Kołowrocki Krzysztof

Kuligowska Ewa

Soszyńska-Budny Joanna

Torbicki Mateusz
Gdynia Maritime University, Gdynia, Poland

Oil transport in port
Part 0
Port oil piping transportation system safety without outside impacts

Keywords

port oil piping transportation system, system free of outside impacts, safety, cost analysis

Abstract

The paper is concerned with the model of critical infrastructure safety prediction without considering outside impacts. The general approach to the prediction of critical infrastructure safety is proposed and the safety indicators are defined for a critical infrastructure free of any outside impacts. Moreover, there is presented the model application for port oil piping transportation system safety prediction. Further, the cost analysis of critical infrastructure operation process is proposed and applied to the considered piping system.

1. Introduction

This paper is a preliminary part of the series of four papers proposed to comprehensive modelling and prediction of the safety and resilience of critical infrastructures with application to the port oil piping transportation system safety prediction in the scope of the EU-CIRCLE project Case Study 2, Storm and Sea Surge at Baltic Sea Port.

First, the basic notions of the critical infrastructure safety analysis are introduced, i.e. the unconditional critical infrastructure safety function, the multistate exponential safety function of the critical infrastructure and the critical infrastructure risk function are defined. Moreover, the critical infrastructure main safety characteristics are determined, i.e. the mean lifetime and standard deviation of the critical infrastructure in the safety state subset and the intensities of degradation (ageing) of the critical infrastructure. Next, the exemplary critical infrastructure safety structures are defined and the critical infrastructure assets safety parameters are determined.

Further, the MCIS Model 0 created in [EU-CIRCLE Report D3.3-Part3, 2017] is applied to the port oil piping transportation system. Safety and resilience indicators are determined to the port oil piping transportation system safety, resilience and operation cost analysis.

2. Critical infrastructure safety – multistate approach

In the multistate safety analysis to define the critical infrastructure with degrading / ageing components / assets, we assume that [Kołowrocki, Soszyńska-Budny, 2011], [EU-CIRCLE Report D3.3-Part 3, 2017]:

- n is the number of the critical infrastructure assets,
- A_i, $i = 1,2,...,n$, are the critical infrastructure assets,
- all assets and the critical infrastructure have the safety state set $\{0,1,...,z\}$, $z \geq 1$,
  the safety states are ordered, the safety state 0 is the worst and the safety state z is the best,
- r, $r \in \{1,2,..., z\}$, is the critical safety state (critical infrastructure and its assets staying in the safety states less than the critical state is highly

dangerous for them and for their operating environment),

- $T_i(u)$, $i = 1,2,...,n$, are independent random variables representing the lifetimes of assets A_i in the safety state subset $\{u,u+1,...,z\}$, $u = 1,2,...,z$, while they were in the safety state z at the moment $t = 0$,
- $T(u)$ is a random variable representing the lifetime of the critical infrastructure in the safety state subset $\{u,u+1,...,z\}$, $u = 1,2,...,z$, while it was in the safety state z at the moment $t = 0$,
- the safety states degrades with time t,
- the assets and the critical infrastructure degrade with time t,
- $s_i(t)$ is the asset A_i safety state at the moment t, $t \in <0,\infty)$, given that it was in the safety state z at the moment $t = 0$.
- $s(t)$ is the critical infrastructure safety state at the moment t, $t \in <0,\infty)$, given that it was in the safety state z at the moment $t = 0$.

The above assumptions mean that the safety states of the critical infrastructure with degrading assets may be changed in time only from better to worse [Kołowrocki, Soszyńska-Budny, 2011], [EU-CIRCLE Report D3.3-Part 3, 2017].

We denote the critical infrastructure unconditional lifetime in the safety state subset $\{u,u+1,...,z\}$, $u = 1,2,...,z$, by $T(u)$ and define the critical infrastructure safety function by the vector [Kołowrocki, Soszyńska-Budny, 2011], [EU-CIRCLE Report D3.3-Part 3, 2017]

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

with the coordinates defined by

$$\boldsymbol{S}(t,u) = P(T(u) > t)\ \text{for}\ t \in <0,\infty),\ \ u = 1,2,...,z.$$

If r is the critical safety state, then the critical infrastructure risk function

$$\boldsymbol{r}(t) = P(s(t) < r \mid s(0) = z) = P(T(r) \le t),\ t \in <0,\infty),$$

is defined as a probability that the critical infrastructure is in the subset of safety states worse than the critical safety state r, $r \in \{1,...,z\}$ while it was in the best safety state z at the moment $t = 0$ and given by [Kołowrocki, Soszyńska-Budny, 2011], [EU-CIRCLE Report D3.3-Part 3, 2017]

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

where $\boldsymbol{S}(t,r)$ is the coordinate of the critical infrastructure unconditional safety function for $u = r$.

The moment τ of exceeding acceptable value of critical infrastructure risk function level δ given by

$$\tau = \boldsymbol{r}^{-1}(\delta),$$

where $\boldsymbol{r}^{-1}(t)$ is the inverse function of the risk function $\boldsymbol{r}(t)$, is interpreted.

3. Critical infrastructure safety structures

On the basis of the approach to critical infrastructure safety analysis in Section 1, the main basic critical infrastructure safety structures were defined in [EU-CIRCLE Report D3.3-Part 3, 2017]. In this section below, we bring up the definition we will use in Section 5.

Definition 1

A critical infrastructure is called "m_i out of l_i"-series if its lifetime $T(u)$ in the safety state subset $\{u,u+1,...,z\}$ is given by

$$T(u) = \min_{1 \le i \le k} T_{(l_i - m_i + 1)}(u),\ m_i = 1,2,...,l_i,\ u = 1,2,...,z,$$

where $T_{(l_i - m_i + 1)}(u)$ is the m_ith maximal order statistic in the set of random variables

$$T_{i1}(u),\ T_{i2}(u),\ ...,\ T_{il_i}(u),\ i = 1,2,...,k,\ u = 1,2,...,z.$$

The above definition means that the "m_i out of l_i"-series critical infrastructure is composed of k critical infrastructures that are "m_i out of l_i" critical infrastructures and it is in the safety state subset $\{u,u+1,...,z\}$ if all its "m_i out of l_i" critical infrastructures are in this safety state subset. In this definition l_i, $i = 1,2,...,k$, are the numbers of assets in the "m_i out of l_i" critical infrastructures. The numbers k, $m_1, m_2, ..., m_k$ and $l_1, l_2,..., l_k$ are called the critical infrastructure structure shape parameters. Joining the justification for the safety structure schemes of the "m_i out of l_i" critical infrastructure and the series critical infrastructure schemes leads to the scheme of a of an "m_i out of l_i"-series critical infrastructure safety structure given in *Figure 1*, where $j_1,\ j_2,...,\ j_{l_i} \in \{1,2,...,l_i\}$, for $i = 1,2,...,k$ and $i_a \ne i_b$ for $a \ne b$.

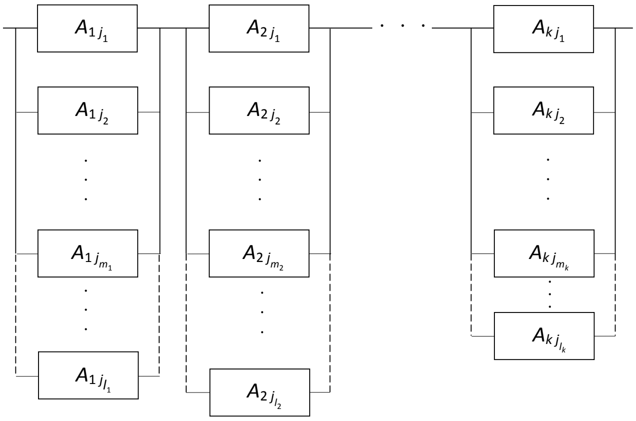

Figure 1. The scheme of "m_i out of l_i"-series critical infrastructure safety structure

The formulae for safety functions of the presented in this section critical infrastructures are given in [EU-CIRCLE Report D3.3-Part 3, 2017].

4. Critical infrastructure safety model – MCIS 0

In this section, we consider the critical infrastructure free of any outside impacts.

4.1. Critical infrastructure safety indicators

We denote the critical infrastructure unconditional lifetime in the safety state subset $\{u, u+1, ..., z\}$, $u = 1,2,...,z$, by $T^0(u)$ and define the first safety indicator, the critical infrastructure safety function (SafI1) by the vector [EU-CIRCLE Report D3.3-Part 3, 2017]

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

with the coordinates defined by

$$\boldsymbol{S}^0(t,u) = P(T^0(u) > t) \text{ for } t \in <0,\infty), \\ u = 1,2,...,z. \quad (2)$$

Moreover, if r is the critical safety state, then the second safety indicator, the critical infrastructure risk function (SafI2)

$$\boldsymbol{r}^0(t) = P(s(t) < r \mid s(0) = z) = P(T^0(r) \le t), \\ t \in <0,\infty), \quad (3)$$

is defined as a probability that the critical infrastructure is in the subset of safety states worse than the critical safety state r, $r \in \{1,...,z\}$ while it was in the best safety state z at the moment $t = 0$ and given by [EU-CIRCLE Report D3.3-Part 3, 2017]

$$\boldsymbol{r}^0(t) = 1 - \boldsymbol{S}^0(t,r),\ t \in <0,\infty), \quad (4)$$

where $\boldsymbol{S}^0(t,r)$ is the coordinate of the critical infrastructure unconditional safety function given by (2) for $u = r$.

The graph of the critical infrastructure risk function is the third safety indicator called the critical infrastructure fragility curve (SafI3).

The critical infrastructure safety function (SafI1), the critical infrastructure risk function (SafI2) and the critical infrastructure fragility curve (SafI3) are proposed as main basic critical infrastructure safety indicators (SafI3).

Other practically useful critical infrastructure safety factors are:

– the mean value of the critical infrastructure lifetime $T^0(r)$ up to exceeding critical safety state r (SafI4) given by

$$\boldsymbol{\mu}^0(r) = \int_0^\infty \boldsymbol{S}^0(t,r)dt, \quad (5)$$

where $\boldsymbol{S}^0(t,r)$ is defined by (2) for $u = r$;

– the standard deviation of the critical infrastructure lifetime $T^0(r)$ up to the exceeding the critical safety state r (SafI5) given by

$$\boldsymbol{\sigma}^0(r) = \sqrt{n^0(r) - [\mu^0(r)]^2}\ , \quad (6)$$

where

$$n^0(r) = 2\int_0^\infty t\ \boldsymbol{S}^0(t,r)dt, \quad (7)$$

and $\boldsymbol{S}^0(t,r)$ is given by (2) for $u = r$ and $\boldsymbol{\mu}^0(r)$ is given by (5);

– the moment τ of exceeding acceptable value of critical infrastructure risk function level δ (SafI6) given by

$$\tau^0 = \boldsymbol{r}^{0\ -1}(\delta), \quad (8)$$

where $\boldsymbol{r}^{0\ -1}(t)$ is the inverse function of the risk function $\boldsymbol{r}^0(t)$ given by (4);

– the intensities of degradation (ageing) of the critical infrastructure / the intensities of critical infrastructure departure from the safety state subset $\{u, u+1, ..., z\}$, $u = 1,2,...,z$, (SafI7), i.e. the coordinates of the vector

$$\boldsymbol{\lambda}^0(t,\cdot) = [0, \boldsymbol{\lambda}^0(t,1), \ldots, \boldsymbol{\lambda}^0(t,z)],$$
$$t \in <0,+\infty), \quad (9)$$

where

$$\boldsymbol{\lambda}^0(t,u) = \frac{-\frac{d\boldsymbol{S}^0(t,u)}{dt}}{\boldsymbol{S}^0(t,u)},$$
$$t \in <0,+\infty),\ u = 1,2,\ldots,z. \quad (10)$$

Further, we will also use the following critical infrastructure safety characteristics [Kołowrocki, Soszyńska-Budny, 2017c]:

– the mean lifetime of the critical infrastructure in the safety state subset $\{u, u+1, \ldots, z\}$, $u = 1,2,\ldots,z$, given by

$$\boldsymbol{\mu}^0(u) = \int_0^\infty [\boldsymbol{S}^0(t,u)]dt,\ u = 1,2,\ldots,z, \quad (11)$$

– the standard deviation of the critical infrastructure lifetime in the safety state subset $\{u, u+1, \ldots, z\}$, $u = 1,2,\ldots,z$, given by

$$\boldsymbol{\sigma}^0(u) = \sqrt{n^0(u) - [\boldsymbol{\mu}^0(u)]^2},\ u = 1,2,\ldots,z, \quad (12)$$

where

$$n^0(u) = 2\int_0^\infty t\boldsymbol{S}^0(t,u)dt,\ u = 1,2,\ldots,z, \quad (13)$$

– the mean lifetimes $\bar{\boldsymbol{\mu}}^0(u)$, $u = 1,2,\ldots,z$, of the critical infrastructure in the particular safety states

$$\bar{\boldsymbol{\mu}}^0(u) = \boldsymbol{\mu}^0(u) - \boldsymbol{\mu}^0(u+1),\ u = 0,1,\ldots,z-1, \quad (14)$$

$$\bar{\boldsymbol{\mu}}^0(z) = \boldsymbol{\mu}^0(z). \quad (15)$$

4.2. Critical infrastructure assets safety parameters

We mark by

$$T_i^0(u),\ u = 1,2,\ldots,z, \quad (16)$$

the asset A_i lifetime $T_i(u)$ in the safety state subset $\{u, u+1, \ldots, z\}$, $u = 1,2,\ldots,z$, and define the asset A_i safety function (SafI1) by the vector [EU-CIRCLE Report D3.3-Part 3, 2017]

$$S_i^0(t,\cdot) = [1, S_i^0(t,1) \ldots, S_i^0(t,\cdot z)],\ t \in <0,\infty),$$
$$i = 1,2,\ldots,n, \quad (17)$$

where

$$S_i^0(t,u) = P(s_i(t) \geq u \mid s_i(0) = z)\ P(T_i^0(u) > t),$$
$$t \in <0,\infty),\ u = 1, 2, \ldots, z,\ i = 1,2,\ldots,n, \quad (18)$$

is the probability that the asset A_i is in the safety state subset $\{u, u+1, \ldots, z\}$, $u = 1,2,\ldots,z$, at the moment t, $t \in <0,\infty)$, while it was in the safety state z at the moment $t = 0$.

The safety functions $S_i^0(t,u)$, $t \in <0,\infty)$, $u = 1,2, \ldots,z$, defined by (18) are called the coordinates of the asset A_i, $i = 1,2,\ldots,n$, safety function $S_i^0(t,\cdot)$, $t \in <0,\infty)$, given by (17).

The mean lifetime of the asset A_i in the safety state subset $\{u, u+1, \ldots, z\}$, $u = 1,2,\ldots,z$, is given by

$$\mu_i^0(u) = \int_0^\infty S_i^0(t,u)dt,\ u = 1,2,\ldots z,\ i = 1,2,\ldots,n. \quad (19)$$

In the case when the critical infrastructure asset A_i, $i = 1,2,\ldots,n$, have the exponential safety functions (SafI1), i.e.

$$S_i^0(t,\cdot) = [1, S_i^0(t,1), \ldots, S_i^0(t,z)],\ t \in <0,\infty),$$
$$i = 1,2,\ldots,n, \quad (20)$$

where

$$S_i^0(t,u) = \exp[-\lambda_i^0(u)t],\ t \in <0,+\infty),\ \lambda_i^0(u) \geq 0,$$
$$u = 1,2,\ldots,z,\ i = 1,2,\ldots,n, \quad (21)$$

the intensities of ageing of the critical infrastructure asset A_i, $i = 1,2,\ldots,n$, / the intensities of critical infrastructure assets A_i, $i = 1,2,\ldots,n$, departure from the safety state subset $\{u, u+1, \ldots, z\}$, $u = 1,2,\ldots,z$, (SafI7), i.e. the coordinates of the vector

$$\lambda_i^0(\cdot) = [0, \lambda_i^0(1), \ldots, \lambda_i^0(z)],\ i = 1,2,\ldots,n, \quad (22)$$

are constant and according to (19)

$$\lambda_i^0(u) = \frac{1}{\mu_i^0(u)},\ u = 1,2,\ldots z,\ i = 1,2,\ldots,n, \quad (23)$$

where $\mu_i^0(u)$, $i = 1,2,\ldots,n$, is the mean value of the critical infrastructure asset A_i, $i = 1,2,\ldots,n$, lifetime $T_i^0(u)$, $i = 1,2,\ldots,n$, in the safety state subset $\{u, u+1, \ldots, z\}$, $u = 1,2,\ldots z$.

5. MCIS 0 application to safety of port oil piping transportation system evaluation

In this section, we consider the port oil piping transportation system free of any outside impacts.

5.1. EU-CIRCLE Case Study 2, Scenario 1: Oil transport in port

5.1.1. Experiment description

The port oil piping transportation system is operating at one of the Baltic Oil Terminals that is designated for the reception from ships, the storage and sending by carriages or cars the oil products. It is also designated for receiving from carriages or cars, the storage and loading the tankers with oil products such like petrol and oil. On the basis of the piping system operation and safety statistical data coming from its operators its safety will be modelled, identified and predicted.

5.1.2. Experiment area dimension and time of execution

Desired Spatial Dimension:
The area in the neighbourhood of the port oil piping transportation system; the approximate length of the port oil piping system is equal to 25 km (*Figures 2-3*).

Maps of Case Study Scenario 1 Location

Figure 2. The port oil piping transportation system operating between the Port of Gdynia and the Terminal in Dębogórze

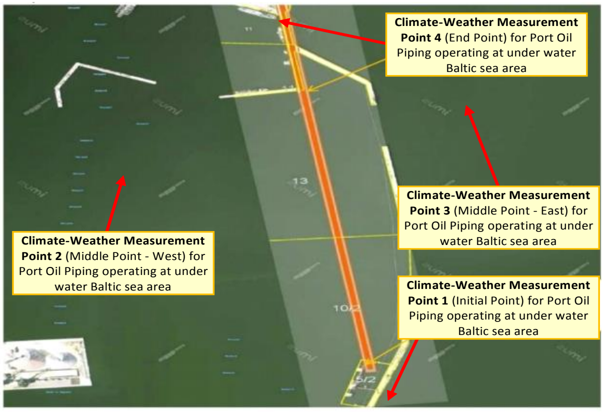

Figure 3. The port oil piping transportation system alignment in the Port of Gdynia

5.1.3. Port oil piping transportation critical infrastructure assets description

The considered terminal is composed of three parts *A*, *B* and *C*, linked by the piping transportation system with the pier. The scheme of this system is presented in *Figure 4*.

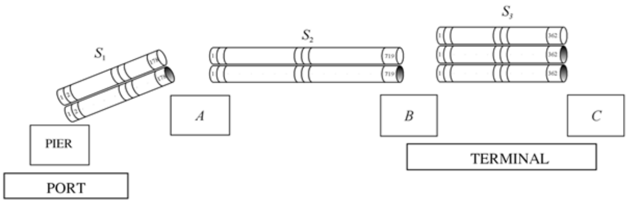

Figure 4. The scheme of the port oil transportation system

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

– the subsystem S_1 composed of two pipelines, each composed of 176 pipe segments and 2 valves,

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

The subsystems S_1, S_2, S_3, indicated in *Figure 4* are forming a general series port oil pipeline system safety structure presented in *Figure 5*.

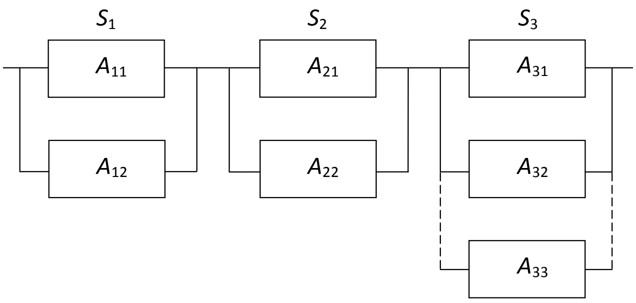

Figure 5. General scheme of the port oil pipeline system safety structure

The system is a series system composed of two series-parallel subsystems S_1, S_2, each containing two pipelines (assets) and one series-"2 out of 3" subsystem S_3 containing 3 pipelines (assets).
The subsystems S_1, S_2 and S_3 are forming a general series port oil pipeline system safety structure presented in *Figure 5*. However, the pipeline system safety structure and its subsystems and components safety depend on changing in time the climate-weather states at its operating area.
The considered port oil piping transportation system alignment is shown in *Figures 2-3*. In *Figure 3*, there are shown additionally, the measurement points from which data describing the climate-weather change process at the port oil piping transportation system operating area were collected.

5.2. Safety parameters of port oil piping transportation system assets

After considering the comments and opinions coming from experts, taking into account the effectiveness and safety aspects of the operation of the port oil piping transportation system and its assets, we fix for all of them [GMU Safety Interactive Platform]:

- the number of safety states (excluding safety state 0): $z = 2$,

and we distinguish their following three $(z+1)$ safety states:

- a safety state 2 – an asset and the port oil piping transportation system operation is fully safe,
- a safety state 1 – an asset and the port oil piping transportation system is less safe and more dangerous because of the possibility of environment pollution,
- a safety state 0 – an asset and the port oil piping transportation system is destroyed,

and, we assume that:

- there are possible the transitions between the assets and the port oil piping transportation system safety states only from better to worse ones,
- the critical safety state of an asset and the port oil piping transportation system is $r = 1$,
- the port oil piping transportation system risk function permitted level $\delta = 0.05$;
- the mean values of the assets A_{11}, A_{12}, A_{21}, A_{22}, A_{31}, A_{32} and A_{33} of the port oil piping transportation system lifetimes in the safety state subsets $\{1,2\}$, $\{2\}$, calculated on the basis of safety data of its components coming from experts, are as follows:
  - for safety state subset $\{1,2\}$

    $\mu_{11}^{0}(1)$ = 276 years,

    $\mu_{12}^{0}(1)$ = 276 years,

    $\mu_{21}^{0}(1)$ = 69 years,

    $\mu_{22}^{0}(1)$ = 69 years,

    $\mu_{31}^{0}(1)$ = 137 years,

    $\mu_{32}^{0}(1)$ = 137 years,

    $\mu_{33}^{0}(1)$ = 114 years;
  - for safety state subset $\{2\}$

    $\mu_{11}^{0}(2)$ = 185 years,

    $\mu_{12}^{0}(2)$ = 185 years,

    $\mu_{21}^{0}(2)$ = 46 years,

    $\mu_{22}^{0}(2)$ = 46 years,

    $\mu_{31}^{0}(2)$ = 110 years,

    $\mu_{32}^{0}(2)$ = 110 years,

    $\mu_{33}^{0}(2)$ = 102 years.

Applying (22) and (23), we get the intensities of ageing of the critical infrastructure assets A_{ij}, $i = 1,2$, $j = 1,2$, $i = 3$, $j = 1,2,3$, / the intensities of critical infrastructure assets A_{ij}, $i = 1,2$, $j = 1,2$, $i = 3$, $j = 1,2,3$, departure from the safety state subset $\{1,2\}$ and $\{2\}$, i.e. the coordinates of the vector are constant

$$\lambda_{ij}^{0}(\cdot) = [0,\ \lambda_{ij}^{0}(1),\ \lambda_{ij}^{0}(2)],\ i = 1,2,\ j = 1,2,\ i = 3,\ j = 1,2,3. \quad (24)$$

follows that the intensities of departure of the assets A_{11}, A_{12}, A_{21}, A_{22}, A_{31}, A_{32} and A_{33} of the port oil piping transportation system are:

- for safety state subset {1,2}

$\lambda^0_{11}(1) = 0.00362,$

$\lambda^0_{12}(1) = 0.00362,$

$\lambda^0_{21}(1) = 0.01444,$

$\lambda^0_{22}(1) = 0.01444,$

$\lambda^0_{31}(1) = 0.00730,$

$\lambda^0_{32}(1) = 0.00730,$

$\lambda^0_{33}(1) = 0.00874;$

- for safety state subset {2}

$\lambda^0_{11}(2) = 0.00540,$

$\lambda^0_{12}(2) = 0.00540,$

$\lambda^0_{21}(2) = 0.02163,$

$\lambda^0_{22}(2) = 0.02163,$

$\lambda^0_{31}(2) = 0.00912,$

$\lambda^0_{32}(2) = 0.00912,$

$\lambda^0_{33}(2) = 0.00984.$

5.3. Port oil piping transportation system safety characteristics

After applying formulae for the safety function of the "m_i out of l_i"-series critical infrastructure from [EU-CIRCLE Report D3.3-Part 3, 2017], we get the safety function of the port oil piping transportation system

$$\boldsymbol{S}^0(t, \cdot) = [\ 1, \boldsymbol{S}^0(t,1), \boldsymbol{S}^0(t, 2)\ ],\ t \geq 0, \quad (25)$$

where

$$\boldsymbol{S}^0(t, 1) = 4\exp[-0.03271t] - 8\exp[-0.04148t] + 8\exp[-0.03418t] - 2\exp[-0.0472t] + 4\exp[-0.05597t] - 4\exp[-0.04867t] - 2\exp[-0.03633t] + 4\exp[-0.0451t] - 4\exp[-0.0378t] + \exp[-0.05082t] - 2\exp[-0.05959t] + 2\exp[-0.05229t],$$
$$t \geq 0, \quad (26)$$

$$\boldsymbol{S}^0(t, 2) = 4\exp[-0.04533t] - 8\exp[-0.05513t] + 8\exp[-0.04604t] - 2\exp[-0.06707t] + 4\exp[-0.07687t] - 4\exp[-0.06778t] - 2\exp[-0.05074t] + 4\exp[-0.06054t] - 4\exp[-0.05145t] + \exp[-0.07248t] - 2\exp[-0.08228t] + 2\exp[-0.07319t],$$
$$t \geq 0. \quad (27)$$

Hence, applying (11)-(13), the mean values and standard deviations of the lifetimes of the port oil piping transportation system are:

– in the safety state subset: {1, 2}

$$\boldsymbol{\mu}^0(1) = 62.5692 \text{ years},$$
$$\boldsymbol{\sigma}^0(1) = 41.8793 \text{ years}, \quad (28)$$

– in the safety state subset {2}

$$\boldsymbol{\mu}^0(2) = 45.8198 \text{ years},$$
$$\boldsymbol{\sigma}^0(2) = 30.7346 \text{ years}. \quad (29)$$

From (28)-(29), applying (14)-(15), the mean lifetimes $\bar{\boldsymbol{\mu}}^0(u)$, $u = 1,2$, of the port oil piping transportation system in the particular safety states are:

$$\bar{\boldsymbol{\mu}}^0(1) = \boldsymbol{\mu}^0(1) - \boldsymbol{\mu}^0(2) = 16.7493 \text{ years},$$
$$\bar{\boldsymbol{\mu}}^0(2) = \boldsymbol{\mu}^0(2) = 45.8198 \text{ years}. \quad (30)$$

The graph of the safety function of the port oil piping transportation system is given in *Figure 6*.

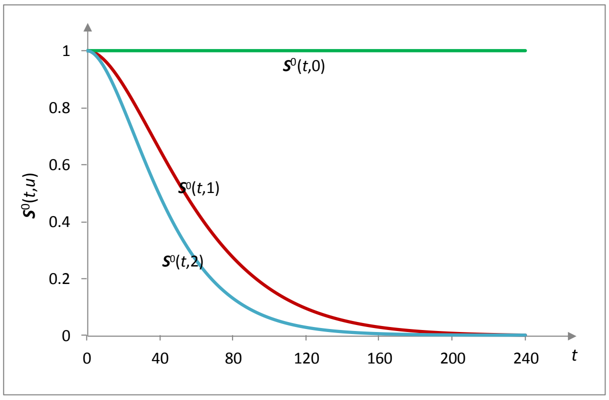

Figure 6. The graphs of the port oil piping transportation system safety function coordinates

As the critical safety state is $r = 1$, then by (4), the port oil piping transportation system risk function is

$$\boldsymbol{r}^0(t) = 1 - \boldsymbol{S}^0(t, 1) = 1 - (4\exp[-0.04533t] - 8\exp[-0.05513t] + 8\exp[-0.04604t] - 2\exp[-0.06707t] + 4\exp[-0.07687t] - 4\exp[-0.06778t] - 2\exp[-0.05074t] + 4\exp[-0.06054t] - 4\exp[-0.05145t] + \exp[-0.07248t] - 2\exp[-0.08228t] + 2\exp[-0.07319t]),\ t \geq 0, \quad (31)$$

and by (8), the moment τ^0 of exceeding acceptable value of critical infrastructure risk function level $\delta = 0.05$ is

$$\tau^0 = (\boldsymbol{r}^0)^{-1}(0.05) = 12.1289 \text{ years}. \quad (32)$$

The graph of the port oil piping transportation system risk function is presented in *Figure 7*.

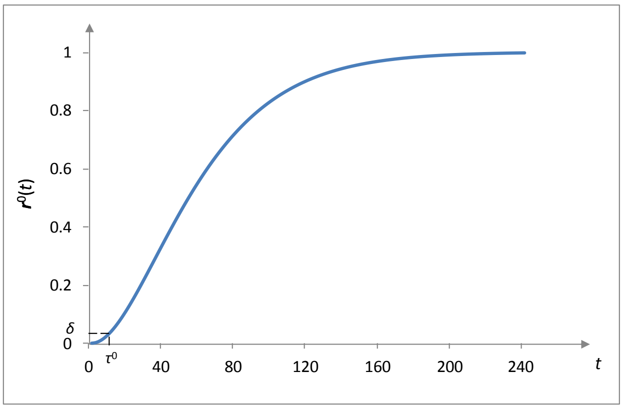

Figure 7. The graph of the port oil piping transportation system risk function

The intensities of degradation (ageing) of the port oil piping transportation system / the intensities the port oil piping transportation system departure from the safety state subset $\{1,2\}$, $\{2\}$, i.e. the coordinates of the vector

$$\boldsymbol{\lambda}^0(t,\cdot) = [0,\ \lambda^0(t,1), \lambda^0(t,2)\ ],\ t \in <0,+\infty), \qquad (33)$$

where

$$\lambda^0(t,1) = \frac{-\frac{d\boldsymbol{S}^0(t,1)}{dt}}{\boldsymbol{S}^0(t,1)},\ \ \lambda^0(t,2) = \frac{-\frac{d\boldsymbol{S}^0(t,2)}{dt}}{\boldsymbol{S}^0(t,2)},$$
$$t \in <0,+\infty), \qquad (34)$$

and $\boldsymbol{S}^0(t, 1)$ is given by (26) and $\boldsymbol{S}^0(t, 2)$ is given by (27).
The values of the intensities of degradation given by (34) stabilize for large time and approximately amounts

$$\lambda^0(1) = \lim_{t\to+\infty} \lambda^0(t,1) \cong 0.03271,$$
$$\lambda^0(2) = \lim_{t\to+\infty} \lambda^0(t,2) \cong 0.04533. \qquad (35)$$

The graphs of the intensities of degradation of the port oil piping transportation system are given in *Figure 8*.

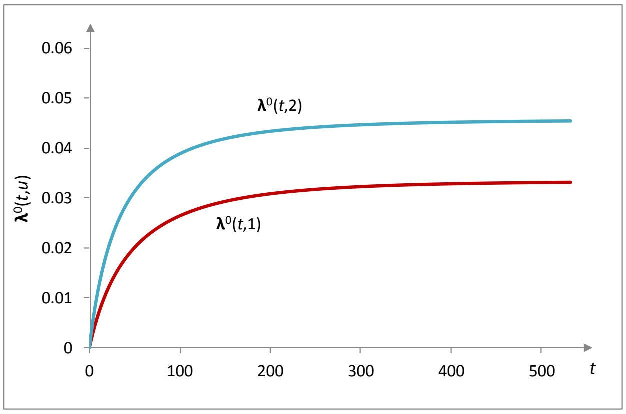

Figure 8. The graphs of the intensities of ageing of the port oil piping transportation system

6. Cost analysis of critical infrastructure operation process

We consider the complex technical multistate system / the critical infrastructure consisted of n components and we assume that the operation costs of its single basic components during the system operation time $\theta,\ \theta \ge 0,$ amount

$$k_i^0(\theta),\ \ i = 1,2,...,n.$$

First, we suppose that the system is non-repairable, i.e. the system during the operation has not exceeded the critical safety state r. In this case, the total cost of the non-repairable system during the operation time $\theta,\ \theta \ge 0,$ is given by

$$\boldsymbol{K}^0(\theta) = \sum_{i=1}^{n} k_i^0(\theta),\ \ \theta \ge 0. \qquad (36)$$

Further, we additionally assume that the system is repairable after exceeding the critical safety state r, its renovation time is ignored and the cost of the system singular renovation is k_{ig}^0.
Then, the approximate total operation cost of the repairable system with ignored its renovation time during the operation time $\theta,\ \theta \ge 0,$ amounts

$$\boldsymbol{K}_{ig}^0(\theta) \cong \sum_{i=1}^{n} k_i^0(\theta) + k_{ig}^0 H^0(\theta,r),\ \ \theta \ge 0, \qquad (37)$$

where $H^0(\theta,r)$ is the mean value of the number of exceeding the critical reliability state r by the system operating at the variable conditions during the operation time θ defined by (3.58) in [Kołowrocki, Soszyńska-Budny, 2011].
Now, we assume that the system is repairable after exceeding the critical safety state r and its renewal time is non-ignored and have distribution function

with the mean value $\mu_0^0(r)$ and the standard deviation $\sigma_0^0(r)$ and the cost of the system singular renovation is k_{nig}^0.

Then, the approximate total operation cost of the repairable system with non-ignored its renovation time during the operation time θ, $\theta \geq 0$, amounts

$$\boldsymbol{K}_{nig}^0(\theta) \cong \sum_{i=1}^{n} k_i^0(\theta) + k_{nig}^0 \, \overline{\overline{H}}^0(\theta, r), \theta \geq 0, \qquad (38)$$

where $\overline{\overline{H}}^0(\theta, r)$ is the mean value of the number of renovations of the system operating at the variable conditions during the operation time θ defined by (3.92) in [Kołowrocki, Soszyńska-Budny, 2011].

The particular expressions for the mean values $H^0(\theta, r)$ and $\overline{\overline{H}}^0(\theta, r)$ for the repairable systems with ignored and non-ignored renovation times existing in the formulae (37) and (38), respectively defined by (3.58) and (3.92), are determined in Chapter 3 in [Kołowrocki, Soszyńska-Budny, 2011] for typical repairable critical infrastructures, i.e. for multistate series, parallel, "*m* out of *n*", consecutive "*m* out of *n*: F", series-parallel, parallel-series, series-"*m* out of *k*", "m_i out of l_i"-series, series-consecutive "*m* out of *k*: F" and consecutive "m_i out of l_i: F"-series critical infrastructures operating at the variable operation conditions.

7. Cost analysis of port oil piping transportation system operation process

The port oil piping transportation system is composed of n =2880 components and according to the information coming from experts, the approximate mean operation costs of its single basic components during the operation time is θ = 1 year, independently of the operation states, amount

$k_i^0(\theta) \cong$ 9.6 PLN, i = 1,2,...,2 880.

Thus, according to (36), if the non-repairable port oil piping transportation system during the operation is θ = 1 year has not exceeded the critical safety state r = 1, then its total operation mean cost during the operation time θ = 1 year is approximately given by

$$\boldsymbol{K}^0(1) \cong \sum_{i=1}^{n} k_i^0(1) \cong 2\,880 \cdot 9.6 = 27\,648 \text{ PLN}. \qquad (39)$$

Further, we assume that the considered the port oil piping transportation system is repairable after exceeding the critical safety state r = 1, its renovation time is ignored and the approximate mean cost of the system singular renovation is

k_{ig}^0 = 88 500 PLN.

In this case, since the expected number of exceeding the critical reliability state r = 1, according to (3.58) in [Kołowrocki, Soszyńska-Budny, 2011], amounts

$H^0(1,1)$ = 1 / 62.5692 = 0.01598,

the total operation cost of the repairable system with ignored its renovation time during the operation time θ = 1 year approximately amounts

$$\boldsymbol{K}_{ig}^0(1) \cong \sum_{i=1}^{n} k_i^0(1) + k_{ig}^0 H^0(1,1) = 2\,880 \cdot 9.6 + 88\,500 \cdot 0.01598 = 27\,648 + 1\,414.23 = 29\,062.23 \text{ PLN}. \qquad (40)$$

If the port oil piping transportation system is repairable after exceeding the critical safety state r = 1 and its renewal time is non-ignored and have distribution function with the mean value

$\mu_0^0(1)$ = 0.2 year

and the cost of the system singular renovation is

k_{nig}^0 = 90 000 PLN

then, since the number of exceeding the critical reliability state r = 1, according to (3.92) in [Kołowrocki, Soszyńska-Budny, 2011], amounts

$\overline{\overline{H}}^0(1,1)$ = 1 / (62.5692 + 0.2) = 0.01593,

the total operation cost of the repairable the port oil piping transportation system with non-ignored its renovation time during the operation time θ = 1 approximately amounts

$$\boldsymbol{K}_{nig}^0(1) \cong \sum_{i=1}^{n} k_i^0(1) + k_{nig}^0 \, \overline{\overline{H}}^0(1,1) = 2\,880 \cdot 9.6 + 90\,000 \cdot 0.01593 = 27\,648 + 1\,433.7 = 29\,081.7 \text{ PLN}. \qquad (41)$$

8. Conclusions

The proposed in [EU-CIRCLE Report D3.3-Part 3, 2017] Model 0 of critical infrastructure safety was applied to safety analysis of the port oil piping transportation system without considering any outside impacts. The application of this model is supported by suitable computer software that is placed at the GMU Safety Interactive Platform http://gmu.safety.am.gdynia.pl/.

The results of this application will be generalized and applied to the safety and resilience analysis of port oil piping transportation system impacted by its operation process and climate-weather change process, in the next parts of the series of 4 papers concerned with the EU-CIRCLE project Case Study 2, Storm and Sea Surge at Baltic Sea Port.

Acknowledgments

The paper presents the results developed in the scope of the EU-CIRCLE project titled “A pan – European framework for strengthening Critical Infrastructure resilience to climate change” that has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 653824. http://www.eu-circle.eu/.

References

[1] Blokus-Roszkowska, A., Bogalecka, M., Kołowrocki, K., Kuligowska, E., Soszyńska-Budny, J., Torbicki, M., *Inventory of Critical Infrastructure Impact Assessment Models for Climate Hazards, Task3.4 Inventory of Critical Infrastructure Impact Assessment Models for Climate Hazards, Task 3.5, Holistic Risk Assessment Propagation Model*, EU-CIRCLE Report D3.3-Part3-Critical Infrastructure Safety and Resilience Indicators-V1.0, 2017.

[2] Kołowrocki, K., Soszyńska-Budny, J., Reliability and *Safety of Complex Technical Systems and Processes: Modeling – Identification – Prediction – Optimization*, 1st ed. London: Springer-Verlag, 2011.

[3] GMU Safety Interactive Platform http://gmu.safety.am.gdynia.pl/