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Modelling safety of global Baltic network of critical infrastructure networks

Keywords

Safety, Global Baltic Network, Critical Infrastructure Network, Network of networks

Abstract

The main aim of the paper is to present the safety model for Global Baltic Network of Critical Infrastructure Networks. To achieve this, the basis of the multistate ageing approach to safety modelling is introduced. Following, the basic parameters important for the safety and risk prediction are presented. Next, the particular elements of the Global Baltic Network of Critical Infrastructure Networks are defined and described. Finally, the safety and risk analysis of the network of networks are presented.

1. Introduction

The Baltic Sea is the region showing significant concentration of different kind of systems, that in case of their failure, can lead to massive negative impact on societies and natural environment within the area and ashore around. Some systems, showing interconnections, interdependencies and interactions, can be categorised as Critical Infrastructure Network (CI network), defined as a set of interconnected and interdependent critical infrastructures interacting directly and indirectly at various levels of their complexity and operating activity [EU-CIRCLE Report D1.1, EU-CIRCLE Taxonomy, 2015].

Investigations processed within the scope of EU-CIRCLE Report [EU-CIRCLE Report D1.2-GMU1], allowed to distinguish eight CI networks operating in the Baltic Sea area. The networks, abbreviated as BCIN (Baltic Critical Infrastructure Network), have been described and analysed in the report mentioned. Further, their operation process model has been developed and introduced in reports [EU-CIRCLE Report D1.4-GMU3] and [EU-CIRCLE Report D3.3-GMU11].

Actual report is devoted to introduce safety modelling of Baltic Critical Infrastructure Networks. The multi-state approach [Amari, 1997], [Aven, 1985, 1999, 1993], [Barlow, Wu, 1978], [Brunelle, Kapur, 1999], [Hudson, Kapur, 1982, 1985], [Lisnianski, Levitin, 2003], [Natvig, 1982], [Ohio, Nishida, 1984], [Hue, 1985], [Xue, Yang, 1995a,b], [Yu et al 1994], [Kołowrocki, Soszyńska-Budny, 2011], is used, with the assumption that each particular network is composed of multi-state assets [EU-CIRCLE Report D3.1-GMU4], with safety states degrading in time [Guze, kolowrocki, 2008], [Kołowrocki, 2004, 2014], [Kołowrocki, Soszyńska-Budny, 2011], [Xue, 1985], [Xue, Yang 1995 a, b], that gives the possibility to precise analysing of their safety and operational processes' effectiveness.

This assumption allowed to distinguish a network 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 network safety characteristic is the time to the moment of exceeding its safety critical state and its distribution, which is called the network risk function. This distribution is strictly related to the safety function that are basic characteristics of the multi-state network.

First, basic notions of the multistate network safety analysis are introduced, i.e. the multistate assets and

the multistate network, multistate asset safety function, the multistate network safety and risk function are defined. Moreover, the multistate asset and the multistate network 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 network risk function exceeds a fixed permitted level are determined.
Furthermore, similar analysis is introduced for Global Baltic Network of Critical Infrastructure Networks (GBNCIN), comprising distinguished Baltic Critical Infrastructure Networks, that are interacting each other, and being also interconnected and interdependent.

2. Modelling safety of Baltic critical infrastructure network

To process the Baltic Critical Infrastructure Network ($BCIN$) with degrading assets safety analysis, it has been assumed that:

- $BCIN \in \left\{ \begin{array}{l} BPCIN, BSCIN, BORCIN, BWFCIN, \\ BECCIN, BGPCIN, BOPCIN, \\ BSTPOICIN \end{array} \right\},$
  is particular Baltic Critical Infrastructure Network, distinguished within the scope of EU-CIRCLE Report [EU-CIRCLE Report D1.2-GMU1], where:
  - $BPCIN-$ the Baltic Port Critical Infrastructure Network;
  - $BSCIN-$the Baltic Shipping Critical Infrastructure Network;
  - $BORCIN-$the Baltic Oil Rig Critical Infrastructure Network;
  - $BWFCIN-$the Baltic Wind Farm Critical Infrastructure Network;
  - $BECCIN-$the Baltic Electric Cable Critical Infrastructure Network;
  - $BGPCIN-$the Baltic Gas Pipeline Critical Infrastructure Network;
  - $BOPCIN-$the Baltic Oil Pipeline Critical Infrastructure Network;
  - $BSTPOICIN-$the Baltic Ship Traffic and Port Operation Information Critical Infrastructure Network.
- n^{BCIN} is the number of the $BCIN$ network assets,
- E_i^{BCIN}, $i = 1,2,...,n^{BCIN}$, are assets of $BCIN$ network,
- all assets and a network under consideration have the safety state set $\{0,1,...,z^{BCIN}\}$, $z^{BCIN} \geq 1$,
- the safety states are ordered, the safety state 0 is the worst and the safety state z^{BCIN} is the best,
- $T_i^{BCIN}(u)$, $i = 1,2,...,n^{BCIN}$, are independent random variables representing the lifetimes of assets E_i^{BCIN} in the safety state subset $\{u, u+1,...,z^{BCIN}\}$, while they were in the safety state z^{BCIN} at the moment $t = 0$,
- $T^{BCIN}(u)$ is a random variable representing the lifetime of a $BCIN$ network in the safety state subset $\{u, u+1,...,z^{BCIN}\}$, while it was in the safety state z^{BCIN} at the moment $t = 0$,
- the network states degrades with time t,
- $s_i^{BCIN}(t)$, $i = 1,2,...,n^{BCIN}$, is an asset E_i^{BCIN} safety state at the moment $t, t \in <0,\infty)$, given that it was in the safety state z^{BCIN} at the moment $t = 0$,
- $s^{BCIN}(t)$ is a network S^{BCIN} safety state at the moment $t, t \in <0,\infty)$, given that it was in the safety state z^{BCIN} at the moment $t = 0$.

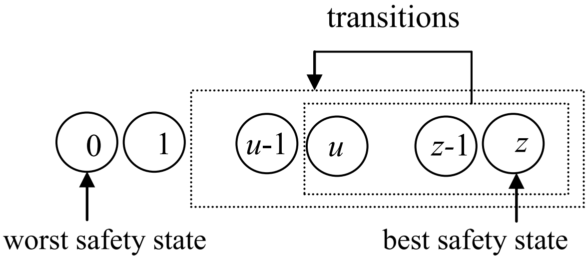

Figure 1. Illustration of a network and assets safety states changing

The above assumptions mean that the safety states of the $BCIN$ network with degrading assets may be changed in time only from better to worse [Guze, Kołowrocki, 2008], [Kołowrocki 2004, 2014], [Kołowrocki, Soszyńska-Budny, 2011], [Xue, 1985], [Xue, Yang 1995 a, b]. The way in which the assets and the network safety states change is illustrated in Figure 1.

Definition 1
A vector

$$S_i^{BCIN}(t,\cdot) = [S_i^{BCIN}(t,0), S_i^{BCIN}(t,1),...,S_i^{BCIN}(t,z^{BCIN})], \quad t \in <0,\infty),\ i = 1,2,...,n^{BCIN}, \tag{1}$$

where

$$S_i^{BCIN}(t,u) = P(s_i^{BCIN}(t) \geq u | s_i^{BCIN}(0) = z^{BCIN}) =$$
$$P(T_i^{BCIN}(u) > t), \ t \in < 0, \infty), \ u = 0,1,...,z^{BCIN}, \qquad (2)$$

is the probability that the asset E_i^{BCIN} is in the safety state subset $\{u, u+1,...,z^{BCIN}\}$, at the moment t, $t \in < 0, \infty)$, while it was in the safety state z^{BCIN} at the moment $t = 0$, is called the safety function of a multistate asset E_i^{BCIN}.

The safety functions $S_i^{BCIN}(t,u)$, $t \in < 0, \infty)$, $u = 0,1,...,z^{BCIN}$, defined by (2) are called the coordinates of the asset E_i^{BCIN}, $i = 1,2,...,n^{BCIN}$, safety function $S_i^{BCIN}(t,\cdot)$ given by (1). Thus, the relationship between the distribution function $F_i^{BCIN}(t,u)$ of the asset E_i^{BCIN}, $i = 1,2,...,n^{BCIN}$, lifetime $T_i^{BCIN}(u)$ in the safety state subset $\{u, u+1,...,z^{BCIN}\}$, and the coordinate $S_i^{BCIN}(t,u)$ of its safety function is given by

$$F_i^{BCIN}(t,u) = P(T_i^{BCIN}(u) \leq t) =$$
$$1 - P(T_i^{BCIN}(u) > t) = 1 - S_i^{BCIN}(t,u), \ t \in < 0, \infty),$$
$$u = 0,1,...,z^{BCIN}.$$

Under *Definition 1* and the agreements, we have the following property of the multistate asset safety function coordinates

$$S_i^{BCIN}(t,0) \geq S_i^{BCIN}(t,1) \geq ... \geq S_i^{BCIN}(t,z^{BCIN}),$$
$$t \in < 0, \infty), \ i = 1,2,...,n^{BCIN},$$

Further, if we denote by

$$p_i^{BCIN}(t,u) = P(s_i^{BCIN}(t) = u | s_i^{BCIN}(0) = z^{BCIN}),$$
$$t \in < 0, \infty), \ u = 0,1,...,z^{BCIN},$$

the probability that the asset E_i^{BCIN} is in the safety state u at the moment t, while it was in the safety state z^{BCIN} at the moment $t = 0$, then by (1)

$$S_i^{BCIN}(t,0) = 1, \ S_i^{BCIN}(t,z^{BCIN}) = p_i^{BCIN}(t,z^{BCIN}),$$
$$t \in < 0, \infty), \ i = 1,2,...,n^{BCIN}, \qquad (3)$$

and

$$p_i^{BCIN}(t,u) = S_i^{BCIN}(t,u) - S_i^{BCIN}(t,u+1),$$
$$u = 0,1,...,z^{BCIN} - 1, \ t \in < 0, \infty),$$
$$i = 1,2,...,n^{BCIN}, \qquad (4)$$

Moreover, if

$$S_i^{BCIN}(t,u) = 1 \text{ for } t \leq 0, \ u = 1,2,...,z^{BCIN},$$
$$i = 1,2,...,n^{BCIN},$$

then

$$\mu_i^{BCIN}(u) = \int_0^\infty S_i^{BCIN}(t,u)dt, \ u = 1,2,...,z^{BCIN},$$
$$i = 1,2,...,n^{BCIN}, \qquad (5)$$

is the mean lifetime of the asset E_i^{BCIN} in the safety state subset $\{u, u+1,...,z^{BCIN}\}$,

$$\sigma_i^{BCIN}(u) = \sqrt{n_i^{BCIN}(u) - [\mu_i^{BCIN}(u)]^2},$$
$$u = 1,2,...,z^{BCIN}, \ i = 1,2,...,n^{BCIN}, \qquad (6)$$

where

$$n_i^{BCIN}(u) = 2\int_0^\infty t S_i^{BCIN}(t,u)dt, \ u = 1,2,...,z^{BCIN},$$
$$i = 1,2,...,n^{BCIN}, \qquad (7)$$

is the standard deviation of the asset E_i^{BCIN} lifetime in the safety state subset $\{u, u+1,...,z^{BCIN}\}$, and

$$\bar{\mu}_i^{BCIN}(u) = \int_0^\infty p_i^{BCIN}(t,u)dt, \ u = 1,2,...,z^{BCIN},$$
$$i = 1,2,...,n^{BCIN}, \qquad (8)$$

is the mean lifetime of the asset E_i^{BCIN} in the safety state u, in the case when the integrals defined by (5), (7) and (8) are convergent.

Next, according to (3), (4), (5) and (8), we have

$$\bar{\mu}_i^{BCIN}(u) = \mu_i^{BCIN}(u) - \mu_i^{BCIN}(u+1),$$
$$u = 0,1,...,z^{BCIN} - 1, \ \bar{\mu}_i^{BCIN}(z^{BCIN}) = \mu_i^{BCIN}(z^{BCIN}),$$
$$i = 1,2,...,n^{BCIN}, \qquad (9)$$

Definition 2
A vector

$$S^{BCIN}(t,\cdot) = [S^{BCIN}(t,0), S^{BCIN}(t,1),..., S^{BCIN}(t,z^{BCIN})],$$
$$t \in < 0, \infty), \qquad (10)$$

where

$$S^{BCIN}(t,u) = P(S^{BCIN}(t) \geq u | S^{BCIN}(0) = z^{BCIN}) = P(T^{BCIN}(u) > t),$$
$$t \in < 0, \infty), \; u = 0,1,\ldots,z^{BCIN}, \qquad (11)$$

is the probability that the $BCIN$ network is in the safety state subset $\{u, u+1,\ldots,z^{BCIN}\}$, at the moment t, $t \in < 0, \infty)$, while it was in the safety state z at the moment $t = 0$, is called the safety function of this multistate network.

The safety functions $S^{BCIN}(t,u)$, $t \in < 0, \infty)$, $u = 0,1,\ldots,z^{BCIN}$, defined by (11) are called the coordinates of the multistate network safety function $S^{BCIN}(t,\cdot)$, given by (10). Consequently, the relationship between the distribution function $F^{BCIN}(t,u)$ of the network S^{BCIN} lifetime $T^{BCIN}(u)$ in the safety state subset $\{u, u+1,\ldots,z\}$, and the coordinate $S^{BCIN}(t,u)$ of its safety function is given by

$$F^{BCIN}(t,u) = P(T^{BCIN}(u) < t) = 1 - P(T^{BCIN}(u) > t) = 1 - S(t,u), \; t \in < 0, \infty),$$
$$u = 0,1,\ldots,z^{BCIN}.$$

The exemplary graph of a five-state (z = 4) system safety function

$$S^{BCIN}(t,\cdot) = [1, S^{BCIN}(t,1), S^{BCIN}(t,2), S^{BCIN}(t,3), S^{BCIN}(t,4)],$$
$$t \in < 0, \infty),$$

is shown in *Figure 2*.

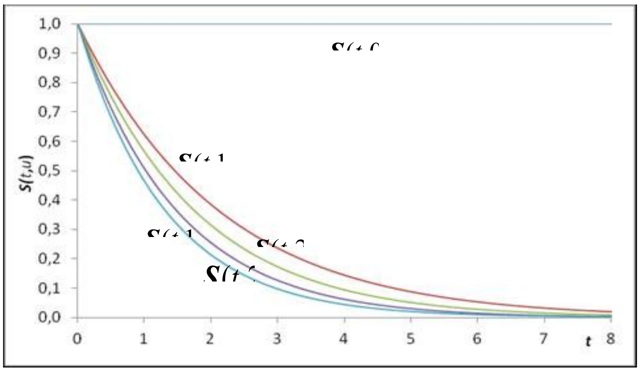

Figure 2. The graph of a five-state network safety function $S^{BCIN}(t,\cdot)$ coordinates

Under *Definition 2*, we have

$$S^{BCIN}(t,0) \geq S^{BCIN}(t,1) \geq \ldots \geq S^{BCIN}(t, z^{BCIN}),$$
$$t \in < 0, \infty),$$

and if

$$p^{BCIN}(t,u) = P(S^{BCIN}(t) = u | S^{BCIN}(0) = z^{BCIN}),$$
$$t \in < 0, \infty), \; u = 0,1,\ldots,z^{BCIN}, \qquad (12)$$

is the probability that the network is in the safety state u at the moment t, $t \in < 0, \infty)$, while it was in the safety state z^{BCIN} at the moment $t = 0$, then

$$S^{BCIN}(t,0) = 1, \; S^{BCIN}(t, z^{BCIN}) = p^{BCIN}(t, z^{BCIN}),$$
$$t \in < 0, \infty), \qquad (13)$$

and

$$p^{BCIN}(t,u) = S^{BCIN}(t,u) - S^{BCIN}(t,u+1), \; t \in < 0, \infty),$$
$$u = 0,1,\ldots,z^{BCIN} - 1. \qquad (14)$$

Moreover, if

$$S^{BCIN}(t,u) = 1 \text{ for } t \leq 0, \; u = 0,1,\ldots,z^{BCIN},$$

then

$$\mu^{BCIN}(u) = \int_0^\infty S^{BCIN}(t,u)dt, \; u = 1,2,\ldots,z^{BCIN}, \qquad (15)$$

is the mean lifetime of the network in the safety state subset $\{u, u+1,\ldots,z^{BCIN}\}$,

$$\sigma^{BCIN}(u) = \sqrt{n^{BCIN}(u) - [\mu^{BCIN}(u)]^2},$$
$$u = 1,2,\ldots,z^{BCIN}, \qquad (16)$$

where

$$n^{BCIN}(u) = 2\int_0^\infty t S^{BCIN}(t,u)dt, \; u = 1,2,\ldots,z^{BCIN}, \qquad (17)$$

is the standard deviation of the network lifetime in the safety state subset $\{u, u+1,\ldots,z^{BCIN}\}$, and moreover

$$\bar{\mu}^{BCIN}(u) = \int_0^\infty p^{BCIN}(t,u)dt, \; u = 1,2,\ldots,z^{BCIN}, \qquad (18)$$

is the mean lifetime of the network in the safety state u while the integrals (15), (17) and (18) are convergent.

Additionally, according to (13), (14), (15) and (18), we get the following relationship

$$\bar{\mu}^{BCIN}(u) = \mu^{BCIN}(u) - \mu^{BCIN}(u+1),$$
$$u = 0,1,\ldots,z^{BCIN}-1,\ \bar{\mu}^{BCIN}(z^{BCIN}) = \mu^{BCIN}(z^{BCIN}). \quad (19)$$

Definition 3
A probability

$$r^{BCIN}(t) = P(S^{BCIN}(t) < r^{BCIN} \mid S^{BCIN}(0) = z^{BCIN}) =$$
$$P(T^{BCIN}(r) \le t),\ t \in <0,\infty),$$

that the network is in the subset of safety states worse than the critical safety state $r,\ r \in \{1,2,\ldots,z^{BCIN}\}$, while it was in the safety state z^{BCIN} at the moment $t = 0$ is called a risk function of the multi-state network [Kołowrocki 2004, 2014], [Kołowrocki, Soszyńska-Budny, 2011].

Under this definition, from (2), we have

$$r^{BCIN}(t) = 1 - P(S^{BCIN}(t) \ge r^{BCIN} \mid S^{BCIN}(0) = z^{BCIN}) =$$
$$1 - S^{BCIN}(t,r),\ t \in <0,\infty), \quad (20)$$

and if τ^{BCIN} is the moment when the $BCIN$ network risk exceeds a permitted level δ^{BCIN}, then

$$\tau^{BCIN} = r^{BCIN^{-1}}(\delta^{BCIN}), \quad (21)$$

where $r^{BCIN^{-1}}(t)$, if exists, is the inverse function of the network risk function $r^{BCIN}(t)$.

The exemplary graph of a four-state network risk function for the critical safety state $r^{BCIN} = 2$

$$r^{BCIN}(t) = 1 - S^{BCIN}(t,2),\ t \in <0,\infty),$$

corresponding to the safety function illustrated in *Figure 2* is shown in *Figure 3*.

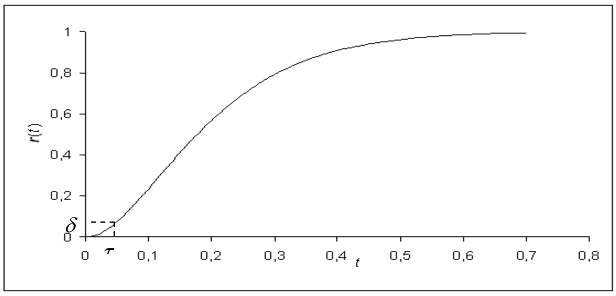

Figure 3. The graph of a five-state network risk function $r^{BCIN}(t)$ (the fragility curve)

Now, after introducing the notion of the multistate safety analysis, we may define multi-state safety structure of $BCIN$ networks.
Each $BCIN$ network will be analysed under the assumption it is multi-state series system.

Definition 4
A multistate $BCIN$ network is series if its lifetime $T^{BCIN}(u)$ in the safety state subset $\{u,u+1,\ldots,z^{BCIN}\}$, is given by

$$T^{BCIN}(u) = \min_{1 \le i \le n}\{T_i^{BCIN}(u)\},\ u = 1,2,\ldots,z^{BCIN}.$$

The number n is called the $BCIN$ network structure shape parameter.

The above definition means that a multi-state series $BCIN$ network is in the safety state subset $\{u,u+1,\ldots,z^{BCIN}\}$, if and only if all its n^{BCIN} components are in this subset of safety states. That meaning is very close to the definition of a two-state series system considered in a classical reliability analysis that is not failed if all its components are not failed. This fact can justify the safety structure scheme for a multistate series $BCIN$ network presented in *Figure 4.*

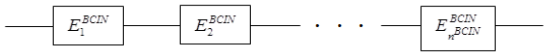

Figure 4. The scheme of a series $BCIN$ network safety structure

It is easy to work out that the safety function of the multi-state series $BCIN$ network, composed of the assets $E_i^{BCIN},\ i = 1,2,\ldots,n^{BCIN}$, is given by the vector [Kołowrocki 2004, 2014], [Kołowrocki, Soszyńska-Budny, 2011]

$$S^{BCIN}(t,\cdot) = [1, S^{BCIN}(t,1), S^{BCIN}(t,2), \ldots, S^{BCIN}(t, z^{BCIN})], \qquad (22)$$

with the coordinates

$$S^{BCIN}(t,u) = \prod_{i=1}^{n} S_i^{BCIN}(t,u), \; t \in < 0, \infty), \; u = 1,2,\ldots,z^{BCIN}, \qquad (23)$$

where $S_i^{BCIN}(t,u)$ is the safety function of the asset E_i^{BCIN}, $i = 1,2,\ldots,n^{BCIN}$,

If assets E_i^{BCIN}, $i = 1,2,\ldots,n^{BCIN}$, of the multi-state series *BCIN* network have the exponential safety functions

$$S_i^{BCIN}(t,\cdot) = [1, S_i^{BCIN}(t,1), \ldots, S_i^{BCIN}(t, z^{BCIN})], \; t \in < 0, \infty), \qquad (24)$$

where

$$S_i^{BCIN}(t,u) = \exp[-\lambda_i^{BCIN}(u) t], \text{ for } t \geq 0, \; \lambda_i^{BCIN}(u) > 0, \; i = 1,2,\ldots,n^{BCIN}, \; u = 1,2,\ldots,z^{BCIN}, \qquad (25)$$

Safety function of the multi-state series network is given by

$$S^{BCIN}(t,\cdot) = [1, S^{BCIN}(t,1), S^{BCIN}(t,2), \ldots, S^{BCIN}(t, z^{BCIN})], \qquad (26)$$

where

$$S^{BCIN}(t,u) = \exp[-\sum_{i=1}^{n^{BCIN}} \lambda_i^{BCIN}(u) t] = \exp[-\lambda^{BCIN}(u) t] \text{ for } t \geq 0, \; u = 1,2,\ldots,z^{BCIN}, \qquad (27)$$

3. Safety and risk prediction of Baltic critical infrastructure networks

3.1. Parameters and assumptions adopted to evaluate safety and risk prediction of Baltic critical infrastructure networks

Basing on outcomes of Chapter 2 above, following parameters and assumptions have been undertaken to analyse safety and risk prediction of particular *BCIN* networks:

- number of *BCIN* network assets: n^{BCIN},
- E_i^{BPCIN}, $i = 1,2,\ldots,n^{BCIN}$, are assets of *BCIN* network,
- four safety states $(z^{BCIN} = 3)$, of each *BCIN* network, and the network assets, have been distinguished as follows:
  - *BCIN* network/ asset state of full ability: z_3^{BCIN},
  - *BCIN* network/ asset impendency over safety state: z_2^{BCIN},
  - state of *BCIN* network/ asset unreliability: z_1^{BCIN},
  - state of full inability of the *BCIN* network/ asset: z_0^{BCIN},
- the critical safety state of the *BCIN* network: $r^{BCIN} = 2$,
- as indicated earlier, the safety states of the *BCIN* network with degrading assets may be changed in time only from better to worse, the way the assets and the network safety states change is illustrated in Figure 1.,
- $T_i^{BCIN}(u)$, $i = 1,2,\ldots,n^{BCIN}$, are independent random variables representing the lifetimes of assets E_i^{BCIN} in the safety state subset $\{u, u+1, \ldots, 3\}$, while they were in the safety state z_3^{BCIN} at the moment $t = 0$,
- $T^{BCIN}(u)$ is a random variable representing the lifetime of a *BCIN* network in the safety state subset $\{u, u+1, \ldots, 3\}$, while it was in the safety state z_3^{BCIN} at the moment $t = 0$,
- the *BCIN* network states degrade with time t,
- $s_i^{BCIN}(t)$, $i = 1,2,\ldots,n^{BCIN}$, is an asset E_i^{BCIN} safety state at the moment t, $t \in < 0, \infty)$, given that it was in the safety state z_3^{BCIN} at the moment $t = 0$,
- $s^{BCIN}(t)$ is a network S^{BCIN} safety state at the moment t, $t \in < 0, \infty)$, given that it was in the safety state z_3^{BCIN} at the moment $t = 0$,
- $S_i^{BCIN}(t,\cdot) = [S_i^{BCIN}(t,0), S_i^{BCIN}(t,1), \ldots, S_i^{BCIN}(t,3)]$, $t \in < 0, \infty)$, $i = 1,2,\ldots,n^{BCIN}$,
  where $S_i^{BCIN}(t,u) = \exp[-\lambda_i^{BCIN}(u) t]$, is the safety function of a multistate asset E_i^{BCIN} - the probability that the asset E_i^{BCIN} is in the safety

state subset $\{u, u+1, \ldots, 3\}$, at the moment t, $t \in <0, \infty)$, while it was in the safety state z_3^{BCIN} at the moment $t = 0$,

- $S^{BCIN}(t, \cdot) =$ $[1, S^{BCIN}(t,1), S^{BCIN}(t,2), \ldots, S^{BCIN}(t,3)]$, $t \in <0, \infty)$, where $S^{BCIN}(t,u) = \exp[-\lambda^{BCIN}(u)t]$, and $\lambda^{BCIN}(u) = \sum_{i=1}^{n^{BCIN}} \lambda_i^{BCIN}(u)$, is the safety function of the $BCIN$ multistate network - the probability that the $BCIN$ network is in the safety state subset $\{u, u+1, \ldots, 3\}$, at the moment t, $t \in <0, \infty)$, while it was in the safety state z_3^{BCIN} at the moment $t = 0$,

4. Safety and risk prediction of Baltic port critical infrastructure network

4.1. Baltic port critical infrastructure network description

There have been [EU-CIRCLE Report D1.2-GMU1] 21 Baltic seaports pointed as belonging to the port core network: 2 Danish ports (Aarhus, Copenhagen), 2 German ports (Lubeck, Rostock), 1 Estonian port (Tallinn), 2 Latvian ports (Riga, Ventspils), 1 Lithuanian port (Klaipeda), 4 Polish ports (Gdansk, Gdynia, Szczecin, Swinoujscie), 4 Finnish (Helsinki, Turku, Kotka, Hamina), 5 Swedish ports (Gothenburg, Lulea, Malmoe, Stockholm, Trelleborg). However, among these ports, three pairs of ports are under a single port authority, namely Copenhagen-Malmoe in Sweden/Denmark, Kotka-Hamina in Finland, and Szczecin-Swinoujscie in Poland. These pairs of ports are treated as single ports and this way the number of Baltic core ports is fixed as 18 [EU-CIRCLE Report D1.2-GMU1]. These ports distribution at the Baltic area is illustrated in *Figure 5*.

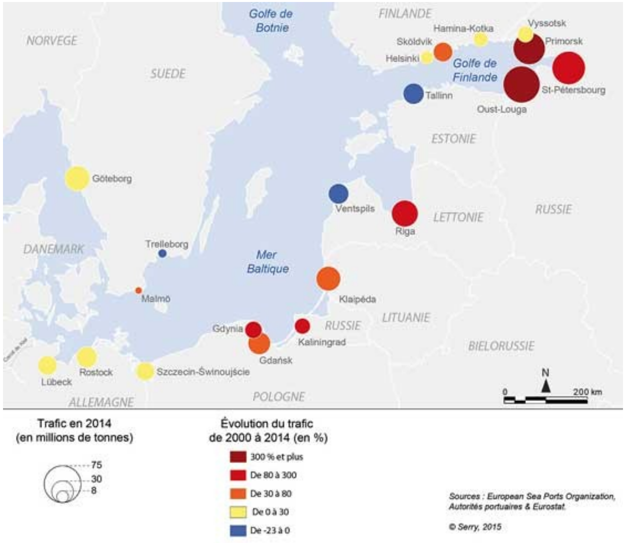

Figure 5. Distribution of core Baltic Sea ports
Source: European Sea Port Organisation (http://www.espo.be)

Outcomes of EU-CIRCLE reports [EU-CIRCLE Report D1.2-GMU1] and [EU-CIRCLE Report D3.1-GMU4], allowed to point out below assets, forming series safety structure of the Baltic Port Critical Infrastructure Network:

- Cargo storage facilities - E_1^{BPCIN},
- Port internal transport and cargo handling equipment - E_2^{BPCIN},
- Docks and quays - E_3^{BPCIN},
- Port channels and roadsteads - E_4^{BPCIN},
- Port protection resources - E_5^{BPCIN},
- Aids to navigation - E_6^{BPCIN},
- Telecommunication and protection systems - E_7^{BPCIN}.

The structure is shown in *Figure 6*.

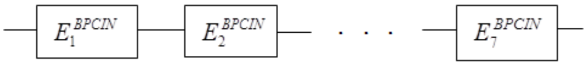

Figure 6. General scheme of the Baltic Port Critical Infrastructure Network safety structure

4.2. Parameters of the Baltic port critical infrastructure network

Considering features quoted in chapter 3.2.1 above, Baltic Port Critical Infrastructure Network ($BPCIN$) has been described by following parameters:

- number of the $BPCIN$ network assets: $n^{BPCIN} = 7$,
- E_i^{BPCIN}, $i = 1,2,\dots,7$, are assets of $BPCIN$ network,
- $T_i^{BPCIN}(u)$, $i = 1,2,\dots,7$, are independent random variables representing the lifetimes of assets E_i^{BPCIN} in the safety state subset $\{u, u+1,\dots,3\}$, while they were in the safety state z_3^{BPCIN} at the moment $t = 0$,
- $T^{BPCIN}(u)$ is a random variable representing the lifetime of a $BPCIN$ network in the safety state subset $\{u, u+1,\dots,3\}$, while it was in the safety state z_3^{BPCIN} at the moment $t = 0$,
- $s_i^{BPCIN}(t)$, $i = 1,2,\dots,7$, is an asset E_i^{BPCIN} safety state at the moment t, $t \in <0,\infty)$, given that it was in the safety state z_3^{BPCIN} at the moment $t = 0$,
- $s^{BPCIN}(t)$ is a network S^{BPCIN} safety state at the moment t, $t \in <0,\infty)$, given that it was in the safety state z_3^{BPCIN} at the moment $t = 0$.
- $S_i^{BPCIN}(t,\cdot) =$
  $[S_i^{BPCIN}(t,0), S_i^{BPCIN}(t,1),\dots,S_i^{BPCIN}(t,3)]$,
  $t \in <0,\infty)$, $i = 1,2,\dots,7$,
  where $S_i^{BPCIN}(t,u) = \exp[-\lambda_i^{BPCIN}(u)t]$, is the safety function of a multistate asset E_i^{BPCIN} - the probability that the asset E_i^{BPCIN} is in the safety state subset $\{u, u+1,\dots,3\}$, at the moment t, $t \in <0,\infty)$, while it was in the safety state z_3^{BPCIN} at the moment $t = 0$,
- $S^{BPCIN}(t,\cdot) =$
  $[1, S^{BPCIN}(t,1), S^{BPCIN}(t,2),\dots,S^{BPCIN}(t,3)]$,
  $t \in <0,\infty)$,
  where $S^{BPCIN}(t,u) = \exp[-\lambda^{BPCIN}(u)t]$, and $\lambda^{BPCIN}(u) = \sum_{i=1}^{7} \lambda_i^{BPCIN}(u)$, is the safety function of the $BPCIN$ multistate network - the probability that the $BPCIN$ network is in the safety state subset $\{u, u+1,\dots,3\}$, at the moment t, $t \in <0,\infty)$, while it was in the safety state z_3^{BPCIN} at the moment $t = 0$,

4.3. Safety and risk prediction of Baltic shipping critical infrastructure network

4.3.1. Baltic Shipping Critical Infrastructure Network Description

The Baltic Sea and the Skagerrak are heavily trafficked. More than 10 000 vessels (fishing vessels excluded), visit the region every year (Swedish Institute for the Marine Environment, 2014). Although traffic is most intensive along the routes through the Sound, the Great Belt, the Baltic Proper and the Gulf of Finland, shipping affects the entire marine environment.

The most common type of vessel in the Baltic Sea and Skagerrak is the cargo ship (containerships, Ro-Ro vessels, dry bulk carriers and other vessels carrying dry or packed cargoes). The next most common vessel types are tankers (crude oil carriers and product tankers), and passenger ones.

Different types of vessel have different environmental impacts. For example, fewer passenger vessels than tankers sail in the Baltic Sea, but the former are faster and so cover greater distances and produce more emissions of for example carbon dioxide. Average speed is an important factor, because a vessel's fuel consumption increases considerably with speed. An analysis of traffic intensity in the Baltic Sea (Figure 7), shows that the traffic is most intensive along the routes through the Sound, the Great Belt, the Baltic Proper and the Gulf of Finland. It also reveals that no part of the sea area studied was completely free from shipping.

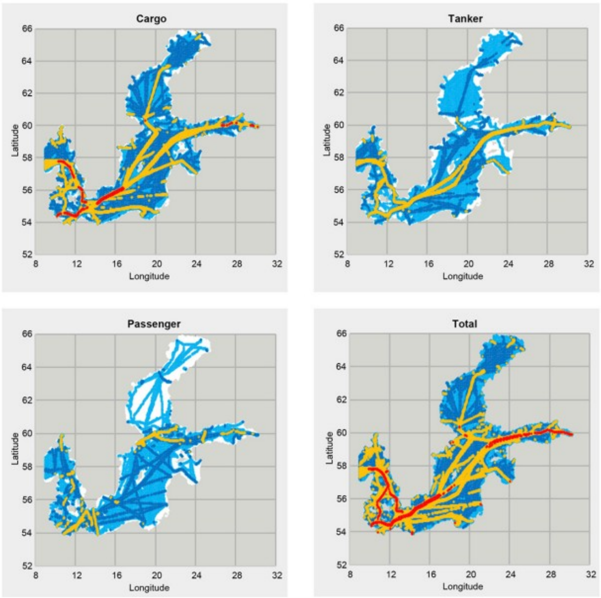

Figure 7. Traffic intensity for different types of vessel in different parts of the Baltic Sea

The colour coding shows the number of vessels visiting each sea square (approx. 3 km by 5 km), in 2013 as follows: white = no vessels, light blue = 1-99 vessels, dark blue = 100-999 vessels, orange = 1,000-9,999 vessels, and red = 10,000 or more vessels
Source: Swedish Institute for the Marine Environment (www.havsmiljoinstitutet.se)

Shipping is very important component of the maritime transportation system, being maritime segment of the general transportation system. This is making shipping an important component of critical infrastructure. Their condition, crew training, traffic safety are influential factors for whole safety of transportation system. Influence of climate change on shipping and its safety is crucial.

Basing on EU-CIRCLE reports [EU-CIRCLE Report D1.2-GMU1] and [EU-CIRCLE Report D3.1-GMU4], following assets, forming series safety structure of the Baltic Shipping Critical Infrastructure Network, have been distinguished:

- Cargo handling equipment - E_1^{BSCIN},
- Towage, berthing and anchoring facilities - E_2^{BSCIN},
- Telecommunication and protection systems - E_3^{BSCIN},
- Navigation means - E_4^{BSCIN},
- Stabilty control resources - E_5^{BSCIN},
- Propulsion and movement control systems - E_6^{BSCIN}.

The structure is introduced in Figure 8.

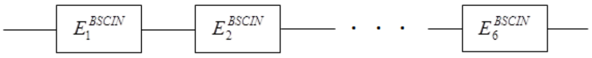

Figure 8. Baltic Shipping Critical Infrastructure Network safety structure

4.3.2. Defining the parameters of the Baltic shipping critical infrastructure network

Considering features quoted in chapter 3.3.1 above, Baltic Shipping Critical Infrastructure Network ($BSCIN$) has been described by following parameters:

- number of the $BPCIN$ network assets:
  $n^{BSCIN} = 6$,
- E_i^{BSCIN}, $i = 1,2,...,6$, are assets of $BSCIN$ network,
- $T_i^{BSCIN}(u)$, $i = 1,2,...,6$, are independent random variables representing the lifetimes of assets E_i^{BSCIN} in the safety state subset $\{u, u+1,...,3\}$, while they were in the safety state z_3^{BSCIN} at the moment $t = 0$,
- $T^{BSCIN}(u)$ is a random variable representing the lifetime of a $BSCIN$ network in the safety state subset $\{u, u+1,...,3\}$, while it was in the safety state z_3^{BSCIN} at the moment $t = 0$,
- $s_i^{BSCIN}(t)$, $i = 1,2,...,6$, is an asset E_i^{BSCIN} safety state at the moment t, $t \in <0,\infty)$, given that it was in the safety state z_3^{BSCIN} at the moment $t = 0$,
- $s^{BSCIN}(t)$ is a network S^{BSCIN} safety state at the moment t, $t \in <0,\infty)$, given that it was in the safety state z_3^{BSCIN} at the moment $t = 0$.
- $S_i^{BSCIN}(t,\cdot) =$
  $[S_i^{BSCIN}(t,0), S_i^{BSCIN}(t,1),...,S_i^{BSCIN}(t,3)]$, $t \in <0,\infty)$,
  $i = 1,2,...,6$,
  where $S_i^{BSCIN}(t,u) = \exp[-\lambda_i^{BSCIN}(u)t]$, is the safety function of a multistate asset E_i^{BSCIN} - the probability that the asset E_i^{BSCIN} is in the safety state subset $\{u, u+1,...,3\}$, at the moment t, $t \in <0,\infty)$, while it was in the safety state z_3^{BSCIN} at the moment $t = 0$,
- $S^{BSCIN}(t,\cdot) =$
  $[1, S^{BSCIN}(t,1), S^{BSCIN}(t,2),...,S^{BSCIN}(t,3)]$,
  $t \in <0,\infty)$,
  where $S^{BSCIN}(t,u) = \exp[-\lambda^{BSCIN}(u)t]$, and $\lambda^{BSCIN}(u) = \sum_{i=1}^{6} \lambda_i^{BSCIN}(u)$, is the safety function of the $BSCIN$ multistate network - the probability that the $BSCIN$ network is in the safety state subset $\{u, u+1,...,3\}$, at the moment t, $t \in <0,\infty)$, while it was in the safety state z_3^{BSCIN} at the moment $t = 0$,

4.4. Safety and risk prediction of Baltic oil rig critical infrastructure network

4.4.1. Baltic oil rig critical infrastructure network description

Energy production and transportation in, on or across the Baltic Sea has fossil and renewable dimensions.

Oil is extracted from four oil platforms, all of them being located In the south-eastern part of the Baltic Sea. Three of the platforms, Baltic Beta, Petro Baltic and PG-1, are in Polish waters, and one, MLSP D-6, is in Russian waters. The reserves in these oil fields (Kravtsovskoye, B-3) are estimated to last until 2030 or longer [EU-CIRCLE Report D1.2-GMU1]. Interests in oil exploration in the Baltic Sea are growing.

Exploration in Polish waters is performed by Lotos Petrobaltic S.A. - Polish company that explores and produces oil, gas and hydrocarbons. Fields are located in the eastern part of the Polish Off-shore Economic Zone. The company owns one drilling rig "Petrobaltic" and two production rigs "Baltic Beta" and "PG-1".

The 'LOTOS Petrobaltic' is capable of drilling in offshore areas at depths up to 350 ft. (105 m).

Lukoil's Kravtsovskoye (D-6) oil field is located in the Russian sector of the Baltic Sea. It was discovered in 1983 at a distance of 22.5km from the coast of Kaliningrad region. The depth of the water is 25m to 35m. The initial exploration drilling followed a geological survey by Lukoil-Kaliningradmorneft. *Figure 9.* shows approximate locations of Polish and Russion oil rigs.

Figure 9. Approximate locations of Polish and Russion oil rigs at southern Baltic

Following assets, forming series safety structure of the Baltic Oil Rig Critical Infrastructure Network, have been specified:

- Provisions handling equipment - E_1^{BORCIN},
- Towage and mooring facilities - E_2^{BORCIN},
- Telecommunication and protection systems - E_3^{BORCIN},
- Oil and gas pumping and handling means - E_4^{BORCIN},
- Movement and position control systems - E_5^{BORCIN}.

Safety structure is presented in Figure 10.

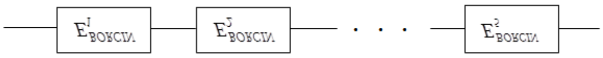

Figure 10. Baltic Oil Rig Critical Infrastructure Network safety structure

4.4.2. Defining the parameters of the Baltic oil rig critical infrastructure network

Basing on issues mentioned in chapter 3.4.1 above, Baltic Oil Rig Critical Infrastructure Network ($BORCIN$) has been described by following parameters:

- number of the $BORCIN$ network assets: $n^{BORCIN} = 5$,
- E_i^{BORCIN}, $i = 1,2,...,5$, are assets of $BORCIN$ network,
- $T_i^{BORCIN}(u)$, $i = 1,2,...,5$, are independent random variables representing the lifetimes of assets E_i^{BORCIN} in the safety state subset $\{u, u+1,...,3\}$, while they were in the safety state z_3^{BORCIN} at the moment $t = 0$,
- $T^{BORCIN}(u)$ is a random variable representing the lifetime of a $BORCIN$ network in the safety state subset $\{u, u+1,...,3\}$, while it was in the safety state z_3^{BORCIN} at the moment $t = 0$,
- $s_i^{BORCIN}(t)$, $i = 1,2,...,5$, is an asset E_i^{BORCIN} safety state at the moment t, $t \in < 0, \infty)$, given that it was in the safety state z_3^{BORCIN} at the moment $t = 0$,
- $s^{BORCIN}(t)$ is a network S^{BORCIN} safety state at the moment t, $t \in < 0, \infty)$, given that it was in the safety state z_3^{BORCIN} at the moment $t = 0$.
- $S_i^{BORCIN}(t,\cdot) =$ $[S_i^{BORCIN}(t,0), S_i^{BORCIN}(t,1),..., S_i^{BORCIN}(t,3)]$, $t \in < 0, \infty)$, $i = 1,2,...,5$, where $S_i^{BORCIN}(t,u) = \exp[-\lambda_i^{BORCIN}(u)t]$, is the safety function of a multistate asset E_i^{BORCIN} - the probability that the asset E_i^{BORCIN} is in the safety state subset $\{u, u+1,...,3\}$, at the moment t,

$t \in < 0, \infty)$, while it was in the safety state z_3^{BORCIN} at the moment $t = 0$,

– $S^{BORCIN}(t, \cdot) =$
$[1, S^{BORCIN}(t,1), S^{BORCIN}(t,2), \ldots, S^{BORCIN}(t,3)]$,
$t \in < 0, \infty)$,
where $S^{BORCIN}(t,u) = \exp[-\lambda^{BORCIN}(u)t]$, and $\lambda^{BORCIN}(u) = \sum_{i=1}^{5} \lambda_i^{BORCIN}(u)$, is the safety function of the *BORCIN* multistate network - the probability that the *BORCIN* network is in the safety state subset $\{u, u+1, \ldots, 3\}$, at the moment t, $t \in < 0, \infty)$, while it was in the safety state z_3^{BORCIN} at the moment $t = 0$,

4.5. Safety and risk prediction of Baltic wind farm critical infrastructure network

4.5.1. Baltic wind farm critical infrastructure network description

At present, more than 91% (8,045MW) of all offshore wind installations can be found in European waters: mainly in the North Sea (5,094.2 MW: 63.3%), Atlantic Ocean (1,808.6 MW: 22.5%) and in the Baltic Sea (1,142.5 MW: 14.2%). The number of offshore wind turbines in Europe at the end of 2014 was 2,488. Europe's offshore wind potential is enormous and it is assumed that the installed capacity will amount to 40 GW by 2020, and to 150 GW by 2030. This will meet 14% of the European Union electricity demand, or 562 TWh, and prevent 87 million tons of CO2 emissions [EU-CIRCLE Report D1.2-GMU1].

A critical and challenging factor in offshore wind industry is the grid connection of offshore wind farms. Electricity generated at sea must be fed into the transmission network and transported to consumers. This requires submarine cables able to transmit vast amounts of power over distances of 100 km and more.

Offshore wind farms located nearshore (mainly in Denmark, Sweden and the German Baltic Sea) are connected to the mainland via high voltage alternating current (HVAC) cables. However, for longer distances and high wind farm capacities, high transmission losses arise from the use of AC technology. Therefore, most German offshore wind farms in the North Sea are connected via high voltage direct current (HVDC) technology.

In general, each offshore wind farm has its own transformer platform, to which wind energy turbines are connected in groups and where the voltage is transformed to a higher level for transmission. For AC connections, the power then goes directly to the next grid node on land (Figure 11). With most DC connections, power from several neighboring wind farms is then usually collected in an additional converter platform at sea (so-called cluster connections). Then the electricity is transmitted via a sea cable, with high level capacities of up to 900 MW [Tonderski & Jędrzejewska, 2013].

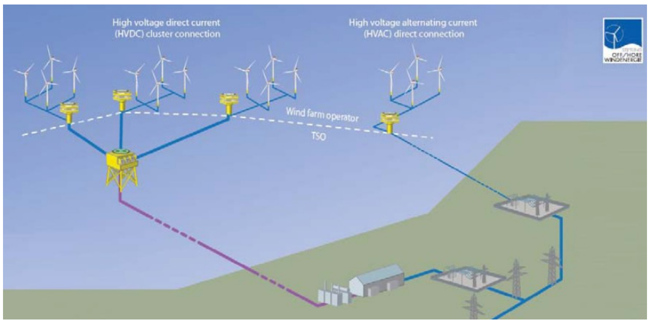

Figure 11. Grid connections of offshore wind farms (in blue: AC cables, in purple: HVDC cables)

Figure 12 gives an overall view of wind farm areas in all stages of development in Europe (European Environment Agency, 2015).

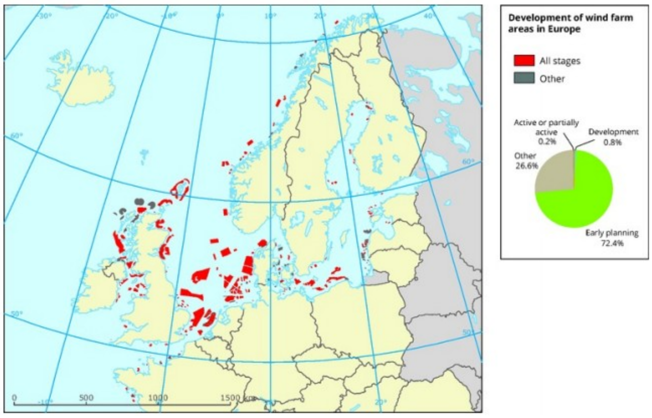

Figure 12. Wind farm areas in all stages of development in Europe
Source: European Environment Agency (www.eea.europa.eu)

As a result of above mentioned issues, and outcomes of EU-CIRCLE reports [EU-CIRCLE Report D1.2-GMU1] and [EU-CIRCLE Report D3.1-GMU4], below assets, forming series safety structure of the Baltic Wind Farm Critical Infrastructure Network, have been pointed:

- AC transmission cables - E_1^{BWFCIN},
- Transformer platforms - E_2^{BWFCIN},

- HVDC transmission cables - E_3^{BWFCIN},
- Submarine/ Land transmission cables interconnections - E_4^{BWFCIN},
- Telecommunication and protection systems - E_5^{BWFCIN},
- Remote control and management resources - E_6^{BWFCIN}.

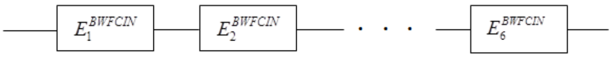

Figure 13. Baltic Wind Farm Critical Infrastructure Network safety structure

4.5.2. Defining the parameters of the Baltic wind farm critical infrastructure network

Analysis of features quoted in chapter 3.5.1 above, Baltic Wind Farm Critical Infrastructure Network ($BWFCIN$) has led to describe it by following parameters:

- number of the $BWFCIN$ network assets: $n^{BWFCIN} = 6,$
- E_i^{BWFCIN}, $i = 1,2,...,6,$ are assets of $BWFCIN$ network,
- $T_i^{BWFCIN}(u)$, $i = 1,2,...,6,$ are independent random variables representing the lifetimes of assets E_i^{BWFCIN} in the safety state subset $\{u, u+1,...,3\}$, while they were in the safety state z_3^{BWFCIN} at the moment $t = 0,$
- $T^{BWFCIN}(u)$ is a random variable representing the lifetime of a $BWFCIN$ network in the safety state subset $\{u, u+1,...,3\}$, while it was in the safety state z_3^{BWFCIN} at the moment $t = 0,$
- $s_i^{BWFCIN}(t)$, $i = 1,2,...,6,$ is an asset E_i^{BWFCIN} safety state at the moment t, $t \in <0,\infty)$, given that it was in the safety state z_3^{BWFCIN} at the moment $t = 0,$
- $s^{BWFCIN}(t)$ is a network S^{BWFCIN} safety state at the moment t, $t \in <0,\infty)$, given that it was in the safety state z_3^{BWFCIN} at the moment $t = 0.$
- $S_i^{BWFCIN}(t,\cdot) =$ $[S_i^{BWFCIN}(t,0), S_i^{BWFCIN}(t,1),..., S_i^{BWFCIN}(t,3)],$ $t \in <0,\infty)$, $i = 1,2,...,6,$ where $S_i^{BWFCIN}(t,u) = \exp[-\lambda_i^{BWFCIN}(u)t]$, is the safety function of a multistate asset E_i^{BWFCIN} - the probability that the asset E_i^{BWFCIN} is in the safety state subset $\{u, u+1,...,3\}$, at the moment t, $t \in <0,\infty)$, while it was in the safety state z_3^{BWFCIN} at the moment $t = 0,$
- $S^{BWFCIN}(t,\cdot) =$ $[1, S^{BWFCIN}(t,1), S^{BWFCIN}(t,2),..., S^{BWFCIN}(t,3)],$ $t \in <0,\infty),$

where $S^{BWFCIN}(t,u) = \exp[-\lambda^{BWFCIN}(u)t]$, and $\lambda^{BWFCIN}(u) = \sum_{i=1}^{6} \lambda_i^{BWFCIN}(u)$, is the safety function of the $BWFCIN$ multistate network - the probability that the $BWFCIN$ network is in the safety state subset $\{u, u+1,...,3\}$, at the moment t, $t \in <0,\infty)$, while it was in the safety state z_3^{BWFCIN} at the moment $t = 0,$

4.6. Safety and risk prediction of Baltic electric cable critical infrastructure network

4.6.1. Baltic electric cable critical infrastructure network description

There are several electric cable connections between the BSR countries: Konti-Skan, Baltic Cable, Kontek, EstLink, Fenno-Skan, SwePol Link, NordBalt and a direct current connection from Russia to Finland [Wilk, 2012].

Konti-Skan (*Figure 14*) was the first interconnection between Sweden and the western grid in Denmark. The converter stations were firstly situated in Stenkullen and Vester Hassing. The second Konti-Skan cable (replacing the first one), with a capacity of 300 MW connects Lindome and Vester Hassing since 1988.

Figure 14. Konti-Skan electric cable (www.new.abb.com)

Baltic Cable (*Figure 15*) links the Swedish and German power systems since 1994. The capacity of this submarine cable is 600 MW.

Figure 15. Baltic Cable (www.new.abb.com)

Kontek (*Figure 16*) is an interconnection between Denmark and Germany with the capacity of 600 MW. It has been operational since 1995, providing higher security of operation, and better opportunities of power exchange and trading.

Figure 16. Kontek electric cable (www.new.abb.com)

An electric cable between Estonia and Finland, called EstLink I (*Figure 17*), opened in 2007 in order to secure energy supplies and develop a common market with Nordic countries. EstLink I has a capacity of 350 MW and is owned by Estonian, Latvian, Lithuanian and Finnish enterprises.

Figure 17. EstLink I electric cable (www.new.abb.com)

At the begining of 2014, EstLink 2 (Figure 18), increasing the security of electricity supply in Estonia and the Baltics, became operational. EstLink 2 plays an important role in the effective functioning of the electricity market. Together with EstLink 1, EstLink 2 increases the transmission capacity between Estonia and Finland to 1,000 MW, making Finland and Estonia essentially one market area.

Figure 18. EstLink II electric cable (www.estlink2.elering.ee)

Another high-voltage direct current (HVDC) transmission, Fenno-Skan (*Figure 19*) connects Rauma in Finland with Dannebo in Sweden. Fenno-Skan 1 started its commercial operation in 1989. The 200 km long connection with the capacity of 500 MW was designed for further extension with a second cable and pole. Fenno-Skan 2 became fully operational in December 2011 with its transmission capacity of 800 MW, connecting Finnbole in Sweden with Rauma in Finland, making Fenno-Skan a bipolar link.

Figure 19. Fenno-Skan electric cable (www.new.abb.com)

In order to establish power system security within the countries participating in the Baltic Ring and connect the grid of Continental Europe with Nordic electric network, the HVDC transmission mono-polar link between Sweden and Poland – SwePol Link (Figure

20), has started its operation in 2000. The 600 MW transmission capacity link eases connection of different power systems with different demands.

Figure 20. SwePol Link electric cable (www.new.abb.com)

The NordBalt (*Figure 21*), commissioned in 2016, is the world's longest HVDC extruded underground and subsea cable system. The cable, with power rating at 700 MW, will help to strengthen the security of the power supply in the three Baltic countries and in southern Sweden, and integrate an emerging joint Baltic electricity market with the Nordic and European markets.

Figure 21. NordBalt electric cable (www.new.abb.com)

The 20 MW, 100 kV Gotland 1 HVDC link from 1954 was the first commercial HVDC transmission in the world. In 1983, a new cable was laid between the inverter station near Vastervik on Sweden's west coast and Ygne station on Gotland. Gotland 2's transmission capacity rated at 130 MW. Gotland 2 and Gotland 1 operated independently and together met Gotland's power needs. Increasing demand and concern about supply safety led to a decision in 1985 to build another HVDC link to Gotland, the Gotland 3, which usually works with Gotland 2 to form a bipolar link (*Figure 22*), but can also work independently. The total transmission capacity is 260 MW.

Figure 22. Gotland 2 and 3 electric cable (www.new.abb.com)

All electric transmission links forming Baltic Electric Cable Critical Infrastructure Network are shown in *Figure 23.*

Figure 23. Baltic Electric Cable Critical Infrastructure Network (Blokus-Roszkowska, Kołowrocki, Soszyńska-Budny, 2016)

Analysis of above mentioned information, and EU-CIRCLE reports [EU-CIRCLE Report D1.2-GMU1] and [EU-CIRCLE Report D3.1-GMU4], let to form series safety structure (Figure 24), of the Baltic Electric Cable Critical Infrastructure Network, consisting of below mentioned assets:

- Overhead transmission AC lines - E_1^{BECCIN},
- AC/DC converter stations - E_2^{BECCIN},
- Undeground DC transmission cables - E_3^{BECCIN},
- Connection joints for the underground cable and submarine cable - E_4^{BECCIN},
- Submarine DC cables - E_5^{BECCIN},
- Telecommunication and protection systems - E_6^{BECCIN},

- Remote control and management resources - E_7^{BECCIN}.

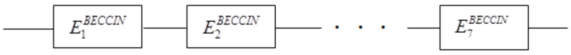

Figure 24. Baltic Electric Cable Critical Infrastructure Network safety structure

4.6.2. Defining the parameters of the baltic electric cable critical infrastructure network

Considering features quoted in chapter 3.6.1 above, Baltic Electric Cable Critical Infrastructure Network ($BECCIN$) has been described by following parameters:

- number of the $BECCIN$ network assets: $n^{BECCIN} = 7$,
- E_i^{BECCIN}, $i = 1,2,...,7$, are assets of $BECCIN$ network,
- $T_i^{BECCIN}(u)$, $i = 1,2,...,7$, are independent random variables representing the lifetimes of assets E_i^{BECCIN} in the safety state subset $\{u, u+1,...,3\}$, while they were in the safety state z_3^{BECCIN} at the moment $t = 0$,
- $T^{BECCIN}(u)$ is a random variable representing the lifetime of a $BECCIN$ network in the safety state subset $\{u, u+1,...,3\}$, while it was in the safety state z_3^{BECCIN} at the moment $t = 0$,
- $s_i^{BECCIN}(t)$, $i = 1,2,...,7$, is an asset E_i^{BECCIN} safety state at the moment t, $t \in <0, \infty)$, given that it was in the safety state z_3^{BECCIN} at the moment $t = 0$,
- $s^{BECCIN}(t)$ is a network S^{BECCIN} safety state at the moment t, $t \in <0, \infty)$, given that it was in the safety state z_3^{BECCIN} at the moment $t = 0$.
- $S_i^{BECCIN}(t,\cdot) =$ $[S_i^{BECCIN}(t,0), S_i^{BECCIN}(t,1),..., S_i^{BECCIN}(t,3)]$, $t \in <0, \infty)$, $i = 1,2,...,7$, where $S_i^{BECCIN}(t,u) = \exp[-\lambda_i^{BECCIN}(u)t]$, is the safety function of a multistate asset E_i^{BECCIN} - the probability that the asset E_i^{BECCIN} is in the safety state subset $\{u, u+1,...,3\}$, at the moment t, $t \in <0, \infty)$, while it was in the safety state z_3^{BECCIN} at the moment $t = 0$,
- $S^{BECCIN}(t,\cdot) =$ $[1, S^{BECCIN}(t,1), S^{BECCIN}(t,2),..., S^{BECCIN}(t,3)]$, $t \in <0, \infty)$, where $S^{BECCIN}(t,u) = \exp[-\lambda^{BECCIN}(u)t]$, and $\lambda^{BECCIN}(u) = \sum_{i=1}^{7} \lambda_i^{BECCIN}(u)$, is the safety function of the $BECCIN$ multistate network - the probability that the $BECCIN$ network is in the safety state subset $\{u, u+1,...,3\}$, at the moment t, $t \in <0, \infty)$, while it was in the safety state z_3^{BECCIN} at the moment $t = 0$,

4.7. Safety and risk prediction of Baltic gas pipeline critical infrastructure network

4.7.1. Baltic gas pipeline critical infrastructure network description

It is foreseen usage of LNG will constantly grow in near future, thus, there are several projects pending concerning building of new gas pipeline infrastructure also within the Baltic Sea area [Wilk, 2012]. *Figure 25* presents actual status of Gas Pipeline infrastructure at the Baltic Sea area (dated May 2016).

Figure 25. Baltic Gas Pipeline Critical Infrastructure Network (http://www.entsog.eu/maps/transmission-capacity-map)

Nord Stream is already existing submarine gas pipeline connecting Russian natural gas supplies, near the city Vyborg with the European grid near Greifswald in Germany, which allows transporting gas for the upcoming 50 years. It consists of two 1224 km long lines, with the total capacity of 55 billion cubic meters (bcm) of gas a year. Line 1 was put into operation in November 2011, while Line 2 was ready in April 2012 and started its operation in October 2012. Nord stream is a long term private investment, of which Nord Stream AG is in charge, a joint venture of Russian, German, French and Dutch companies of energy sector.

Baltic Pipe is a 230 km long planned submarine pipeline which would connect Redvig in Denmark and Niechorze in Poland with the capacity of 3 bcm a year. Researches on the sea bottom have been finished in order to mark out the route of the pipeline and estimate the real costs. Currently, there are plans to introduce gas flow in both directions. Poland sees the pipeline as an export route for surplus gas from its planned LNG terminal in Swinoujscie, while Denmark expects to import the Russian gas through Poland.

Balticconnector is a proposed natural gas pipeline, linking the Finnish, Estonian and Latvian natural gas grid. The pipeline will provide two-way gas flows between Finland and Estonia and more gas supply capacity and flexibility for the whole region. The project consists of an offshore gas pipeline, compressor stations on both landfalls and connecting onshore pipelines to the existing grids. There are two alternative routes for the pipeline, one 80 km long from Inkoo in Finland to Paldiski in Estonia and the other one, 140 km long from Vuosaari in Finland to Paldiski as well.

At present, there are only a few working installations for the handling of LNG in the Baltic Sea Region. However, many countries are working on the projects concerning an establishment of large scale import terminals (see Figure 6.26), for LNG in order to increase the diversity of energy supply and to provide alternative supply routes for gas in the Baltic Sea countries. Large import terminals are expected to come into operation in Tallinn, Klaipeda, Swinoujscie, Lysekil and possibly in Riga. Regarding bunkering of LNG, within a few more years it could be possible in Helsinki, Gdansk, Gävle, Oxelösund and Trelleborg. Increase of the LNG capacity among the Baltic ports is crucial for the region and its energy security.

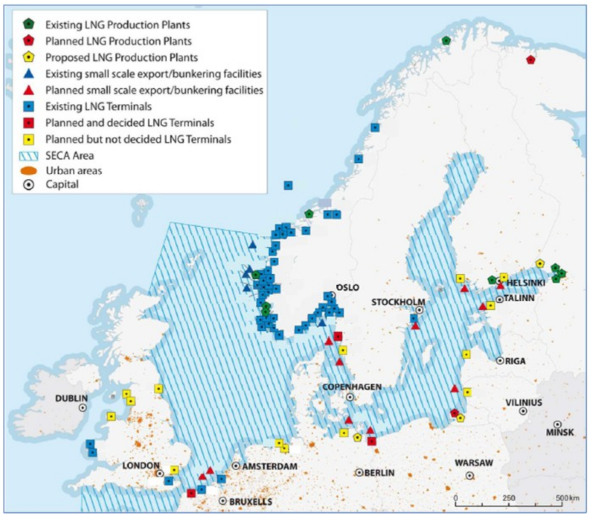

Figure 26. Existing and planned LNG installations at Baltic Sea area [Wilk, 2012]

Outcomes of above mentioned data, and EU-CIRCLE reports [EU-CIRCLE Report D1.2-GMU1] and [EU-CIRCLE Report D3.1-GMU4], let to form series safety structure (Figure 27), of the Baltic Gas Pipeline Critical Infrastructure Network, consisting of below mentioned assets:

- Land (overhead and underground) gas pipelines - E_1^{BGPCIN},
- Connection joints for land and submarine gas pipelines - E_2^{BGPCIN},
- Gas pumping and handling stations, LNG terminals - E_3^{BGPCIN},
- Submarine gas pipelines - E_4^{BGPCIN},
- Telecommunication and protection systems - E_5^{BGPCIN},
- Remote control and management resources - E_6^{BGPCIN},

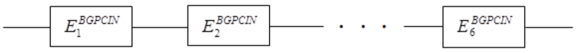

Figure 27. Baltic Gas Pipeline Critical Infrastructure Network safety structure

4.7.2. Defining the parameters of the Baltic gas pipeline critical infrastructure network

Analysis of features quoted in chapter 3.7.1 above, Baltic Gas Pipeline Critical Infrastructure Network ($BGPCIN$) has led to describe it by following parameters:

- number of the $BGPCIN$ network assets: $n^{BGPCIN} = 6$,
- E_i^{BGPCIN}, $i = 1,2,\ldots,6$, are assets of $BGPCIN$ network,
- $T_i^{BGPCIN}(u)$, $i = 1,2,\ldots,6$, are independent random variables representing the lifetimes of assets E_i^{BGPCIN} in the safety state subset $\{u, u+1,\ldots,3\}$, while they were in the safety state z_3^{BGPCIN} at the moment $t = 0$,
- $T^{BGPCIN}(u)$ is a random variable representing the lifetime of a $BGPCIN$ network in the safety state subset $\{u, u+1,\ldots,3\}$, while it was in the safety state z_3^{BGPCIN} at the moment $t = 0$,
- $s_i^{BGPCIN}(t)$, $i = 1,2,\ldots,6$, is an asset E_i^{BGPCIN} safety state at the moment t, $t \in <0,\infty)$, given that it was in the safety state z_3^{BGPCIN} at the moment $t = 0$,
- $s^{BGPCIN}(t)$ is a network S^{BGPCIN} safety state at the moment t, $t \in <0,\infty)$, given that it was in the safety state z_3^{BGPCIN} at the moment $t = 0$.
- $S_i^{BGPCIN}(t,\cdot) =$
  $[S_i^{BGPCIN}(t,0), S_i^{BGPCIN}(t,1),\ldots,S_i^{BGPCIN}(t,3)]$,
  $t \in <0,\infty)$, $i = 1,2,\ldots,6$,
  where $S_i^{BGPCIN}(t,u) = \exp[-\lambda_i^{BGPCIN}(u)t]$, is the safety function of a multistate asset E_i^{BGPCIN} - the probability that the asset E_i^{BGPCIN} is in the safety state subset $\{u, u+1,\ldots,3\}$, at the moment t, $t \in <0,\infty)$, while it was in the safety state z_3^{BGPCIN} at the moment $t = 0$,
- $S^{BGPCIN}(t,\cdot) =$
  $[1, S^{BGPCIN}(t,1), S^{BGPCIN}(t,2),\ldots,S^{BGPCIN}(t,3)]$,
  $t \in <0,\infty)$,

where $S^{BGPCIN}(t,u) = \exp[-\lambda^{BGPCIN}(u)t]$, and $\lambda^{BGPCIN}(u) = \sum_{i=1}^{6} \lambda_i^{BGPCIN}(u)$, is the safety function of the $BGPCIN$ multistate network - the probability that the $BGPCIN$ network is in the safety state subset $\{u, u+1,\ldots,3\}$, at the moment t, $t \in <0,\infty)$, while it was in the safety state z_3^{BGPCIN} at the moment $t = 0$,

4.8. Safety and risk Prediction of Baltic oil pipeline critical infrastructure network

4.8.1. Baltic oil pipeline critical infrastructure network description

There are few strategic oil pipelines in the Baltic coast region (in EU). Latvian port Ventspils is linked to oil extraction fields and transportation routes of Russian Federation via system of two pipelines, from which only one is still operational. It is an oil product pipeline from Skrudaliena (Russian - Latvian border) to Ventspils (*Figure 28*), with annual capacity of 6 mln tons. Maintenance and management of the pipelines is carried out by Latvian – Russian joint-stock company LatRosTrans.

Figure 28. Oil product pipeline from Skrudaliena to Ventspils [EU-CIRCLE Report D1.2-GMU1]

Another oil pipeline in the Baltic States is a crude oil pipelines between Mazeikiai Refinery and Butinge Terminal operated by Orlen Lietuva company (*Figure 29*).

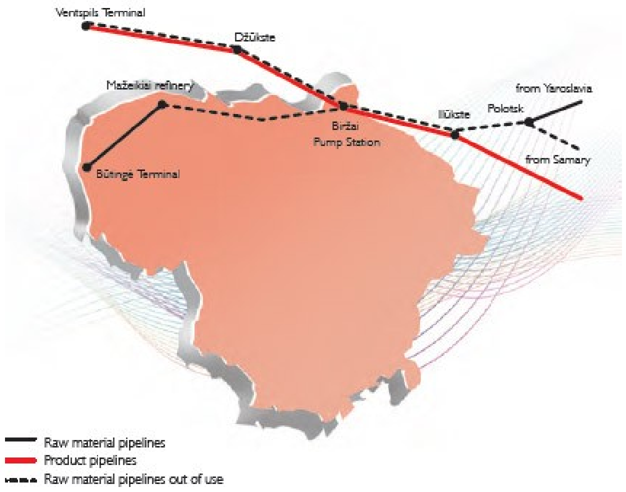

Figure 29. Crude oil pipelines between Mazeikiai Refinery and Butinge Terminal [http://raportroczny.orlen.pl/report_en_markets_lithuania_logistics_2011]

The valves and pumps of the crude oil pipeline Mazeikiai – Butinge are controlled at Butinge control room. The pipeline pressures are controlled in the similar manner.

Butinge was planned and designed as a single-point offshore mooring with a capacity to offload up to 4932 m3/h. The mooring is in the form of a floating buoy. There is a pipeline, pumping stations, and an offshore terminal. The facilities are capable of handling 8 million tons of crude oil for exports and 5 to 6 million tons for import. An offshore submarine pipeline measuring 0.91 m in diameter and 7.5 kilometers in length connects to the shore facilities. A 560 mm pipeline connects to three 50,000-cubic-metre oil storage tanks which are floating roof tanks for crude oil storage. Pumping stations and a single-point mooring terminal have also been built. Tanks for storing diesel and oil are on the roof. Pumps load crude oil to tankers and transport the same over a distance of 91.5 kilometers to the refinery of Orlen Lietuva near Mazeikai.

There are no many oil pipelines located in Poland at the seaside. One of them is The Pomeranian Pipeline connecting Storage Tank Farm in Plock with Tank Farm in Oil Terminal Gdansk (Figure 30). Russian crude oil is transported through the pipeline to Gdansk Lotos Refinery and Oil Terminal for export. Capacity of the pipeline is close to 30 mln tons per year towards Plock and about 27 mln tons per year towards Gdansk.

Figure 30. Pipelines connecting Plock with Gdansk and Schwedt with Rostock [http://infoship.pl]

Schwedt-Rostock connection (*Figure 30*), is part of Friendship pipeline that has 200 km and transports crude oil imported from Russia to terminal in Rostock. The strategic nature of the oil plant in Schwedt lies in its location. In addition to being connected to the Friendship pipeline, the plant can also receive raw crude by sea via a terminal on the port of Rostock, which is connected to the 2 processing plants through an exclusive 200km - long pipeline running from Rostock to Schwedt. The pipeline has limited capacity (about 7 million tons per year). The chief problem is the limited port handling capacity in Rostock (about 9 million tons), which, so far can only handle tankers with a maximum capacity of 100 ,000 DWT.

Gdynia Port – Dębogórze Terminal and Oil Piping Transportation System (Figure 31), 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. It is composed of three parts A, B and C, linked by the piping transportation system with the pier. 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 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 to the terminal part B. This section 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 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.

Figure 31. Oil pipelines from Gdynia Port to Terminal in Debogórze [EU-CIRCLE Report D1.2-GMU1]

Basing on above information, and on EU-CIRCLE reports [EU-CIRCLE Report D1.2-GMU1] and [EU-CIRCLE Report D3.1-GMU4], following series safety structure (*Figure 32*), of the Baltic Oil Pipeline Critical Infrastructure Network, has been distinguished:

- Land (overhead and underground) oil pipelines - E_1^{BOPCIN},

- Connection joints for land and submarine oil pipelines - E_2^{BOPCIN},
- Oil pumping and handling stations, oil terminals - E_3^{BOPCIN},
- Submarine oil pipelines - E_4^{BOPCIN},
- Telecommunication and protection systems - E_5^{BOPCIN},
- Remote control and management resources - E_6^{BOPCIN},

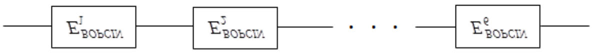

Figure 32. Baltic Oil Pipeline Critical Infrastructure Network safety structure

4.8.2. Defining the parameters of the Baltic oil pipeline critical infrastructure network

Outcomes of chapter 3.8.1 above, have led to describe the Baltic Oil Pipeline Critical Infrastructure Network ($BOPCIN$) by following parameters:

- number of the $BOPCIN$ network assets: $n^{BOPCIN} = 6,$
- E_i^{BOPCIN}, $i = 1,2,...,6,$ are assets of $BOPCIN$ network,
- $T_i^{BOPCIN}(u)$, $i = 1,2,...,6,$ are independent random variables representing the lifetimes of assets E_i^{BOPCIN} in the safety state subset $\{u, u+1,...,3\}$, while they were in the safety state z_3^{BOPCIN} at the moment $t = 0,$
- $T^{BOPCIN}(u)$ is a random variable representing the lifetime of a $BOPCIN$ network in the safety state subset $\{u, u+1,...,3\}$, while it was in the safety state z_3^{BOPCIN} at the moment $t = 0,$
- $s_i^{BOPCIN}(t)$, $i = 1,2,...,6,$ is an asset E_i^{BOPCIN} safety state at the moment t, $t \in <0,\infty)$, given that it was in the safety state z_3^{BOPCIN} at the moment $t = 0,$
- $s^{BOPCIN}(t)$ is a network S^{BOPCIN} safety state at the moment t, $t \in <0,\infty)$, given that it was in the safety state z_3^{BOPCIN} at the moment $t = 0.$
- $S_i^{BOPCIN}(t,\cdot) =$ $[S_i^{BOPCIN}(t,0), S_i^{BOPCIN}(t,1),...,S_i^{BOPCIN}(t,3)],$ $t \in <0,\infty),$ $i = 1,2,...,6,$

  where $S_i^{BOPCIN}(t,u) = \exp[-\lambda_i^{BOPCIN}(u)t]$, is the safety function of a multistate asset E_i^{BOPCIN} - the probability that the asset E_i^{BOPCIN} is in the safety state subset $\{u, u+1,...,3\}$, at the moment t, $t \in <0,\infty)$, while it was in the safety state z_3^{BOPCIN} at the moment $t = 0,$
- $S^{BOPCIN}(t,\cdot) =$ $[1, S^{BOPCIN}(t,1), S^{BOPCIN}(t,2),..., S^{BOPCIN}(t,3)],$ $t \in <0,\infty),$

where $S^{BOPCIN}(t,u) = \exp[-\lambda^{BOPCIN}(u)t]$, and $\lambda^{BOPCIN}(u) = \sum_{i=1}^{6} \lambda_i^{BOPCIN}(u)$, is the safety function of the $BOPCIN$ multistate network - the probability that the $BOPCIN$ network is in the safety state subset $\{u, u+1,...,3\}$, at the moment t, $t \in <0,\infty)$, while it was in the safety state z_3^{BOPCIN} at the moment $t = 0,$

4.9. Safety and risk prediction of Baltic ship traffic and port operation information critical infrastructure network

4.9.1. Baltic ship traffic and port operation information critical infrastructure network description

Maritime transportation and information network (*Figure 33*). The structure and flow of the inner, outer and cross dependencies of the maritime transportation system and the maritime information system. The nodes of this network are the ships (vessels) or overland users (VTS Centers, Maritime Offices, etc.). A route is a single link between two nodes that are part of a larger network that can refer to tangible routes as sea corridors or information and communication connections (links).

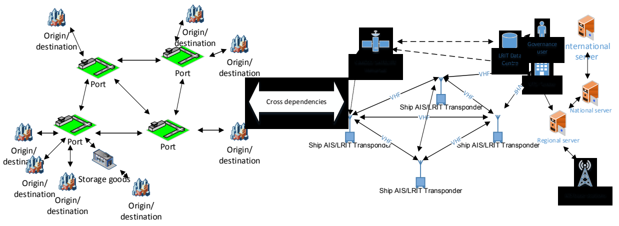

Figure 33. The scheme of Maritime Transportation and Information Network [EU-CIRCLE Report D1.2-GMU1]

Maritime transportation system. Maritime Transportation System consists of waterways, ports with their intermodal connections, vessels, vehicles, and system users. Each component is a complex system with the inner and outer dependencies. It is represented by maritime transportation network.

Maritime transportation network (*Figure 34*). The maritime transportation system with its structure and flow. The nodes of this network can be ports (or terminals), goods storages or origin/destination places. A route (edge) is a single link between two nodes.

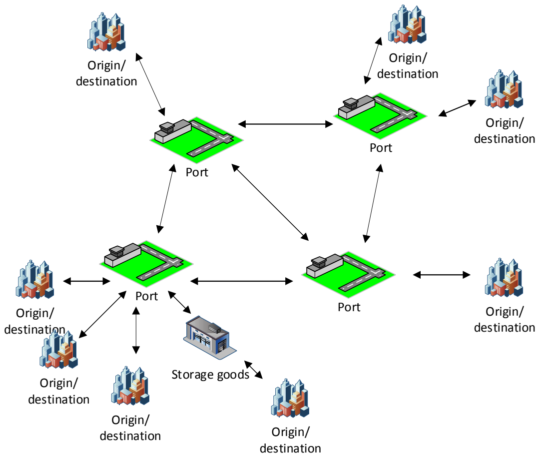

Figure 34. The scheme of Maritime Transportation Network [EU-CIRCLE Report D1.2-GMU1]

Maritime information system. It consists of the LRIT, the AIS and VHF ship equipment, base stations and data centers, vessel and overland computer systems and other computing hardware devices (in ports, terminals, Maritime Offices, etc.) that are linked together through communication and information channels to facilitate communication, information and resource-sharing among a wide range of users. It is represented by maritime information network.

Maritime information network. The maritime information system with its structure and flow. The nodes of this network can be base stations, satellites, VTS Centers, ports (or terminals), Maritime Offices, data centers, vessels, goods storages or origin/destination places. A route (edge) is a single link between two nodes.

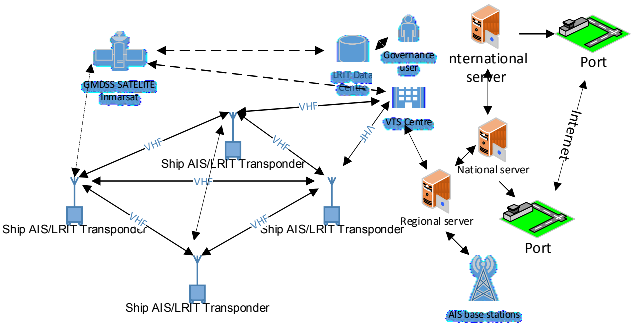

Figure 35. The scheme of the Ship Traffic and Operation Information Network

Maritime transportation and Information critical infrastructure network - Application to Baltic Sea. The network of interconnected and interdependent critical infrastructures located in the maritime transportation and information environment of South Baltic Sea.

Vessel reporting service. EMSA facilitates technical cooperation between Member States and the Commission for the exchange of EU vessel traffic information (SafeSeaNet), the long-range identification and tracking of vessels (LRIT), and to support EU operational reporting services, including the electronic transmission of reporting formalities. Member States and EMSA operate SafeSeaNet, the vessel traffic monitoring and information system covering the waters in and around Europe. It acts as a platform for maritime data exchange, linking together maritime authorities from across the continent. It works by tracking Automatic Identification System (AIS) radio signals transmitted by ships. These provide identity details, latest positions and other status information in near-real-time for around 17,000 vessels operating in and around EU waters. Tracking vessels outside the range of AIS coastal networks requires the use of satellites. Long-Range Identification and Tracking (LRIT) is a mandatory international system to track ships around the world. Vessels send signals via telecommunication satellites, which are received by Data Centers in flag States. EMSA operates the EU LRIT Cooperative Data Centre, covering over 35 countries. The Agency also hosts the International Data Exchange, for the exchange of ship positions between Data Centers around the world. Emerging technologies now enable AIS signals to be received by satellite. This will progressively extend the geographical range of the AIS system. EMSA is at the forefront of exploring how this can support the European vessel traffic monitoring community.
[EMSA,
http://www.emsa.europa.eu/operations/vessel-reporting-services.html]

Polish national maritime safety system. The monitoring and management system for maritime traffic in sensitive areas of Polish waters, based on modern solutions for radar, the automatic identification system, the system of video cameras and the VHF communications.

Pomeranian data communication bus. It is a broadband connection to use by Polish National Maritime Safety System and Automated Radar Supervision System Polish national waters.

Vessel traffic service. It is a maritime traffic monitoring system established by harbor or port authorities. Typical VTS system use radar, closed-circuit television, VHF radiotelephony and automatic identification system (AIS) to keep track of vessel movements and provide navigational safety in a limited geographical area.

VTS Zatoka Gdańska. The VTS system operating in the Gulf of Gdansk area.

Above issues, and EU-CIRCLE reports [EU-CIRCLE Report D1.2-GMU1] and [EU-CIRCLE Report D3.1-GMU4] outcomes, let to specify following series safety structure (Figure 36), of the Baltic Ship Traffic and Port Operation Information Critical Infrastructure Network:

- Aids to navigation - $E_1^{BSTPOICIN}$,
- Vessel Traffic Management - $E_2^{BSTPOICIN}$,
- Vessel Traffic Monitoring - $E_3^{BSTPOICIN}$,
- Port information management - $E_4^{BSTPOICIN}$,
- Safety information services - $E_5^{BSTPOICIN}$,
- Databases - $E_6^{BSTPOICIN}$,

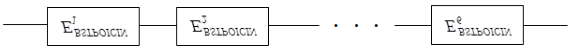

Figure 36. Baltic Ship Traffic and Port Operation Information Critical Infrastructure Network safety structure

4.9.2. Defining the parameters of the Baltic ship traffic and port operation information critical infrastructure network

Outcomes of chapter 3.9.1 above, have led to describe the Baltic Ship Traffic and Port Operation Information Critical Infrastructure Network ($BSTPOICIN$) by following parameters:

- number of the $BSTPOICIN$ network assets: $n^{BSTPOICIN} = 6$,
- $E_i^{BSTPOICIN}$, $i = 1,2,...,6$, are assets of $BSTPOICIN$ network,
- $T_i^{BSTPOICIN}(u)$, $i = 1,2,...,6$, are independent random variables representing the lifetimes of assets $E_i^{BSTPOICIN}$ in the safety state subset $\{u, u+1,...,3\}$, while they were in the safety state $z_3^{BSTPOICIN}$ at the moment $t = 0$,
- $T^{BSTPOICIN}(u)$ is a random variable representing the lifetime of a $BSTPOICIN$ network in the safety state subset $\{u, u+1,...,3\}$, while it was in the safety state $z_3^{BSTPOICIN}$ at the moment $t = 0$,
- $s_i^{BSTPOICIN}(t)$, $i = 1,2,...,6$, is an asset $E_i^{BSTPOICIN}$ safety state at the moment t, $t \in < 0, \infty)$, given that it was in the safety state $z_3^{BSTPOICIN}$ at the moment $t = 0$,
- $s^{BSTPOICIN}(t)$ is a network $S^{BSTPOICIN}$ safety state at the moment t, $t \in < 0, \infty)$, given that it was in the safety state $z_3^{BSTPOICIN}$ at the moment $t = 0$.
- $S_i^{BSTPOICIN}(t, \cdot) =$
  $[S_i^{BSTPOICIN}(t,0), S_i^{BSTPOICIN}(t,1),...,S_i^{BSTPOICIN}(t,3)]$,
  $t \in < 0, \infty)$, $i = 1,2,...,6$,
  where $S_i^{BSTPOICIN}(t,u) = \exp[-\lambda_i^{BSTPOICIN}(u)t]$, is the safety function of a multistate asset $E_i^{BSTPOICIN}$ - the probability that the asset $E_i^{BSTPOICIN}$ is in the safety state subset $\{u, u+1,...,3\}$, at the moment t, $t \in < 0, \infty)$, while it was in the safety state $z_3^{BSTPOICIN}$ at the moment $t = 0$,
- $S^{BSTPOICIN}(t, \cdot) =$
  $[1, S^{BSTPOICIN}(t,1), S^{BSTPOICIN}(t,2),...,$
  $S^{BSTPOICIN}(t,3)]$,
  $t \in < 0, \infty)$,

where $S^{BSTPOICIN}(t,u) = \exp[-\lambda^{BSTPOICIN}(u)t]$, and $\lambda^{BSTPOICIN}(u) = \sum_{i=1}^{6} \lambda_i^{BSTPOICIN}(u)$, is the safety function of the $BSTPOICIN$ multistate network - the probability that the $BSTPOICIN$ network is in the safety state subset $\{u, u+1,...,3\}$, at the moment t, $t \in < 0, \infty)$, while it was in the safety state $z_3^{BSTPOICIN}$ at the moment $t = 0$.

5. Modelling safety of global Baltic network of critical infrastructure networks

As it has been previously stated, Baltic Critical Infrastructure Networks, distinguished and analysed in previous chapter, are interacting each other and being interconnected and interdependent, forming the Global Baltic Network of Critical Infrastructure Networks ($GBNCIN$).

To process the $GBNCIN$ Network safety analysis, it has been assumed that:

- Following Baltic Critical Infrastructure Networks, distinguished within the scope of EU-CIRCLE Report [EU-CIRCLE Report D1.2-GMU1], are components of the $GBNCIN$ Network:
    - $BPCIN-$ the Baltic Port Critical Infrastructure Network;
    - $BSCIN-$the Baltic Shipping Critical Infrastructure Network;
    - $BORCIN-$the Baltic Oil Rig Critical Infrastructure Network;
    - $BWFCIN$ – the Baltic Wind Farm Critical Infrastructure Network;
    - $BECCIN-$the Baltic Electric Cable Critical Infrastructure Network;
    - $BGPCIN-$the Baltic Gas Pipeline Critical Infrastructure Network;
    - $BOPCIN-$the Baltic Oil Pipeline Critical Infrastructure Network;
    - $BSTPOICIN-$ the Baltic Ship Traffic and Port Operation Information Critical Infrastructure Network.
- $n^{GBNCIN}=8,$ is the number of networks, constituting the $GBNCIN$ Network,
- E_i^{GBNCIN}, $i=1,2,...,8,$ are $BCIN$ networks of the $GBNCIN$ Network,
- all $BCIN$ networks and the $GBNCIN$ Network under consideration have the safety state set $\{0,1,...,z^{GBNCIN}\}$, $z^{GBNCIN}\geq 1,$
- the safety states are ordered, the safety state 0 is the worst and the safety state z^{GBNCIN} is the best,
- $T_i^{GBNCIN}(u)$, $i=1,2,...,8,$ are independent random variables representing the lifetimes of $BCIN$ networks E_i^{GBNCIN}, in the safety state subset $\{u,u+1,...,z^{GBNCIN}\}$, while they were in the safety state z^{GBNCIN} at the moment $t=0,$
- $T^{GBNCIN}(u)$ is a random variable representing the lifetime of a $GBNCIN$ Network in the safety state subset $\{u,u+1,...,z^{GBNCIN}\}$, while it was in the safety state z^{GBNCIN} at the moment $t=0,$
- the $BCIN$ networks and the $GBNCIN$ Network states degrades with time $t,$
- $s_i^{GBNCIN}(t)$, $i=1,2,...,8,$ is the $BCIN$ network E_i^{GBNCIN} safety state at the moment t, $t\in<0,\infty),$ given that it was in the safety state z^{GBNCIN} at the moment $t=0,$
- $s^{GBNCIN}(t)$ is the $GBNCIN$ Network S^{GBNCIN} safety state at the moment t, $t\in<0,\infty),$ given that it was in the safety state z^{GBNCIN} at the moment $t=0.$

The above assumptions mean that the safety states of the $GBNCIN$ Network with degrading $BCIN$ networks may be changed in time only from better to worse [Guze, Kołowrocki, 2008], [Kołowrocki 2004, 2014], [Kołowrocki, Soszyńska-Budny, 2011], [Xue, 1985], [Xue, Yang 1995 a, b].

Thus, following relations apply to safety and risk prediction of Global Baltic Network of Critical Infrastructure Networks.

The probability that the $BCIN$ network E_i^{GBNCIN} is in the safety state subset $\{u,u+1,...,z^{GBNCIN}\}$, at the moment t, $t\in<0,\infty)$, while it was in the safety state z^{GBNCIN} at the moment $t=0$, determined as the safety function of a $BCIN$ network E_i^{GBNCIN}, is a vector

$$S_i^{GBNCIN}(t,\cdot)=$$
$$[S_i^{GBNCIN}(t,0),S_i^{GBNCIN}(t,1),...,S_i^{GBNCIN}(t,z^{GBNCIN})],$$
$$t\in<0,\infty),\ i=1,2,...,8, \tag{28}$$

where

$$S_i^{GBNCIN}(t,u)=$$
$$P(s_i^{GBNCIN}(t)\geq u|s_i^{GBNCIN}(0)=z^{GBNCIN})=$$
$$=P(T_i^{GBNCIN}(u)>t),\ t\in<0,\infty),$$
$$u=0,1,...,z^{GBNCIN}, \tag{29}$$

The safety functions $S_i^{GBNCIN}(t,u)$, $t\in<0,\infty)$, $u=0,1,...,z^{GBNCIN}$, defined by (29) are called the coordinates of the $BCIN$ network E_i^{GBNCIN}, $i=1,2,...,8,$ safety function $S_i^{GBNCIN}(t,\cdot)$, given by (28). Thus, the relationship between the distribution function $F_i^{GBNCIN}(t,u)$ of the $BCIN$ network E_i^{GBNCIN}, $i=1,2,...,8,$ lifetime

$T_i^{GBNCIN}(u)$ in the safety state subset $\{u, u+1, ..., z^{GBNCIN}\}$, and the coordinate $S_i^{GBNCIN}(t,u)$ of its safety function is given by

$$\begin{gathered} F_i^{GBNCIN}(t,u) = P(T_i^{GBNCIN}(u) \le t) = \\ 1 - P(T_i^{GBNCIN}(u) > t) = 1 - S_i^{GBNCIN}(t,u),\ t \in <0,\infty), \\ u = 0,1,...,z^{GBNCIN}. \end{gathered}$$

Under outcomes of above, we have the following property of the multistate asset safety function coordinates

$$\begin{gathered} S_i^{GBNCIN}(t,0) \ge S_i^{GBNCIN}(t,1) \ge ... \ge S_i^{GBNCIN}(t, z^{GBNCIN}), \\ t \in <0,\infty),\ i = 1,2,...,8, \end{gathered}$$

Further, if we denote by

$$\begin{gathered} p_i^{GBNCIN}(t,u) = \\ P(s_i^{GBNCIN}(t) = u \,|\, s_i^{GBNCIN}(0) = z^{GBNCIN}),\ t \in <0,\infty), \\ u = 0,1,...,z^{GBNCIN}, \end{gathered}$$

the probability that the *BCIN* network E_i^{GBNCIN} is in the safety state u at the moment t, while it was in the safety state z^{GBNCIN} at the moment $t = 0$, then by (28)

$$\begin{gathered} S_i^{GBNCIN}(t,0) = 1, \\ S_i^{GBNCIN}(t, z^{GBNCIN}) = p_i^{GBNCIN}(t, z^{GBNCIN}),\ t \in <0,\infty), \\ i = 1,2,...,8, \end{gathered} \tag{30}$$

and

$$\begin{gathered} p_i^{GBNCIN}(t,u) = S_i^{GBNCIN}(t,u) - S_i^{GBNCIN}(t,u+1), \\ u = 0,1,...,z^{GBNCIN} - 1,\ t \in <0,\infty), \\ i = 1,2,...,8, \end{gathered} \tag{31}$$

Moreover, if

$$\begin{gathered} S_i^{GBNCIN}(t,u) = 1 \text{ for } t \le 0,\ u = 1,2,...,z^{GBNCIN}, \\ i = 1,2,...,8, \end{gathered}$$

then

$$\begin{gathered} \mu_i^{GBNCIN}(u) = \int_0^\infty S_i^{GBNCIN}(t,u)dt,\ u = 1,2,...,z^{GBNCIN}, \\ i = 1,2,...,8, \end{gathered} \tag{32}$$

is the mean lifetime of the *BCIN* network E_i^{GBNCIN} in the safety state subset $\{u, u+1, ..., z^{GBNCIN}\}$,

$$\begin{gathered} \sigma_i^{GBNCIN}(u) = \sqrt{n_i^{GBNCIN}(u) - [\mu_i^{GBNCIN}(u)]^2}, \\ u = 1,2,...,z^{GBNCIN},\ i = 1,2,...,8, \end{gathered} \tag{33}$$

where

$$\begin{gathered} n_i^{GBNCIN}(u) = 2\int_0^\infty t S_i^{GBNCIN}(t,u)dt,\ u = 1,2,...,z^{GBNCIN}, \\ i = 1,2,...,8, \end{gathered} \tag{34}$$

is the standard deviation of the *BCIN* network E_i^{GBNCIN} lifetime in the safety state subset $\{u, u+1, ..., z^{GBNCIN}\}$, and

$$\begin{gathered} \bar{\mu}_i^{GBNCIN}(u) = \int_0^\infty p_i^{GBNCIN}(t,u)dt,\ u = 1,2,...,z^{GBNCIN}, \\ i = 1,2,...,8, \end{gathered} \tag{35}$$

is the mean lifetime of the *BCIN* network E_i^{GBNCIN} in the safety state u, in the case when the integrals defined by (32), (34) and (35) are convergent.

Next, according to (30), (31), (32) and (35), we have

$$\begin{gathered} \bar{\mu}_i^{GBNCIN}(u) = \mu_i^{GBNCIN}(u) - \mu_i^{GBNCIN}(u+1), \\ u = 0,1,...,z^{GBNCIN} - 1, \\ \bar{\mu}_i^{GBNCIN}(z^{GBNCIN}) = \mu_i^{GBNCIN}(z^{GBNCIN}),\ i = 1,2,...,8, \end{gathered} \tag{36}$$

Then, the probability that the *GBNCIN* Network is in the safety state subset $\{u, u+1, ..., z^{GBNCIN}\}$, at the moment t, $t \in <0,\infty)$, while it was in the safety state z^{GBNCIN} at the moment $t = 0$, called safety function of this Network is a vector

$$\begin{gathered} S^{GBNCIN}(t,\cdot) = \\ [S^{GBNCIN}(t,0), S^{GBNCIN}(t,1), ..., S^{GBNCIN}(t, z^{GBNCIN})], \\ t \in <0,\infty), \end{gathered} \tag{37}$$

where

$$\begin{gathered} S^{GBNCIN}(t,u) = P(S^{GBNCIN}(t) \ge u \,|\, S^{GBNCIN}(0) \\ = z^{GBNCIN}) = P(T^{GBNCIN}(u) > t),\ t \in <0,\infty), \\ u = 0,1,...,z^{GBNCIN}, \end{gathered} \tag{38}$$

The safety functions $S^{GBNCIN}(t,u),\ t \in <0,\infty),\ u = 0,1,...,z^{GBNCIN}$, defined by (38) are called the coordinates of the *GBNCIN* Network safety function $S^{GBNCIN}(t,\cdot)$, given by (37).

Consequently, the relationship between the distribution function $F^{GBNCIN}(t,u)$ of the Network S^{GBNCIN} lifetime $T^{GBNCIN}(u)$ in the safety state subset $\{u,u+1,...,z^{GBNCIN}\}$, and the coordinate $S^{GBNCIN}(t,u)$ of its safety function is given by

$$F^{GBNCIN}(t,u) = P(T^{GBNCIN}(u) < t) =$$
$$1 - P(T^{GBNCIN}(u) > t) = 1 - S^{GBNCIN}(t,u),\ t \in < 0,\infty),$$
$$u = 0,1,...,z^{GBNCIN}.$$

Under above statements, we have

$$S^{GBNCIN}(t,0) \geq S^{GBNCIN}(t,1) \geq ... \geq S^{GBNCIN}(t,z^{GBNCIN}),$$
$$t \in < 0,\infty),$$

and if

$$p^{GBNCIN}(t,u) =$$
$$P(S^{GBNCIN}(t) = u | S^{GBNCIN}(0) = z^{GBNCIN}),\ t \in < 0,\infty),$$
$$u = 0,1,...,z^{GBNCIN}, \tag{39}$$

is the probability that the *GBNCIN* Network is in the safety state u at the moment t, $t \in < 0,\infty)$, while it was in the safety state z^{GBNCIN} at the moment $t = 0$, then

$$S^{GBNCIN}(t,0) = 1,$$
$$S^{GBNCIN}(t,z^{GBNCIN}) = p^{GBNCIN}(t,z^{GBNCIN}),$$
$$t \in < 0,\infty), \tag{40}$$

and

$$p^{GBNCIN}(t,u) = S^{GBNCIN}(t,u) - S^{GBNCIN}(t,u+1),$$
$$t \in < 0,\infty),\ u = 0,1,...,z^{GBNCIN} - 1. \tag{41}$$

Moreover, if

$$S^{GBNCIN}(t,u) = 1 \text{ for } t \leq 0,\ u = 0,1,...,z^{GBNCIN},$$

then

$$\mu^{GBNCIN}(u) = \int_0^\infty S^{GBNCIN}(t,u)dt,$$
$$u = 0,1,...,z^{GBNCIN}, \tag{42}$$

is the mean lifetime of the *GBNCIN* Network in the safety state subset $\{u,u+1,...,z^{GBNCIN}\}$,

$$\sigma^{GBNCIN}(u) = \sqrt{n^{GBNCIN}(u) - [\mu^{GBNCIN}(u)]^2},$$
$$u = 1,2,...,z^{GBNCIN}, \tag{43}$$

where

$$n^{GBNCIN}(u) = 2\int_0^\infty t S^{GBNCIN}(t,u)dt,$$
$$u = 1,2,...,z^{GBNCIN}, \tag{44}$$

is the standard deviation of the *GBNCIN* Network lifetime in the safety state subset $\{u,u+1,...,z^{GBNCIN}\}$, and moreover

$$\bar{\mu}^{GBNCIN}(u) = \int_0^\infty p^{GBNCIN}(t,u)dt,$$
$$u = 1,2,...,z^{GBNCIN}, \tag{45}$$

is the mean lifetime of the *GBNCIN* Network in the safety state u while the integrals (42), (44) and (45) are convergent.

Additionally, according to (40), (41), (42) and (45), we get the following relationship

$$\bar{\mu}^{GBNCIN}(u) = \mu^{GBNCIN}(u) - \mu^{GBNCIN}(u+1),$$
$$u = 0,1,...,z^{GBNCIN} - 1,$$
$$\bar{\mu}^{GBNCIN}(z^{GBNCIN}) = \mu^{GBNCIN}(z^{GBNCIN}). \tag{46}$$

Further, a probability that the *GBNCIN* Network is in the subset of safety states worse than the critical safety state r, $r \in \{1,2,...,z^{BCIN}\}$, while it was in the safety state z^{GBNCIN} at the moment $t = 0$, called as risk function of the multi-state network [Kołowrocki 2004, 2014], [Kołowrocki, Soszyńska-Budny, 2011], is given by following relation

$$r^{GBNCIN}(t) =$$
$$P(S^{GBNCIN}(t) < r^{GBNCIN} | S^{GBNCIN}(0) = z^{GBNCIN}) =$$
$$P(T^{GBNCIN}(r) \leq t),\ t \in < 0,\infty),$$

Consequently, by (29), we have

$$r^{GBNCIN}(t) =$$
$$1 - P(S^{GBNCIN}(t) \geq r^{GBNCIN} | S^{GBNCIN}(0) = z^{GBNCIN}) =$$
$$1 - S^{GBNCIN}(t,r),\ t \in < 0,\infty), \tag{47}$$

and if τ^{GBNCIN} is the moment when the *GBNCIN* Network risk exceeds a permitted level δ^{GBNCIN}, then

$$\tau^{GBNCIN} = r^{GBNCIN^{-1}}(\delta^{GBNCIN}), \qquad (48)$$

where $r^{GBNCIN^{-1}}(t)$, if exists, is the inverse function of the network risk function $r^{GBNCIN}(t)$.

Now, after introducing the notion of the multistate safety analysis, we may define multi-state safety structure of *GBNCIN* Network. The Network will be analysed under the assumption it is multi-state series system.

A multistate *GBNCIN* Network is series if its lifetime $T^{GBNCIN}(u)$ in the safety state subset $\{u, u+1, ..., z^{GBNCIN}\}$, is given by

$$T^{GBNCIN}(u) = \min_{1 \le i \le n}\{T_i^{GBNCIN}(u)\},\ u = 1,2,...,z^{GBNCIN}.$$

The number n is called the *GBNCIN* Network structure shape parameter.

The above definition means that a multi-state series *GBNCIN* Network is in the safety state subset $\{u, u+1, ..., z^{GBNCIN}\}$, if and only if all its *BCIN* networks are in this subset of safety states. That meaning is very close to the definition of a two-state series system considered in a classical reliability analysis that is not failed if all its components are not failed. This fact can justify the safety structure scheme for a multistate series *GBNCIN* Network presented in *Figure 37*.

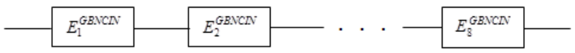

Figure 37. The scheme of a series *GBNCIN* Network safety structure

It is easy to work out that the safety function of the multi-state series *GBNCIN* Network, composed of the *BCIN* networks, is given by the vector [Kołowrocki 2004, 2014], [Kołowrocki, Soszyńska-Budny, 2011]

$$S^{GBNCIN}(t,\cdot) =$$

$$S^{GBNCIN}(t,\cdot) = [1, S^{GBNCIN}(t,1), S^{GBNCIN}(t,2), ..., S^{GBNCIN}(t, z^{GBNCIN})], \qquad (49)$$

with the coordinates

$$S^{GBNCIN}(t,u) = \prod_{i=1}^{8} S_i^{GBNCIN}(t,u),\ t \in <0,\infty), \quad u = 1,2,...,z^{GBNCIN}, \qquad (50)$$

where $S_i^{GBNCIN}(t,u)$ is the safety function of the asset E_i^{GBNCIN}, $i = 1,2,...,8$,

If *BCIN* networks E_i^{GBNCIN}, $i = 1,2,...,8$, of the multi-state series *GBNCIN* Network have the exponential safety functions

$$S_i^{GBNCIN}(t,\cdot) = [1, S_i^{GBNCIN}(t,1), \ldots, S_i^{GBNCIN}(t, z^{GBNCIN})], \quad t \in <0,\infty), \qquad (51)$$

where

$$S_i^{GBNCIN}(t,u) = \exp[-\lambda_i^{GBNCIN}(u)t],\ \text{for } t \ge 0, \quad \lambda_i^{GBNCIN}(u) > 0,\ i = 1,2,...,8,\ u = 1,2,...,z^{GBNCIN}, \qquad (52)$$

Safety function of the multi-state series *GBNCIN* Network is given by

$$S^{GBNCIN}(t,\cdot) = [1, S^{GBNCIN}(t,1), S^{GBNCIN}(t,2), ..., S^{GBNCIN}(t, z^{GBNCIN})], \qquad (53)$$

where

$$S^{GBNCIN}(t,u) = \exp[-\sum_{i=1}^{8} \lambda_i^{GBNCIN}(u)t] = \exp[-\lambda^{GBNCIN}(u)t]\ \text{for } t \ge 0, \qquad (54)$$

6. Conclusions

Safety model of Global Baltic Network of Critical Infrastructure Networks, proposed in this chapter, is basic background for considerations in further Tasks of the EU-CIRCLE Project. The model, together with the model of the GBNCIN Network operation process, presented in [EU-CIRCLE Report D3.3-GMU11 – GBNCINOP - Model 8, 2016], will be used for further works on Integrated model of GBNCIN Network safety related to its operation process [EU-CIRCLE Report D3.3-GMU11 - IM GBNCIN S - Model 8, 2016].

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