of components having multistate exponential safety functions.

The subsystem S_3 consist of $k = 2$ subsystems, each composed of $n(i)$ components $E_{ij}^{(3)}$, $i = 1,2,$ $j = 1,2,...,n(i)$ i.e. $l_1 = 146,$ $l_2 = 18$ with the exponential safety functions given below.

In particular Ship Traffic and Port Operation Information Critical Infrastructure Network there are:

- *n(i)* components with the multistate safety functions co-ordinates

$$S_{ij}^{(3)}(t,1) = \exp[-\lambda_{ij}^{(3)}(1)\, t],$$

$$S_{ij}^{(3)}(t,2) = \exp[-\lambda_{ij}^{(3)}(2)\, t],$$

$$S_{ij}^{(3)}(t,3) = \exp[-\lambda_{ij}^{(3)}(3)\, t],$$

$$S_{ij}^{(3)}(t,4) = \exp[-\lambda_{ij}^{(3)}(4)\, t],\ i = 1,2,\ \ j = 1,2,...,l_i.$$

Considering the safety model parameters from Section 2 in [EU-CIRCLE Report D3.3-GMU3] and Section 4.2.1 concerned with the fixed system safety structures and their shape parameters and with the assumed the exponential models of the safety functions of the system components and the results of the evaluations of the system components intensities of departures from the safety state subsets we may to perform the prediction of the Baltic Ship Traffic and Port Operation Information Critical Infrastructure Network safety characteristics.

The subsystems $S_{3\upsilon}$, $\upsilon = 1,2,,$ are the five-state systems and we consider the following cases of their safety structures:

Case 1. It is a complex series systems composed of 146 (S_{31}) and 18 (S_{32}) components as it was mentioned above.

The subsystems S_{3i}, i = 1,2,, are the five-state series systems and according to (2.22)-(2.23) in [EU-CIRCLE Report D3.3-GMU3] their five-state safety function is given by

$$\boldsymbol{S}^{(3)}(t,\cdot) = [1,\ \boldsymbol{S}^{(3)}(t,1),\ \boldsymbol{S}^{(3)}(t,2),\ \boldsymbol{S}^{(3)}(t,3),$$
$$\boldsymbol{S}^{(3)}(t,4)\,],\ t \geq 0, \qquad (35)$$

where according to the formulae (2.22)-(2.23) and (2.58)-(2.59) in [EU-CIRCLE Report D3.3-GMU3],we have

$$\boldsymbol{S}^{(3)}(t,u) = \prod_{j=1}^{l_i} S_{ij}^{(3)}(t,u) =$$
$$S_{i1}^{(3)}(t,u) \cdot S_{i2}^{(3)}(t,u) \cdot \ldots \cdot S_{il_i}^{(3)}(t,u), \qquad (36)$$

for $t \in <0,\infty)$, $i = 1,2$, $u = 1,2,3,4$

and particularly

$$\boldsymbol{S}^{(3)}(t,1) = S_{i1}^{(3)}(t,1) \cdot S_{i2}^{(3)}(t,1) \cdot \ldots \cdot S_{il_i}^{(3)}(t,1) = \exp[-$$
$$\lambda_{i1}^{(3)}(1)\,t]\,\exp[-\lambda_{i2}^{(3)}(1)\,t]\,\ldots\exp[-\lambda_{il_i}^{(3)}(1)\,t], \qquad (37)$$

$$\boldsymbol{S}^{(3)}(t,2) = S_{i1}^{(3)}(t,2) \cdot S_{i2}^{(3)}(t,2) \cdot \ldots \cdot S_{il_i}^{(3)}(t,2) = \exp[-$$
$$\lambda_{i1}^{(3)}(2)\,t]\,\exp[-\lambda_{i2}^{(3)}(2)\,t]\,\ldots\exp[-\lambda_{il_i}^{(3)}(2)\,t], \qquad (38)$$

$$\boldsymbol{S}^{(3)}(t,3) = S_{i1}^{(3)}(t,3) \cdot S_{i2}^{(3)}(t,3) \cdot \ldots \cdot S_{il_i}^{(3)}(t,3) = \exp[-$$
$$\lambda_{i1}^{(3)}(3)\,t]\,\exp[-\lambda_{i2}^{(3)}(3)\,t]\ldots\,\exp[-\lambda_{il_i}^{(3)}(3)\,t], \qquad (39)$$

$$\boldsymbol{S}^{(3)}(t,4) = S_{i1}^{(3)}(t,4) \cdot S_{i2}^{(3)}(t,4) \cdot \ldots \cdot S_{il_i}^{(3)}(t,4) = \exp[-$$
$$\lambda_{i1}^{(3)}(4)\,t]\,\exp[-\lambda_{i2}^{(3)}(4)\,t]\ldots\,\exp[-\lambda_{il_i}^{(3)}(4)\,t]. \qquad (40)$$

Case 2. It is a complex "k out of l" systems composed of 146 (S_{31}) and 18 (S_{32}) components as it was mentioned above.

The subsystem S_{31} is the five-state "73 out of 146" system and according to (2.22)-(2.23) in [EU-CIRCLE Report D3.3-GMU3] their five-state safety function is given by

$$\boldsymbol{S}^{(31)}(t,\cdot) = [1,\ \boldsymbol{S}^{(31)}(t,1),\ \boldsymbol{S}^{(31)}(t,2),\ \boldsymbol{S}^{(31)}(t,3),$$
$$\boldsymbol{S}^{(31)}(t,4)\,],\ t \ge 0, \qquad (41)$$

with the coordinates

$$\boldsymbol{S}(t,u) = 1 - \sum_{\substack{r_1,r_2,\ldots,r_{146}=0 \\ r_1+r_2+\ldots+r_{146} \le 72}}^{1} [S_i^{(31)}(t,u)]^{r_i}\,[F_i^{(31)}(t,u)]^{1-r_i},$$
$$t \in <0,\infty),\ u = 1,2,3,4,\ i = 1,2,\ldots,146. \qquad (42)$$

The subsystem S_{32} is the five-state "3 out of 18" system and according to (2.22)-(2.23) in [EU-CIRCLE Report D3.3-GMU3] their five-state safety function is given by

$$\boldsymbol{S}^{(32)}(t,\cdot) = [1,\ \boldsymbol{S}^{(32)}(t,1),\ \boldsymbol{S}^{(32)}(t,2),\ \boldsymbol{S}^{(32)}(t,3),$$
$$\boldsymbol{S}^{(32)}(t,4)\,],\ t \ge 0, \qquad (43)$$

with the coordinates

$$\boldsymbol{S}(t,u) = 1 - \sum_{\substack{r_1,r_2,\ldots,r_{18}=0 \\ r_1+r_2+\ldots+r_{18} \le 2}}^{1} [S_i^{(32)}(t,u)]^{r_i}\,[F_i^{(32)}(t,u)]^{1-r_i},$$
$$t \in <0,\infty),\ u = 1,2,3,4,\ i = 1,2,\ldots,18. \qquad (44)$$

Case 3. It is a complex consecutive "k out of l:F" systems composed of 146 (S_{31}) and 18 (S_{32}) components as it was mentioned above.

The subsystem S_{31} is the five-state consecutive "2 out of 146: F" system and according to (2.22)-(2.23) in [EU-CIRCLE Report D3.3-GMU3] their five-state safety function is given by

$$\boldsymbol{S}^{(31)}(t,\cdot) = [1,\ \boldsymbol{S}^{(31)}(t,1),\ \boldsymbol{S}^{(31)}(t,2),\ \boldsymbol{S}^{(31)}(t,3),$$
$$\boldsymbol{S}^{(31)}(t,4)\,],\ t \ge 0, \qquad (45)$$

with the coordinates

$$\boldsymbol{S}(t,u) = \boldsymbol{S}_n(t,u) =$$
$$\begin{cases} 1 & \text{for } n < m, \\ 1 - \prod_{i=1}^{n} F_i(t,u) & \text{for } n = m, \\ S_n(t,u)\boldsymbol{S}_{n-1}(t,u) + & \\ \sum_{i=1}^{m-1} S_{n-i}(t,u)\boldsymbol{S}_{n-i-1}(t,u) \cdot & \\ \prod_{j=n-i+1}^{n} F_j(t,u) & \text{for } n > m, \end{cases} \qquad (46)$$

$$t \in <0,\infty),\ u = 1,2,3,4.$$

The subsystem S_{32} is the five-state "2 out of 18" system and according to (2.22)-(2.23) in [EU-CIRCLE Report D3.3-GMU3] their five-state safety function is given by

$$\boldsymbol{S}^{(32)}(t,\cdot) = [1,\ \boldsymbol{S}^{(32)}(t,1),\ \boldsymbol{S}^{(32)}(t,2),\ \boldsymbol{S}^{(32)}(t,3),$$
$$\boldsymbol{S}^{(32)}(t,4)\,],\ t \ge 0, \qquad (47)$$

with the coordinates

$$\boldsymbol{S}(t,u) = \boldsymbol{S}_n(t,u) = \begin{cases} 1 & \text{for } n < m, \\ 1 - \prod_{i=1}^{n} F_i(t,u) & \text{for } n = m, \\ S_n(t,u)\boldsymbol{S}_{n-1}(t,u) + \\ \sum_{i=1}^{m-1} S_{n-i}(t,u)\boldsymbol{S}_{n-i-1}(t,u) \cdot \\ \prod_{j=n-i+1}^{n} F_j(t,u) & \text{for } n > m, \end{cases} \tag{48}$$

$t \in <0,\infty)$, $u = 1,2,3,4$.

Considering that the Baltic Ship Traffic and Port Operation Information Critical Infrastructure Network is a five-state series system, after applying (2.24)-(2.25) in [EU-CIRCLE Report D3.3-GMU3], its safety function is given by

$$\boldsymbol{S}(t,\cdot) = [1, \boldsymbol{S}(t,1), \boldsymbol{S}(t,2), \boldsymbol{S}(t,3), \boldsymbol{S}(t,4)], \quad t \geq 0, \tag{49}$$

with coordinates given by

$$\boldsymbol{S}(t,u) = \ddot{\boldsymbol{S}}_3(t,u) = \prod_{i=1}^{2} \boldsymbol{S}^{(3i)}(t,u) \quad \text{for } u = 1,2,3,4, \tag{50}$$

and particularly

$$\boldsymbol{S}^{(3)}(t,1) = \prod_{j=1}^{l_i} \exp[-\lambda_{ij}^{(3)}(1)t], \quad i = 1,2, \text{ for } t \geq 0, \tag{51}$$

$$\boldsymbol{S}^{(3)}(t,2) = \prod_{j=1}^{l_i} \exp[-\lambda_{ij}^{(3)}(2)], \quad i = 1,2, \text{ for } t \geq 0, \tag{52}$$

$$\boldsymbol{S}^{(3)}(t,3) = \prod_{j=1}^{l_i} \exp[-\lambda_{ij}^{(3)}(3)], \quad i = 1,2, \text{ for } t \geq 0, \tag{53}$$

$$\boldsymbol{S}^{(3)}(t,4) = \prod_{j=1}^{l_i} \exp[-\lambda_{ij}^{(3)}(4)], \quad i = 1,2, \text{ for } t \geq 0, \tag{54}$$

The expected values and standard deviations of the ship traffic and port operation information critical infrastructure network lifetimes in the safety state subsets calculated from the results given by (5.51)-(5.54), according to the formulae (2.15)-(2.17) in [EU-CIRCLE Report D3.3-GMU3] respectively are:

$$\mu^{(3)}(1),\ \mu^{(3)}(2),\ \mu^{(3)}(3),\ \mu^{(3)}(4)$$

and

$$\sigma^{(3)}(1),\ \sigma^{(3)}(2),\ \sigma^{(3)}(3),\ \sigma^{(3)}(4),$$

and further, using above results , from (2.19) in [EU-CIRCLE Report D3.3-GMU3], the mean values of the ship traffic and port operation information critical infrastructure network conditional lifetimes in the particular safety states are:

$$\bar{\mu}^{(3)}(1),\ \bar{\mu}^{(3)}(2),\ \bar{\mu}^{(3)}(3),\ \bar{\mu}^{(3)}(4).$$

As the critical safety state is r =2, then the Baltic Ship Traffic and Port Operation Information Critical Infrastructure Network risk function, according to (52), is given by

$$\boldsymbol{r}(\mathrm{t}) = 1 - \boldsymbol{S}(t,2) = 1 - \prod_{j=1}^{l_i} \exp[-\lambda_{ij}^{(3)}(2)], \quad i = 1,2, \text{ for } t \geq 0. \tag{55}$$

5. Safety and Risk Prediction of Joint Network of Port, Shipping and Ship Traffic and Port Operation Information Critial infrastructure Networks

5.1. Joint Network of Port, Shipping and Ship Traffic and Port Operation Information Critial infrastructure Networks Description

The Joint Network of Baltic Port, Shipping and Ship Traffic and Port Operation Information Critical Infrastructure Networks (JNBPSSTPOICIN) is operating at the Baltic Sea Region. We assume that this system is composed of a number of main subsystems having an essential influence on its safety.
There are distinguished following subsystems:

- S_1 - the Port Critical Infrastructure Network subsystem,
- S_2 - the Shipping Critical Infrastructure Network subsystem,
- S_3 - the Ship Traffic and Port Operation Information Critcal Infrastructure subsystem.

5.2. Defining the Parameters of the Joint Network of Port, Shipping and Ship Traffic and Port Operation Information Critial infrastructure Networks Safety Model

According to the effectiveness and safety aspects of the operation of the Joint Network of Baltic Port, Shipping and Ship Traffic and Port Operation Information Critical Infrastructure Networks, we fix:

- the number of JNBPSSTPOICIN safety states $(z = 4)$ and we distinguish the following five safety states:
  - a safety state 4 – JNBPSSTPOICIN operations are fully safe,
  - a safety state 3 – JNBPSSTPOICIN operations are less safe and more dangerous, because of fact that one of the three CINs is less safe,
  - a safety state 2 – JNBPSSTPOICIN operations are less safe and more dangerous, , because of fact that two of the three CINs are less safe,
  - a safety state 1 – JNBPSSTPOICIN operations are less safe and very dangerous, three CINs are less safe,
  - a safety state 0 – JNBPSSTPOICIN is destroyed, three CINs are dangerous for users and environment.

Moreover, by the expert opinions, we assume that there are possible the transitions between the components safety states only from better to worse ones;

- the safety structure of the system and subsystems

The JNBPSSTPOICIN is a complex series system composed of

Case 1. Three series subsystems S_1, S_2 S_3.

Case 2. Two “m out of n” subsystems S_1, S_2 and one series S_3.

Case 3. Two consecutive “k out of n:F” subsystems S_1, S_2 and one series S_3.

Each of them containing fixed number of components as it was mentioned above in Sections 2-4.

The unknown parameters of the multistate ageing system safety model are:

- the number of safety states of the system and components z,

- the critical safety state of the system r,

- the system risk permitted level δ,

- the parameters of a system and subsystems safety structure.

5.3. Defining the Input Parameters of the Joint Network of Port, Shipping and Ship Traffic and Port Operation Information Critial infrastructure Networks Safety Model

The input necessary parameters of the Joint Network of Baltic Port, Shipping and Ship Traffic and Port Operation Information Critical Infrastructure Networks safety models are as follows [EU-CIRCLE Report D3.3-GMU1, 2016], [EU-CIRCLE Report D2.2-GMU1] :

- the number of safety states of the system and components z=4,

- the critical safety state of the system $r = 2$,

- the system risk permitted level $\delta = 0.05$,

- the parameters of a system safety structure:

- series system
  - the number of components (subsystem) n, n=3
  - the parameters of the subsystems $S^{(i)}$, $i = 1,2,3$ safety structures
    - Case 1 - series system
      - the number of components (subsystem) n_i, $i = 1,2,3$,

        $n_1 = 18$

        $n_2 = a \cdot b$

        $n_3 = 164;$
    - Case 2 – “m_i out of n_i” system
      - the number of components (subsystem) n_i, $i = 1,2$,

        $n_1 = 18$

        $n_2 = a \cdot b$
      - the threshold number of subsystems m_i, $i = 1,2$,

        $m_1 = 3$

        $m_2 = \lceil 0.5 \cdot a \cdot b \rceil$
    - Case 3 – consecutive “m_i out of n_i: F” system
      - the number of components (subsystem) n_i, $i = 1,2$,

        $n_1 = 18$

$n_2 = a \cdot b$

- the threshold number of subsystems m_i, $i = 1,2$,

  $m_1 = 2$

  $m_2 = \lfloor 0.25 \cdot a \cdot b \rfloor$

- the intensities of components departure from the safety states subset {1,2,3,4}, {2,3,4}, {3,4}, {4}, are as follows:

- for subsystem S_1

$[\lambda_{ij}^{(1)}(1)]$, $[\lambda_{ij}^{(1)}(2)]$, $[\lambda_{ij}^{(1)}(3)]$, $[\lambda_{ij}^{(1)}(4)]$,
$i = 1,2,\ldots,18$ $j = 1,2,3$,

- for subsystem S_2

$[\lambda_{ij}^{(2)}(1)]$, $[\lambda_{ij}^{(2)}(2)]$, $[\lambda_{ij}^{(2)}(3)]$, $[\lambda_{ij}^{(2)}(4)]$,
$i = 1,2,\ldots,a \cdot b$ $j = 1,2,3,\ldots,l_i$,

- for subsystem S_3

$[\lambda_{ij}^{(3)}(1)]$, $[\lambda_{ij}^{(3)}(2)]$, $[\lambda_{ij}^{(3)}(3)]$, $[\lambda_{ij}^{(3)}(4)]$, $i = 1,2$,
$j = 1,2,3,\ldots,l_i$.

5.4. Prediction of the Characteristics of the Joint Network of Port, Shipping and Ship Traffic and Port Operation Information Critical infrastructure Networks Safety Model

We assume that the systems is composed of components having multistate exponential safety functions.

Considering that the Joint Network of Port, Shipping and Ship Traffic and Port Operation Information Critical Infrastructure Networks is a five-state series system, after applying (2.24)-(2.25) in [EU-CIRCLE Report D3.3-GMU3], its safety function is given by

$$\boldsymbol{S}(t,\cdot) = [1, \boldsymbol{S}(t,1), \boldsymbol{S}(t,2), \boldsymbol{S}(t,3), \boldsymbol{S}(t,4)], \quad t \geq 0, \tag{56}$$

with cooridantes given by

$$\widehat{\boldsymbol{S}}_3(t,u) = \prod_{\upsilon=1}^{3} \ddot{\boldsymbol{S}}^{(\upsilon)}(t,u) \text{ for } u = 1,2,3,4, \tag{57}$$

and particularly

$$\ddot{\boldsymbol{S}}^{(\upsilon)}(t,1) = \prod_{\upsilon=1}^{3} \exp[-\lambda_{ij}^{(\upsilon)}(1)t], \; i = 1,2,3,\ldots,l_\upsilon,$$
$$j = 1,2,\ldots,n(i), \text{ for } t \geq 0, \tag{59}$$

$$\ddot{\boldsymbol{S}}^{(\upsilon)}(t,2) = \prod_{\upsilon=1}^{3} \exp[-\lambda_{ij}^{(\upsilon)}(2)t], \; i = 1,2,3,\ldots,l_\upsilon,$$
$$j = 1,2,\ldots,n(i), \text{ for } t \geq 0, \tag{60}$$

$$\ddot{\boldsymbol{S}}^{(\upsilon)}(t,3) = \prod_{\upsilon=1}^{3} \exp[-\lambda_{ij}^{(\upsilon)}(3)t], \; i = 1,2,3,\ldots,l_\upsilon,$$
$$j = 1,2,\ldots,n(i), \text{ for } t \geq 0, \tag{61}$$

$$\ddot{\boldsymbol{S}}^{(\upsilon)}(t,4) = \prod_{\upsilon=1}^{3} \exp[-\lambda_{ij}^{(\upsilon)}(3)t], \; i = 1,2,3,\ldots,l_\upsilon,$$
$$j = 1,2,\ldots,n(i), \text{ for } t \geq 0, \tag{62}$$

The expected values and standard deviations of the joint network of the port, shipping, and ship traffic and port operation information critical infrastructure network lifetimes in the safety state subsets calculated from the results given by (5.56)-(5.62), according to the formulae (2.15)-(2.17) in [EU-CIRCLE Report D3.3-GMU3] respectively are:

$\mu(1)$, $\mu(2)$, $\mu(3)$, $\mu(4)$

and

$\sigma(1)$, $\sigma(2)$, $\sigma(3)$, $\sigma(4)$,

and further, using above results , from (2.19) in [EU-CIRCLE Report D3.3-GMU3], the mean values of the shipping critical infrastructure network conditional lifetimes in the particular safety states are:

$\bar{\mu}(1)$, $\bar{\mu}(2)$, $\bar{\mu}(3)$, $\bar{\mu}(4)$.

As the critical safety state is r =2, then the joint network of the port, shipping and ship traffic and port operation information critical infrastructure networks risk function, according to (2.20), is given by

$$\boldsymbol{r}(\mathrm{t}) = 1 - \widehat{\boldsymbol{S}}_3(t,2) = 1 - \prod_{\upsilon=1}^{3} \ddot{\boldsymbol{S}}^{(\upsilon)}(t,2), \text{ for } t \geq 0 \tag{63}$$

6. Conclusions

The material given in this report delivers the main and practically important safety parameters and characteristics of the joint network of port, shipping, and ship traffic and port operation information critical infrastructure networks defined as complex technical systems. Firstly, the three critical infrastructure networks: port, shipping, and ship

traffic and port operation information, have been described in details. Every chapter about the single critical infrastructure network consists of the definitions of this network, its input safety parameters and the prediction of its safety characteristics. Furthermore, the joint network has been introduced. Its input safety parameters have been defined and its safety characteristics prediction has been done theoretically.
This report is describing the safety model of the port, shipping and ship traffic and port operation information critical infrastructure joint network, which will be used to integrate with operation process. This way, the result will be the model of this network safety related to the operation process changing in time.

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