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Oil transport in port
Part 2
Port oil piping transportation system safety and resilience impacted by the climate-weather change process

Keywords

port oil piping transportation system, climate-weather change impacts, safety, resilience, cost analysis

Abstract

The paper is concerned with the application of the model of critical infrastructure safety prediction with considering its climate-weather change impacts. The general approach to the prediction of critical infrastructure safety and resilience is proposed and the safety and resilience indicators are defined for a critical infrastructure impacted by climate-weather change process. Moreover, there is presented the model application for port oil piping transportation system safety and resilience prediction. Further, the cost analysis of critical infrastructure impacted by climate-weather change process is proposed and applied to the considered piping system.

1. Introduction

This paper is another 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 and resilience prediction in the scope of the EU-CIRCLE project Case Study 2, Storm and Sea Surge at Baltic Sea Port.

First, the climate-weather change process at the critical infrastructure operating area is considered, its parameters are introduced and its main characteristics are found. Next, the notions of the safety analysis of critical infrastructure impacted by climate-weather change are introduced, i.e. the conditional and unconditional safety function of the critical infrastructure related to the climate-weather change process and the critical infrastructure risk function are defined.

Moreover, the critical infrastructure and its assets main safety characteristics and indicators are determined, i.e. the mean lifetime and standard deviation in the safety state subset, the intensities of degradation (ageing) and the indicator of critical infrastructure resilience to climate-weather change process impact.

Further, the IMCIS Model 3 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 model related to climate-weather change process – IMCIS 3

In this section, we consider the critical infrastructure related to the climate-weather change process $C(t)$, $t \in < 0, \infty)$, impacted in a various way at its climate-weather states c_b, $b = 1,2,...,v$. We assume that the changes of the climate-weather states of the climate-weather change process $C(t)$, have an influence on and the critical infrastructure safety structure and on the safety of the critical infrastructure assets A_i, $i = 1,2,...,n$, as well.

The following climate-weather change process parameters (C-WCPP) at the critical infrastructure operating area can be identified either statistically using the methods given in [Kołowrocki, Soszyńska-Budny, Torbicki 2017b] or evaluated approximately by experts:

– the number of climate-weather states (C-WCPP1) w;
– the vector of the initial probabilities (C-WCPP2)

$$q_b(0) = P(C(0) = c_b),\ b = 1,2,...,w,$$

of the climate-weather change process $C(t)$ staying at particular climate-weather states c_b at the moment $t = 0$

$$[q_b(0)]_{1xw} = [q_1(0), q_2(0),..., q_w(0)]$$

– the matrix of probabilities of transition (C-WCPP3) q_{bl}, $b, l = 1,2,...,w,$ of the climate-weather change process $C(t)$ between the climate-weather states c_b and c_l

$$[q_{bl}]_{vxw} = \begin{bmatrix} q_{11}\ q_{12} \dots q_{1w} \\ q_{21}\ q_{22} \dots q_{2w} \\ \dots \\ q_{w1}\ q_{w2} \dots q_{ww} \end{bmatrix};$$

– the matrix of mean values of conditional sojourn times (C-WCPP4) $N_{bl} = E[C_{bl}],\ \ b, l = 1,2,...,w,$ of the climate-weather change process $C(t)$ conditional sojourn times C_{bl} at the climate-weather state c_b when the next state is c_l

$$[N_{bl}]_{wxw} = \begin{bmatrix} N_{11}\ N_{12} \dots N_{1w} \\ N_{21}\ N_{22} \dots N_{2w} \\ \dots \\ N_{w1}\ N_{w2} \dots N_{ww} \end{bmatrix}.$$

The following climate-weather change process characteristics (C-WCPC) at the critical infrastructure operating area can be either calculated analytically using the above parameters of the climate-weather change process or evaluated approximately by experts [Kołowrocki, Soszyńska-Budny, Torbicki 2017b]:

– the vector

$$[q_b]_{1xw} = [q_1, q_2,..., q_v] \tag{1}$$

of limit values of transient probabilities (C-WCPC1)

$$q_b(t) = P(C(t) = c_b),\ t \in < 0,+\infty), \\ b = 1,2,...,w, \tag{2}$$

of the climate-weather change process $C(t)$ at the particular climate-weather states c_b (in the case of a periodic critical infrastructure operation process, the limit transient probabilities c_b, $b = 1,2,...,w,$ at the operation states are the long term proportions of the climate-weather change process $C(t)$ at the critical infrastructure operating area sojourn times at the particular climate-weather states c_b, $b = 1,2,...,w$);

– the vector

$$[\hat{N}_b]_{1xw} = [\hat{N}_1, \hat{N}_2, \dots, \hat{N}_v] \tag{3}$$

of the mean values of the total sojourn times (C-WCPC2)

$$\hat{N}_b = E[\hat{C}_b] = q_b\theta,\ b = 1,2,...,w, \tag{4}$$

of the total sojourn times $\hat{C}_b$ of the climate-weather change process $C(t)$ at the critical infrastructure operating area at the particular climate-weather states c_b, $b = 1,2,...,w,$ during the fixed critical infrastructure opetation time θ.

2.1. Critical infrastructure safety indicators

We denote the critical infrastructure conditional lifetime in the safety state subset $\{u, u+1,..., z\}$, $u = 1,2,...,z,$ while the climate-weather change process $C(t),\ t \in < 0,\infty),$ at the critical infrastructure operating area is at the climate-weather state c_b, $b = 1,2,...,w,$ by $[T^3(u)]^{(b)}$, $u = 1,2,...,z,$ and the conditional safety function of the critical infrastructure related to the climate-weather change process $C(t),\ t \in < 0,\infty),$ by the vector [EU-CIRCLE Report D3.3-Part3, 2017]

$$[\boldsymbol{S}^3(t,\cdot)]^{(b)} = [1,\ [\boldsymbol{S}^3(t,1)]^{(b)},\ ...,\ [\boldsymbol{S}^3(t,z)]^{(b)}], \tag{5}$$

with the coordinates defined by

$$[\boldsymbol{S}^3(t,u)]^{(b)} = P([T^3(u)]^{(b)} > t | Z(t) = z_b) \tag{6}$$

for $t \in <0,\infty)$, $u = 1,2,...,z$, $b = 1,2,...,\nu$.

The safety function $[\boldsymbol{S}^3(t,u)]^{(b)}$, $u = 1,2,...,z$, is the conditional probability that the critical infrastructure related to the climate-weather change process $C(t)$, $t \in <0,\infty)$, lifetime $[T^3(u)]^{(b)}$, $u = 1,2,...,z$, in the safety state subset $\{u, u+1,...,z\}$, $u = 1,2,...,z$, is greater than t, while the climate-weather change process $C(t)$, $t \in <0,\infty)$, is at the climate-weather state c_b.

Next, we denote the critical infrastructure related to the climate-weather change process $C(t)$, $t \in <0,\infty)$, unconditional lifetime in the safety state subset $\{u, u+1,...,z\}$, $u = 1,2,...,z$, by $T^3(u)$, $u = 1,2,...,z$, and the unconditional safety function (SafI1) of the critical infrastructure related to the climate-weather change process $C(t)$, $t \in <0,\infty)$, by the vector

$$\boldsymbol{S}^3(t,\cdot) = [1, \boldsymbol{S}^3(t,1), ..., \boldsymbol{S}^3(t,z)], \quad (7)$$

with the coordinates defined by

$$\boldsymbol{S}^3(t,u) = P(T^3(u) > t) \quad (8)$$

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

In the case when the system operation time θ is large enough, the coordinates of the unconditional safety function of the critical infrastructure related to the climate-weather change process $C(t), t \in <0,\infty)$, defined by (8), are given by

$$\boldsymbol{S}^3(t,u) \cong \sum_{b=1}^{w} q_b [\boldsymbol{S}^3(t,u)]^{(b)}, \ t \geq 0, \ u = 1,2,...,z, \quad (9)$$

where $[\boldsymbol{S}^3(t,u)]^{(b)}$, $u = 1,2,...,z$, $b = 1,2,...,\nu$, are the coordinates of the critical infrastructure related to the climate-weather change process $C(t)$, $t \in <0,\infty)$, conditional safety functions defined by (5)-(6) and q_b, $b = 1,2,...,\nu$, are the climate-weather change process $C(t)$, $t \in <0,\infty)$, limit transient probabilities at the climate-weather states c_b, $b = 1,2,...,\nu$, given by (1)-(2).

If r is the critical safety state, then the second safety indicator of the critical infrastructure related to the climate-weather change process $C(t)$, $t \in <0,\infty)$, the risk function (SafI2)

$$\boldsymbol{r}^3(t) = P(s(t) < r \mid s(0) = z) = P(T^3(r) \leq t), \quad t \in <0,\infty), \quad (10)$$

is defined as a probability that the critical infrastructure related to the climate-weather change process $C(t)$, $t \in <0,\infty)$, 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-Part3, 2017]

$$\boldsymbol{r}^3(t) = 1 - \boldsymbol{S}^3(t,r), \ t \in <0,\infty), \quad (11)$$

where $\boldsymbol{S}^3(t,r)$ is the coordinate of the critical infrastructure related to the climate-weather change process $C(t)$, $t \in <0,\infty)$, unconditional safety function given by (9) for $u = r$.

The graph of the critical infrastructure risk function $\boldsymbol{r}^3(t)$, $t \in <0,\infty)$, defined by (11), is the safety indicator called the fragility curve (SafI3) of the critical infrastructure related to climate-weather change process $C(t)$, $t \in <0,\infty)$.

Other practically useful safety indicators of the critical infrastructure related to the climate-weather change process $C(t)$, $t \in <0,\infty)$, are:

– the mean value of the critical infrastructure unconditional lifetime $T^3(r)$ up to exceeding critical safety state r (SafI4) given by

$$\boldsymbol{\mu}^3(r) = \int_0^\infty [\boldsymbol{S}^3(t,r)]dt \cong \sum_{b=1}^{w} q_b [\mu^3(r)]^{(b)}, \quad (12)$$

where $[\mu^3(r)]^{(b)}$ are the mean values of the critical infrastructure conditional lifetimes $[T^3(r)]^{(b)}$ in the safety state subset $\{r, r+1,...,z\}$ at the climate-weather state c_b, $b = 1,2,...,\nu$, given by

$$[\mu^3(r)]^{(b)} = \int_0^\infty [\boldsymbol{S}^3(t,r)]^{(b)} dt, \quad b = 1,2,...,\nu, \quad (13)$$

and $[\boldsymbol{S}^3(t,r)]^{(b)}$, $b = 1,2,...,\nu$, are defined by (5)-(6) and q_b are given by (2),

– the standard deviation of the critical infrastructure lifetime $T^3(r)$ up to the exceeding the critical safety state r (SafI5) given by

$$\boldsymbol{\sigma}^3(r) = \sqrt{n^3(r) - [\boldsymbol{\mu}^3(r)]^2}, \quad (14)$$

where

$$n^3(r) = 2\int_0^\infty t\, \boldsymbol{S}^3(t,r)dt, \quad (15)$$

and $\boldsymbol{S}^3(t,r)$ is defined by (8) for $u = r$ and $\boldsymbol{\mu}^3(r)$ is given by (12);

- the moment τ^3 of exceeding acceptable value of critical infrastructure risk function level δ (SafI6) given by

$$\tau^3 = \boldsymbol{r}^{3\,-1}(\delta), \tag{16}$$

where $\boldsymbol{r}^{3\,-1}(\delta)$ is the inverse function of the risk function $\boldsymbol{r}^3(t)$ given by (10);

- the intensities of degradation of the critical infrastructure / the intensities of critical infrastructure departure from the safety state subset $\{u, u+1,...,z\}$, $u = 1,2,...,z$, (SafI9), i.e. the coordinates of the vector

$$\boldsymbol{\lambda}^3(t,\cdot) = [0,\ \boldsymbol{\lambda}^3(t,1), \ldots,\ \boldsymbol{\lambda}^3(t,z)],$$
$$t \in <0,+\infty), \tag{17}$$

where

$$\boldsymbol{\lambda}^3(t,u) = \frac{-\dfrac{d\boldsymbol{S}^3(t,u)}{dt}}{\boldsymbol{S}^3(t,u)},\ t \in <0,+\infty),$$
$$u = 1,2,...,z; \tag{18}$$

- the coefficients of climate-weather change process impact on the critical infrastructure intensities of degradation (the coefficients of climate-weather change process impact on critical infrastructure intensities of departure from the safety state subset $\{u, u+1,...,z\}$) (SafI10), i.e. the coordinates of the vector

$$\boldsymbol{\rho}^3(t,\cdot) = [0,\ \boldsymbol{\rho}^3(t,1), \ldots,\ \boldsymbol{\rho}^3(t,z)],$$
$$t \in <0,+\infty), \tag{19}$$

where

$$\boldsymbol{\lambda}^3(t,u) = \boldsymbol{\rho}^3(t,u) \cdot \boldsymbol{\lambda}^0(t,u),\ t \in <0,+\infty),$$
$$u = 1,2,...,z, \tag{20}$$

i.e.

$$\boldsymbol{\rho}^3(t,u) = \frac{\boldsymbol{\lambda}^3(t,u)}{\boldsymbol{\lambda}^0(t,u)},\ t \in <0,+\infty),$$
$$u = 1,2,...,z, \tag{21}$$

and $\boldsymbol{\lambda}^0(t,u)$, $t \in <0,+\infty)$, $u = 1,2,...,z$, are the intensities of degradation of the critical infrastructure without of climate-weather change process impact, i.e. the coordinate of the vector

$$\boldsymbol{\lambda}^0(t,\cdot) = [0,\ \boldsymbol{\lambda}^0(t,1),, \ldots, \boldsymbol{\lambda}^0(t,z)],$$
$$t \in <0,+\infty), \tag{22}$$

and $\boldsymbol{\lambda}^3(t,u)$, $t \in <0,+\infty)$, $u = 1,2,...,z$, are the intensities of degradation of the critical infrastructure with climate-weather change process impact, i.e. the coordinate of the vector

$$\boldsymbol{\lambda}^3(t,\cdot) = [0,\ \boldsymbol{\lambda}^3(t,1), \ldots,\ \boldsymbol{\lambda}^3(t,z)],$$
$$t \in <0,+\infty), \tag{23}$$

- the indicator of critical infrastructure resilience to climate-weather change process impact (ResI1) defined by

$$\boldsymbol{RI}^3(t,r) = \frac{1}{\boldsymbol{\rho}^3(t,r)},\ t \in <0,+\infty), \tag{24}$$

where $\boldsymbol{\rho}^3(t,r)$, $t \in <0,+\infty)$, is the coefficient of climate-weather change process impact on the critical infrastructure intensities of degradation given by (20) for $u = r$.

Further, we also will use the following critical infrastructure safety characteristics:

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

$$\boldsymbol{\mu}^3(u) = \int_0^\infty [\boldsymbol{S}^3(t,u)]dt \cong \sum_{b=1}^{w} q_b [\mu^3(u)]^{(b)},$$
$$u = 1,2,...,z, \tag{25}$$

where $[\mu^3(u)]^{(b)}$, are the mean values of the critical infrastructure conditional lifetimes $[T^3(u)]^{(b)}$, in the safety state subset $\{u, u+1,..., z\}$ at the climate-weather state c_b, $b = 1,2,...,\nu$, given by

$$[\mu^3(u)]^{(b)} = \int_0^\infty [\boldsymbol{S}^3(t,u)]^{(b)} dt,\ u = 1,2,...,z,$$
$$b = 1,2,...,\nu, \tag{26}$$

and $[\boldsymbol{S}^3(t,u)]^{(b)}$, $u = 1,2,...,z$, $b = 1,2,...,v$, are defined by (5)-(6) and q_b are given by (1)-(2);

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

$$\boldsymbol{\sigma}^3(u) = \sqrt{n^3(u) - [\boldsymbol{\mu}^3(u)]^2}\,,\ u = 1,2,...,z, \qquad (27)$$

where

$$n^3(u) = 2\int_0^\infty t\boldsymbol{S}^3(t,u)dt,\ u = 1,2,...,z, \qquad (28)$$

- the mean lifetimes $\bar{\boldsymbol{\mu}}^3(u)$, $u = 1,2,...,z$, of the critical infrastructure in the particular safety states

$$\bar{\boldsymbol{\mu}}^3(u) = \boldsymbol{\mu}^3(u) - \boldsymbol{\mu}^3(u+1),\ u = 0,1,...,z-1,$$
$$\bar{\boldsymbol{\mu}}^3(z) = \boldsymbol{\mu}^3(z). \qquad (29)$$

2.2. Critical infrastructure assets safety parameters

We denote the critical infrastructure asset A_i, $i = 1,2,...,n$, conditional lifetime in the safety state subset $\{u, u+1,..., z\}$ while the climate-weather change process at the critical infrastructure operating area is at the climate-change state c_b, $b = 1,2,...,v$, by $[T_i^3(u)]^{(b)}$ and its conditional safety function (SafI1) by the vector [EU-CIRCLE Report D3.3-Part3, 2017]

$$[S_i^3(t,\cdot)]^{(b)} = [1,\ [S_i^3(t,1)]^{(b)},\ ...,\ [S_i^3(t,z)]^{(b)}],$$
$$t \in <0,\infty),\ b = 1,2,...,v,\ i = 1,2,...,n, \qquad (30)$$

with the coordinates defined by

$$[S_i^3(t,u)]^{(b)} = P([T_i^3(u)]^{(b)} > t | C(t) = c_b) \qquad (31)$$

for $t \in <0,\infty)$, $u = 1,2,...,z$, $b = 1,2,...,v$, $i = 1,2,...,n$.

The safety function $[S_i^3(t,u)]^{(b)}$, is the conditional probability that the asset A_i lifetime $[T_i^3(u)]^{(b)}$, in the safety state subset $\{u, u+1,..., z\}$ is greater than *t*, while the climate-weather change process at the critical infrastructure operating area is at the climate-weather state c_b, $b = 1,2,...,v$.

The conditional safety functions $[S_i^3(t,u)]^{(b)}$, $t \in <0,\infty)$, $u = 1, 2, ..., z$, $b = 1,2,...,v$, $i = 1,2,...,n$, defined by (31) are called the coordinates of the asset A_i, $i = 1,2,...,n$, conditional safety function $[S_i^3(t,\cdot)]^{(b)}$, $t \in <0,\infty)$, $b = 1,2,...,v$, $i = 1,2,...,n$, while the climate-weather change process $C(t)$ is at the climate-weather state c_b, $b = 1,2,...,v$, given by (30). Thus, the relationship between the conditional distribution function $[F_i^3(t,u)]^{(b)}$, $t \in <0,\infty)$, $u = 1, 2, ..., z$, $b = 1,2,...,v$, $i = 1,2,...,n$, of the asset A_i, $i = 1,2,...,n$, lifetime $[T_i^3(u)]^{(b)}$, $u = 1,2,..., z$, $b = 1,2,...,v$, $i = 1,2,...,n$, in the safety state subset $\{u, u+1,..., z\}$, $u = 1,2,...,z$, and the coordinate $[S_i^3(t,u)]^{(b)}$, $t \in <0,\infty)$, $u = 1, 2, ..., z$, $b = 1,2,...,v$, $i = 1,2,...,n$, of its conditional safety function is given by

$$[F_i^3(t,u)]^{(b)} = P([T_i^3(u)]^{(b)} \le t)$$
$$= 1 - P([T_i^3(u)]^{(b)} > t)$$
$$= 1 - [S_i^3(t,u)]^{(b)},\ t \in <0,\infty),$$
$$u = 1, 2, ..., z,\ b = 1,2,...,v,\ i = 1,2,...,n. \qquad (32)$$

Thus, the function

$$[r_i^3(t)]^{(b)} = 1 - [S_i^3(t,r)]^{(b)},\ t \in <0,\infty),\ b = 1,2,...,v,$$
$$i = 1,2,...,n, \qquad (33)$$

is the asset A_i, $i = 1,2,...,n$, the conditional risk function (SafI2) and its graph is the asset A_i, $i = 1,2,...,n$, fragility curve (SafI3) while the climate-weather change process at the critical infrastructure operating area is at the climate-weather state c_b, $b = 1,2,...,v$.

Moreover, the conditional mean lifetime of the asset A_i in the safety state subset $\{u, u+1,..., z\}$, $u = 1,2,...,z$, while the climate-weather change process at the critical infrastructure operating area is at the climate-weather state c_b, $b = 1,2,...,v$, is given by

$$[\mu_i^3(u)]^{(b)} = \int_0^\infty [S_i^3(t,u)]^{(b)} dt,\ u = 1, 2, ..., z,$$
$$b = 1,2,...,v,\ i = 1,2,...,n. \qquad (34)$$

In the case, when the critical infrastructure assets A_i, $i = 1,2,...,n$, at the climate-weather states c_b, $b = 1,2,...,v$, have the exponential safety functions, the coordinates (31) of the vector (30) are given by

$$[S_i^3(t,u)]^{(b)} = P([T_i^3(u)]^{(b)} > t | C(t) = c_b)$$
$$= \exp[-[\lambda_i^3(u)]^{(b)} t],\ t \in <0,\infty),$$
$$u = 1,2,...,z,\ b = 1,2,...,v,\ i = 1,2,...,n. \qquad (35)$$

Existing in (35) the intensities of degradation of the critical infrastructure asset A_i, $i = 1,2,...,n,$ with the climate-weather change process at the critical infrastructure operating area impact at the climate-weather states c_b, (SafI7), i.e. the coordinates of the vector

$$[\lambda_i^3(\cdot)]^{(b)} = [0, [\lambda_i^3(1)]^{(b)}, \ldots, [\lambda_i^3(z)]^{(b)}], t \in <0,+\infty),$$
$$b = 1,2,...,v, \; i = 1,2,...,n, \tag{36}$$

are constant and given by

$$[\lambda_i^3(u)]^{(b)} = \frac{1}{[\mu_i^3(u)]^{(b)}}, \; u = 1,2,...,z, \; b = 1,2,...,v,$$
$$i = 1,2,...,n, \tag{37}$$

and moreover

$$[\lambda_i^3(u)]^{(b)} = [\rho_i^3(u)]^{(b)} \cdot \lambda_i^0(u), \; u = 1,2,...,z,$$
$$b = 1,2,...,v, \; i = 1,2,...,n, \tag{38}$$

where $\lambda_i^0(u)$ are the intensities of degradation of the critical infrastructure asset A_i, $i = 1,2,...,n,$ without the climate-weather change process at the critical infrastructure operating area impact (SafI7), i.e. the coordinate of the vector

$$\lambda_i^0(\cdot) = [0, \lambda_i^0(1), \ldots, \lambda_i^0(z)], \; i = 1,2,...,n, \tag{39}$$

and $[\rho_i^3(u)]^{(b)}$, $u = 1,2,...,z,$ $b = 1,2,...,v,$ $i = 1,2,...,n,$ are the coefficients of the climate-weather change process at the critical infrastructure operating area impact on the critical infrastructure asset A_i, $i = 1,2,...,n,$ intensities of degradation at the climate-weather states c_b, $b = 1,2,...,v,$ (SafI8), i.e. the coordinate of the vector

$$[\rho_i^3(\cdot)]^{(b)} = [0, [\rho_i^3(1)]^{(b)}, \ldots, [\rho_i^3(z)]^{(b)}],$$
$$b = 1,2,...,v, \; i = 1,2,...,n. \tag{40}$$

where by (38)

$$[\rho_i^3(u)]^{(b)} = \frac{[\lambda_i^3(u)]^{(b)}}{\lambda_i^0(u)} = \frac{\mu_i^0(u)}{[\mu_i^3(u)]^{(b)}}, \; u = 1,2,...,z,$$
$$b = 1,2,...,v, \; i = 1,2,...,n, \tag{41}$$

3. IMCIS 3 application to safety of port oil piping transportation system evaluation

In this section, we consider the port oil piping transportation system impacted by the climate-weather change process in its operating area.

3.1. Parameters and characteristics of climate-weather change process at port oil piping transportation system operating area

The piping operating area is divided into two parts – the underwater operating area and the land operating area. We distinguish two different climate-change processes for those two areas:

– the climate-weather change process $C1(t)$, $t \geq 0$, at under water Baltic sea area operating area (the measurement points 1 – 4);
– the climate-weather change process $C2(t)$, $t \geq 0$, at land Baltic seaside area (the measurement point 5).

On the basis of the statistical data and expert opinions, it is possible to fix and to evaluate the following unknown basic parameters of the climate-weather change process $C1(t)$, $t \geq 0$, [GMU Interactive Safety Platform]:

– the number of climate-weather change process states (C-WCPP1): $w1 = 6$ and the climate-weather states:
  - the climate-weather state $c1_1$ – the wave height from 0 up to 2 m and the wind speed from 0 m/s up to 17 m/s;
  - the climate-weather state $c1_2$ – the wave height from 2 m up to 5 m and the wind speed from 0 m/s up to 17 m/s;
  - the climate-weather state $c1_3$ – the wave height from 5 m up to 14 m and the wind speed from 0 m/s up to 17 m/s;
  - the climate-weather state $c1_4$ – the wave height from 0 up to 2 m and the wind speed from 17 m/s up to 33 m/s;
  - the climate-weather state $c1_5$ – the wave height from 2 m up to 5 m and the wind speed from 17 m/s up to 33 m/s;
  - the climate-weather state $c1_6$ – the wave height from 5 m up to 14 m and the wind speed from 17 m/s up to 33 m/s;

The climate-weather change process $C1(t)$ characteristics, determined on the basis of the climate-weather change process data given in [GMU Safety Interactive Platform], are:

– the limit values of transient probabilities (C-WCPC1) of the climate-weather change process $C1(t)$ at the particular operation states $c1_l$, $l = 1,2,...,6,$

$q1_1 = 0.841$, $q1_2 = 0.151$, $q1_3 = 0.001$, $q1_4 = 0$, $q1_5 = 0.006$, $q1_6 = 0.001$; (42)

– the expected values of the total sojourn times $C1_l$, $l = 1,2,..., 6$, (CWCPC2) of the climate-weather change process $C1(t)$ at the particular climate-weather states $c1_l$, $l = 1,2,..., 6$, during the fixed operation time C = 1 year = 365 days:

$\hat{N}\,1_1$ = 0.841 year = 306.965 days,
$\hat{N}\,1_2$ = 0.151 year = 55.115 days,
$\hat{N}\,1_3$ = 0.001 year = 0.365 day,
$\hat{N}\,1_4$ = 0 year = 0 day,
$\hat{N}\,1_5$ = 0.006 year = 2.190 days,
$\hat{N}\,1_6$ = 0.001 year = 0.365 days.

To simplify the calculations of the port oil piping transportation system safety analysis, we consider the impact of only $w1 = 5$ climate-weather change process $C1(t)$ states $c1_1$, $c1_2$, $c1_3$, $c1_5$, $c1_6$ on the piping safety. We can omit the climate-weather state $c1_4$ because its limit value of transient probability $q1_4$ is equal 0.

Further, on the basis of the statistical data and expert opinions, it is possible to fix and to evaluate the following unknown basic parameters of the climate-weather change process $C2(t)$, $t \geq 0$, [GMU Interactive Safety Platform]:

– the number of climate-weather change process states (C-WCPP1): $w2 = 16$ and the climate-weather states:
  - the climate-weather state $c2_1$ – the air temperature from -25°C up to -15°C and the soil temperature from -30°C up to -5°C;
  - the climate-weather state $c2_2$ – the air temperature from -15°C up to 5°C and the soil temperature from -30°C up to -5°C;
  - the climate-weather state $c2_3$ – the air temperature from 5°C up to 25°C and the soil temperature from -30°C up to -5°C;
  - the climate-weather state $c2_4$ – the air temperature from 25°C up to 35°C and the soil temperature from -30°C up to -5°C;
  - the climate-weather state $c2_5$ – the air temperature from -25°C up to -15°C and the soil temperature from -5°C up to 5°C;
  - the climate-weather state $c2_6$ – the air temperature from -15°C up to 5°C and the soil temperature from -5°C up to 5°C;
  - the climate-weather state $c2_7$ – the air temperature from 5°C up to 25°C and the soil temperature from -5°C up to 5°C;
  - the climate-weather state $c2_8$ – the air temperature from 25°C up to 35°C and the soil temperature from -5°C up to 5°C;
  - the climate-weather state $c2_9$ – the air temperature from -25°C up to -15°C and the soil temperature from 5°C up to 20°C;
  - the climate-weather state $c2_{10}$ – the air temperature from -15°C up to 5°C and the soil temperature from 5°C up to 20°C;
  - the climate-weather state $c2_{11}$ – the air temperature from 5°C up to 25°C and the soil temperature from 5°C up to 20°C;
  - the climate-weather state $c2_{12}$ – the air temperature from 25°C up to 35°C and the soil temperature from 5°C up to 20°C;
  - the climate-weather state $c2_{13}$ – the air temperature from -25°C up to -15°C and the soil temperature from 20°C up to 37°C;
  - the climate-weather state $c2_{14}$ – the air temperature from -15°C up to 5°C and the soil temperature from 20°C up to 37°C;
  - the climate-weather state $c2_{15}$ – the air temperature from 5°C up to 25°C and the soil temperature from 20°C up to 37°C;
  - the climate-weather state $c2_{16}$ – the air temperature from 25°C up to 35°C and the soil temperature from 20°C up to 37°C.

The climate-weather change process $C2(t)$ characteristics, determined on the basis of the climate-weather change process data given in [GMU Safety Interactive Platform], are:

– the limit values of transient probabilities (C-WCPC1) of the climate-weather change process $C2(t)$ at the particular operation states $c2_l$, l =1,2,...,16,

$q2_1 = 0$, $q2_2 = 0.026$, $q2_3 = 0$, $q2_4 = 0$, $q2_5 = 0$, $q2_6 = 0.277$, $q2_7 = 0.014$, $q2_8 = 0$, $q2_9 = 0$, $q2_{10} = 0.008$, $q2_{11} = 0.612$, $q2_{12} = 0$, $q2_{13} = 0$, $q2_{14} = 0$, $q2_{15} = 0.062$, $q2_{16} = 0.001$; (43)

– the expected values of the total sojourn times $C2_l$, $l = 1,2,..., 16$, (CWCPC2) of the climate-weather change process $C2(t)$ at the particular climate-weather states $c2_l$, $l = 1,2,..., 16$, during the fixed operation time C = 1 year = 365 days:

$\hat{N}\,2_1 = 0$, $\hat{N}\,2_2$ = 0.026 year = 9.49 days,
$\hat{N}\,2_3 = 0$, $\hat{N}\,2_4 = 0$, $\hat{N}\,2_5 = 0$,
$\hat{N}\,2_6$ = 0.277 year = 101.105 days,
$\hat{N}\,2_7$ = 0.014 year = 5.11 days, $\hat{N}\,2_8 = 0$,
$\hat{N}\,2_9 = 0$, $\hat{N}\,2_{10}$ = 0.008 year = 2.92 days,
$\hat{N}\,2_{11}$ = 0.612 year = 223.38 days,
$\hat{N}\,2_{12} = 0$, $\hat{N}\,2_{13} = 0$, $\hat{N}\,2_{14} = 0$,
$\hat{N}\,2_{15}$ = 0.062 year = 22.63 days,
$\hat{N}\,2_{16}$ = 0.001 year = 0.365 days.

To simplify the safety analysis of the port oil piping transportation system we consider the impact of only $w2 = 7$ climate-weather change process $C2(t)$ states $c2_2$, $c2_6$, $c2_7$, $c2_{10}$, $c2_{11}$, $c2_{15}$, $c2_{16}$, on the piping safety. We can omit the climate-weather states $c2_1$, $c2_3$, $c2_4$, $c2_5$, $c2_8$, $c2_9$, $c2_{12}$, $c2_{13}$, $c2_{14}$, because their limit values of transient probabilities $q2_1$, $q2_3$, $q2_4$, $q2_5$, $q2_8$, $q2_9$, $q2_{12}$, $q2_{13}$, $q2_{14}$, are equal 0.

3.2. Parameters of climate-weather change process impact on port oil piping transportation system safety

The coefficients of the climate-weather change process impact on the port oil piping transportation system intensities of ageing at the climate-weather change processes states are as follows [GMU Interactive Safety Platform] for the assets A_{ij}, $i = 1,2$, $j = 1,2$, $i = 3$, $j = 1,2,3$:

$$[\rho 1^3_{ij}(1)]^{(b)} = 1.00,\ [\rho 1^3_{ij}(2)]^{(b)} = 1.00,$$
$$b = 1,2,\ i = 1,\ j = 1,2,$$
$$[\rho 1^3_{ij}(1)]^{(b)} = 1.036,\ [\rho 1^3_{ij}(2)]^{(b)} = 1.048,$$
$$b = 3,5,6,\ i = 1,\ j = 1,2,$$
$$[\rho 2^3_{ij}(1)]^{(b)} = 1.00,\ [\rho 2^3_{ij}(2)]^{(b)} = 1.00,$$
$$b = 2,6,7,10,11,15,16,\ i = 1,\ j = 1,2, \qquad (44)$$

$$[\rho 1^3_{ij}(1)]^{(b)} = 1.00,\ [\rho 1^3_{ij}(2)]^{(b)} = 1.00,$$
$$b = 1,2,3,5,6,\ i = 2,\ j = 1,2,$$
$$[\rho 2^3_{ij}(1)]^{(b)} = 1.00,\ [\rho 2^3_{ij}(2)]^{(b)} = 1.00,$$
$$b = 2,15,16,\ i = 2,\ j = 1,2,$$
$$[\rho 2^3_{ij}(1)]^{(b)} = 1.004,\ [\rho 2^3_{ij}(2)]^{(b)} = 1.007,$$
$$b = 6,7,10,11,\ i = 2,\ j = 1,2, \qquad (45)$$

$$[\rho 1^3_{ij}(1)]^{(b)} = 1.00,\ [\rho 1^3_{ij}(2)]^{(b)} = 1.00,$$
$$b = 1,2,3,5,6,\ i = 3,\ j = 1,2,3,$$
$$[\rho 2^3_{ij}(1)]^{(b)} = 1.00,\ [\rho 2^3_{ij}(2)]^{(b)} = 1.00,$$
$$b = 2,6,7,10,11,15,16,\ i = 3,\ j = 1,2,3. \qquad (46)$$

3.3. Safety parameters of port oil piping transportation system assets impacted by its operation process

Since according to (38), we have

$$[\lambda 1^3_{ij}(u)]^{(l)} = [\rho 1^3_{ij}(u)]^{(l)} \cdot \lambda^0_{ij}(u),\ l = 1,2,3,5,6,$$
$$u = 1,2,\ i = 1,2,\ j = 1,2;\ i = 3,\ j = 1,2,3, \qquad (47)$$

$$[\lambda 2^3_{ij}(u)]^{(l)} = [\rho 2^3_{ij}(u)]^{(l)} \cdot \lambda^0_{ij}(u), l=2,6,7,10,11,15,16,$$
$$u = 1,2,\ i = 1,2,\ j = 1,2;\ i = 3,\ j = 1,2,3, \qquad (48)$$

then applying the above formula to the parameters defined in [EU-CIRCLE Report for D6.4-Part 0, 2017] and (44)-(46), 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} impacted by the climate-weather change process, i.e. the coordinates of the vector

$$[\lambda 1^3_{ij}(\cdot)]^{(l)} = [0, [\lambda 1^3_{ij}(1)]^{(l)}, [\lambda 1^3_{ij}(2)]^{(l)}],$$
$$l = 1,2,3,5,6,\ i = 1,2,\ j = 1,2;\ i = 3,\ j = 1,2,3,$$
$$[\lambda 2^3_{ij}(\cdot)]^{(l)} = [0, [\lambda 2^3_{ij}(1)]^{(l)}, [\lambda 2^3_{ij}(2)]^{(l)}],$$
$$l = 2,6,7,10,11,15,16,\ i = 1,2,\ j = 1,2;\ i = 3,$$
$$j = 1,2,3, \qquad (49)$$

follows:

- the intensities of departure of the asset A_{11} and A_{12}
  - for safety state subset {1,2}

$$[\lambda 1^3_{11}(1)]^{(l)} = [\lambda 1^3_{12}(1)]^{(l)} = 0.00362,\ l = 1,2,$$
$$[\lambda 1^3_{11}(1)]^{(l)} = [\lambda 1^3_{12}(1)]^{(l)} = 0.00375032,$$
$$l = 3,5,6,$$
$$[\lambda 2^3_{11}(1)]^{(l)} = [\lambda 2^3_{12}(1)]^{(l)} = 0.00362,$$
$$l = 2,6,7,10,11,15,16,$$

  - for safety state subset {2}

$$[\lambda 1^3_{11}(2)]^{(l)} = [\lambda 1^3_{12}(2)]^{(l)} = 0.00540,\ l = 1,2,$$
$$[\lambda 1^3_{11}(2)]^{(l)} = [\lambda 1^3_{12}(2)]^{(l)} = 0.0056592,$$
$$l = 3,5,6,$$
$$[\lambda 2^3_{11}(2)]^{(l)} = [\lambda 2^3_{12}(2)]^{(l)} = 0.00540,$$
$$l = 2,6,7,10,11,15,16,$$

- the intensities of departure of the assets A_{21} and A_{22}
  - for safety state subset {1,2}

$$[\lambda 1^3_{21}(1)]^{(l)} = [\lambda 1^3_{22}(1)]^{(l)} = 0.01444,$$
$$l = 1,2,3,5,6,$$
$$[\lambda 2^3_{21}(1)]^{(l)} = [\lambda 2^3_{22}(1)]^{(l)} = 0.01444,$$
$$l = 6,7,10,11,$$
$$[\lambda 2^3_{21}(1)]^{(l)} = [\lambda 2^3_{22}(1)]^{(l)} = 0.01449776,$$
$$l = 2,15,16,$$

  - for safety state subset {2}

$$[\lambda 1^3_{21}(2)]^{(l)} = [\lambda 1^3_{22}(2)]^{(l)} = 0.02163,$$
$$l = 1,2,3,5,6,$$

$[\lambda 2^{3}_{21}(2)]^{(l)} = [\lambda 2^{3}_{22}(2)]^{(l)} = 0.02163,$
$l = 6,7,10,11,$
$[\lambda 2^{3}_{21}(2)]^{(l)} = [\lambda 2^{3}_{22}(2)]^{(l)} = 0.02178141,$
$l = 2,15,16,$

– the intensities of departure of the assets A_{31} and A_{32}
  - for safety state subset {1,2}

$[\lambda 1^{3}_{31}(1)]^{(l)} = [\lambda 1^{3}_{32}(1)]^{(l)} = 0.00730,$
$l = 1,2,3,5,6,$
$[\lambda 2^{3}_{31}(1)]^{(l)} = [\lambda 2^{3}_{32}(1)]^{(l)} = 0.00730,$
$l = 2,6,7,10,11,15,16,$

  - for safety state subset {2}

$[\lambda 1^{3}_{31}(2)]^{(l)} = [\lambda 1^{3}_{32}(2)]^{(l)} = 0.00912,$
$l = 1,2,3,5,6;$
$[\lambda 2^{3}_{31}(2)]^{(l)} = [\lambda 2^{3}_{32}(2)]^{(l)} = 0.00912,$
$l = 2,6,7,10,11,15,16;$

– the intensities of departure of the asset A_{33}
  - for safety state subset {1,2}

$[\lambda 1^{3}_{33}(1)]^{(l)} = [\lambda 1^{3}_{33}(1)]^{(l)} = 0.00874,$
$l = 1,2,3,5,6,$
$[\lambda 2^{3}_{33}(1)]^{(l)} = [\lambda 2^{3}_{33}(1)]^{(l)} = 0.00874,$
$l = 2,6,7,10,11,15,16,$

  - for safety state subset {2}

$[\lambda 1^{3}_{33}(2)]^{(l)} = [\lambda 1^{3}_{33}(2)]^{(l)} = 0.00984,$
$l = 1,2,3,5,6,$
$[\lambda 2^{3}_{33}(2)]^{(l)} = [\lambda 2^{3}_{33}(2)]^{(l)} = 0.00984,$
$l = 2,6,7,10,11,15,16.$

3.4. Characteristics of port oil piping transportation system safety impacted by climate-weather change process

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

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

where

$$\begin{aligned}
\boldsymbol{S}^3(t,1) = {} & 0.353152\exp[-0.03276796t] \\
& - 0.706304\exp[-0.04153796t] \\
& + 0.706304\exp[-0.03423796t] \\
& - 0.176576\exp[-0.04731592t] \\
& + 0.353152\exp[-0.05608592t] \\
& - 0.353152\exp[-0.04878592t] \\
& - 0.176576\exp[-0.03638796t] \\
& + 0.353152\exp[-0.04515796t] \\
& - 0.353152\exp[-0.03785796t] \\
& + 0.088288\exp[-0.05093592t] \\
& - 0.176576\exp[-0.05970592t] \\
& + 0.176576\exp[-0.05240592t] \\
& + 3.614848\exp[-0.03271t] \\
& - 7.229696\exp[-0.04148t] \\
& + 7.229696\exp[-0.03418t] \\
& - 1.807424\exp[-0.0472t] \\
& + 3.614848\exp[-0.05597t] \\
& - 3.614848\exp[-0.04867t] \\
& - 1.807424\exp[-0.03633t] \\
& + 3.614848\exp[-0.0451t] \\
& - 3.614848\exp[-0.0378t] \\
& + 0.903712\exp[-0.05082t] \\
& - 1.807424\exp[-0.05959t] \\
& + 1.807424\exp[-0.05229t] \\
& + 0.002848\exp[-0.03289828t] \\
& - 0.005696\exp[-0.04166828t] \\
& + 0.005696\exp[-0.03436828t] \\
& - 0.001424\exp[-0.04744624t] \\
& + 0.002848\exp[-0.05621624t] \\
& - 0.002848\exp[-0.04891624t] \\
& - 0.001424\exp[-0.0366486t] \\
& + 0.002848\exp[-0.0454186t] \\
& - 0.002848\exp[-0.0381186t] \\
& + 0.000712\exp[-0.05119656t] \\
& - 0.001424\exp[-0.05996656t] \\
& + 0.001424\exp[-0.05266656t] \\
& + 0.029152\exp[-0.03284032t] \\
& - 0.058304\exp[-0.04161032t] \\
& + 0.058304\exp[-0.03431032t] \\
& - 0.014576\exp[-0.04733032t] \\
& + 0.029152\exp[-0.05610032t] \\
& - 0.029152\exp[-0.04880032t] \\
& - 0.014576\exp[-0.03659064t] \\
& + 0.029152\exp[-0.04536064t] \\
& - 0.029152\exp[-0.03806064t] \\
& + 0.007288\exp[-0.05108064t] \\
& - 0.014576\exp[-0.05985064t] \\
& + 0.014576\exp[-0.05255064t],\ t \ge 0, \quad (50)
\end{aligned}$$

$$\begin{aligned}
\boldsymbol{S}^3(t,2) = {} & 0.353152\exp[-0.04548218t] \\
& - 0.706304\exp[-0.05528218t] \\
& + 0.706304\exp[-0.04619218t] \\
& - 0.176576\exp[-0.06737436t] \\
& + 0.353152\exp[-0.07717436t] \\
& - 0.353152\exp[-0.06808436t] \\
& - 0.176576\exp[-0.05089218t] \\
& + 0.353152\exp[-0.06069218t]
\end{aligned}$$

$$
\begin{aligned}
&- 0.353152\exp[-0.05160218t] \\
&+ 0.088288\exp[-0.07278436t] \\
&- 0.176576\exp[-0.08258436t] \\
&+ 0.176576\exp[-0.07349436t] \\
&+ 3.614848\exp[-0.04533t] \\
&- 7.229696\exp[-0.05513t] \\
&+ 7.229696\exp[-0.04604t] \\
&- 1.807424\exp[-0.06707t] \\
&+ 3.614848\exp[-0.07687t] \\
&- 3.614848\exp[-0.06778t] \\
&- 1.807424\exp[-0.05074t] \\
&+ 3.614848\exp[-0.06054t] \\
&- 3.614848\exp[-0.05145t] \\
&+ 0.903712\exp[-0.07248t] \\
&- 1.807424\exp[-0.08228t] \\
&+ 1.807424\exp[-0.07319t] \\
&+ 0.002848\exp[-0.04574186t] \\
&- 0.005696\exp[-0.05554186t] \\
&+ 0.005696\exp[-0.04645186t] \\
&- 0.001424\exp[-0.06763404t] \\
&+ 0.002848\exp[-0.07743404t] \\
&- 0.002848\exp[-0.06834404t] \\
&- 0.001424\exp[-0.05141154t] \\
&+ 0.002848\exp[-0.06121154t] \\
&- 0.002848\exp[-0.05212154t] \\
&+ 0.000712\exp[-0.07330372t] \\
&- 0.001424\exp[-0.08310372t] \\
&+ 0.001424\exp[-0.07401372t] \\
&+ 0.029152\exp[-0.04558968t] \\
&- 0.058304\exp[-0.05538968t] \\
&+ 0.058304\exp[-0.04629968t] \\
&- 0.014576\exp[-0.06732968t] \\
&+ 0.029152\exp[-0.07712968t] \\
&- 0.029152\exp[-0.06803968t] \\
&- 0.014576\exp[-0.05125936t] \\
&+ 0.029152\exp[-0.06105936t] \\
&- 0.029152\exp[-0.05196936t] \\
&+ 0.007288\exp[-0.07299936t] \\
&- 0.014576\exp[-0.08279936t] \\
&+ 0.014576\exp[-0.07370936t],\ t \geq 0. \quad (51)
\end{aligned}
$$

The graph of the safety function of the port oil piping transportation system is given in *Figure 1*.

According to (26), the conditional expected values of the port oil piping transportation system are:

– in the safety state subset {1,2}:

$[[\boldsymbol{\mu}^3(1)]^{(b\ l)}]_{b\,=\,1,2,3,5,6,\ l\,=\,2,6,7,10,11,15,16} =$
[62.44878222, 62.569171993, 62.569171993, 62.569171993, 62.569171993;
62.44878222, 62.44878222; 62.44878222, 62.569171993, 62.569171993;
62.569171993, 62.569171993, 62.44878222, 62.44878222, 62.312580782;
62.432288774, 62.432288774, 62.432288774, 62.432288774, 62.312580782;
62.312580782, 62.312580782, 62.432288774, 62.432288774, 62.432288774;
62.432288774, 62.312580782, 62.312580782, 62.312580782, 62.432288774;
62.432288774, 62.432288774, 62.432288774, 62.312580782, 62.312580782], (52)

– in the safety state subset {2}:

$[[\boldsymbol{\mu}^3(2)]^{(b\ l)}]_{b\,=\,1,2,3,5,6,\ l\,=\,2,6,7,10,11,15,16} =$
[45.645088033, 45.819833072, 45.819833072, 45.819833072, 45.819833072, 45.645088033;
45.645088033, 45.645088033, 45.819833072, 45.819833072, 45.819833072, 45.819833072;
45.645088033, 45.645088033, 45.490854221, 45.66409207, 45.66409207, 45.66409207;
45.66409207, 45.490854221, 45.490854221, 45.490854221, 45.66409207, 45.66409207;
45.66409207, 45.66409207, 45.490854221, 45.490854221, 45.490854221, 45.66409207;
45.66409207, 45.66409207, 45.66409207, 45.490854221, 45.490854221]. (53)

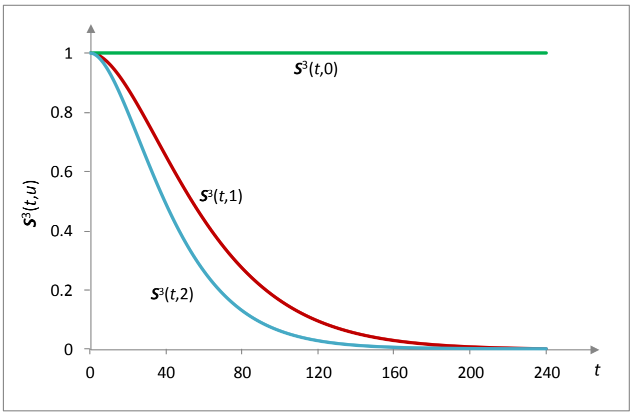

Figure 1. The graphs of the port oil piping transportation system safety function coordinates

After applying (25) and (13)-(15) to (42) and (52)-(53), the mean values and standard deviations of the unconditional lifetimes of the port oil piping transportation system are:

– in the safety state subset: {1,2}

$$\boldsymbol{\mu}^3(1) \cong \sum_{b=1}^{6}\sum_{l=1}^{16} q1_b\, q2_l [\boldsymbol{\mu}^3(1)]^{(b,l)} = 62.5574 \text{ years}, \quad (54)$$

$$\boldsymbol{\sigma}^3(1) = 41.8715 \text{ years},$$

– in the safety state subset {2}

$$\mu^3(2) \cong \sum_{b=1}^{6} \sum_{l=1}^{16} q1_b q2_l [\mu^3(2)]^{(b,l)}$$
$$= 45.8030 \text{ years}, \quad (55)$$

$$\sigma^3(2) = 30.7239 \text{ years}.$$

From (54)-(55), applying (29), the mean lifetimes $\bar{\mu}^3(u)$, $u = 1,2$, of the port oil piping transportation system in the particular safety states are:

$$\bar{\mu}^3(1) = \mu^3(1) - \mu^3(2) = 16.7544 \text{ years},$$
$$\bar{\mu}^3(2) = \mu^3(2) = 45.8030 \text{ years}. \quad (56)$$

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

$$r^3(t) = 1 - S^3(t, 1), \quad (57)$$

where $S^3(t, 1)$ is given by (50). By (16), the moment τ^3 of exceeding acceptable value of critical infrastructure risk function level $\delta = 0.05$ is

$$\tau^3 = (r^3)^{-1}(0.05) = 12.1266 \text{ years}. \quad (58)$$

The graph of the port oil piping transportation system risk function is presented in *Figure 2*.

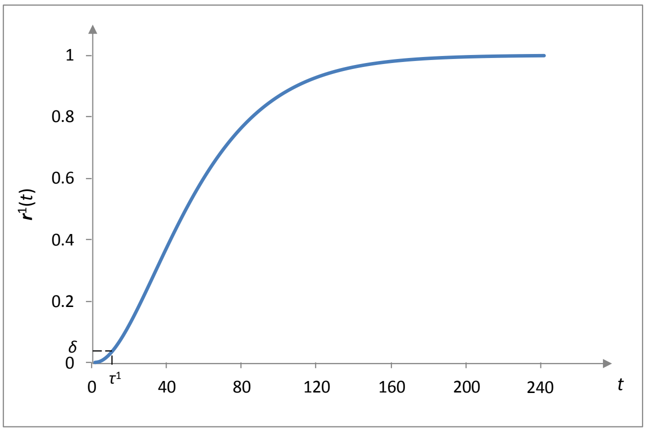

Figure 2. The graph of the port oil piping transportation system risk function

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

$$\lambda^3(t,\cdot) = [0, \lambda^3(t,1), \lambda^0(t,2)], \; t \in <0,+\infty), \quad (59)$$

where

$$\lambda^3(t,u) = \frac{-\frac{dS^3(t,u)}{dt}}{S^3(t,u)}, \; u = 1,2, \; t \in <0,+\infty), \quad (60)$$

and $S^3(t, u)$, $u = 1,2$, are given by (50)-(51)
The values of the intensities of degradation given by (60) stabilize for large time and approximately amounts

$$\lambda^3(1) = \lim_{t\to+\infty} \lambda^3(t,1) \cong 0.03271,$$
$$\lambda^3(2) = \lim_{t\to+\infty} \lambda^3(t,2) \cong 0.04533. \quad (61)$$

The graphs of the intensities of degradation of the port oil piping transportation system are given in *Figure 3*.

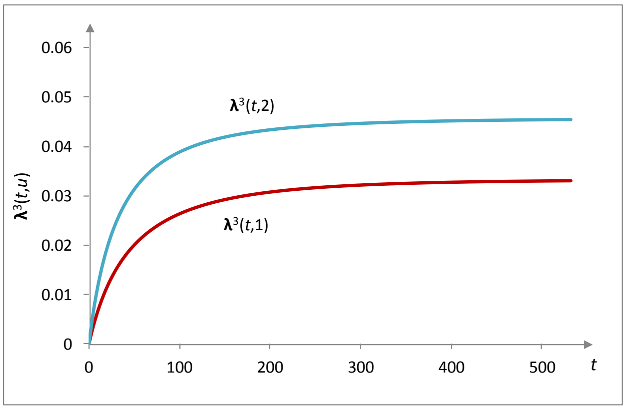

Figure 3. The graphs of the intensities of ageing of the port oil piping transportation system

According to (21) and (24), considering (4.42) from [EU-CIRCLE Report for D6.4-Part 0, 2017] and (61), the limit value of the indicator of critical infrastructure resilience to climate-weather change process impact is given by

$$RI^3(1) = \lim_{t\to+\infty} RI^3(t,1) = \lim_{t\to=\infty} \frac{\lambda^0(t,1)}{\lambda^3(t,1)}$$
$$\cong 0.03271/0.03271 \cong 1.00 = 100\%. \quad (62)$$

If we replace in the above formula the intensities of degradation by the appropriate mean values, assuming

$$\lambda^0(t,1) \cong 1/\mu^0(1), \; \lambda^3(t,1) \cong 1/\mu^3(1), \quad (63)$$

then by (21), considering (4.36) from [EU-CIRCLE Report for D6.4 - Part 0, 2017] and (54), the approximate mean value of the indicator of critical infrastructure resilience to operation process impact is given by

$$\boldsymbol{RI}^3(1) \cong \frac{\boldsymbol{\mu}^3(1)}{\boldsymbol{\mu}^0(1)} \cong 62.5574/62.5692 \cong 0.9998$$
$$= 99.98\%. \quad (64)$$

4. Cost analysis of critical infrastructure impacted by climate-weather change process

We consider the critical infrastructure impacted by the operation process related to climate-weather change process $C(t)$ consisted of n components and we assume that the operation costs of its single basic components at the climate-weather state c_l, $l = 1,2,...,w,$ during the system operation time $\theta,$ $\theta \geq 0,$ amount

$$k_i^3(\theta,l), \; l = 1,2,...w, \quad i = 1,2,...,n.$$

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 $\theta,$ $\theta \geq 0,$ is given by

$$\boldsymbol{K}^3(\theta) = \sum_{l=1}^{w} q_l \sum_{i=1}^{n} k_i^3(\theta,l), \; \theta \geq 0, \quad (65)$$

where q_l, $l = 1,2,...w,$ are the transient probabilities defined by (1)-(2).

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}^3.

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

$$\boldsymbol{K}_{ig}^3(\theta) \cong \sum_{l=1}^{w} q_l \sum_{i=1}^{n} k_i^3(\theta,l) + k_{ig}^3 H^3(\theta,r), \; \theta \geq 0, \quad (66)$$

where q_l, $l = 1,2,...w,$ are the transient probabilities defined by (1)-(2) and $H^3(\theta,r)$ 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 $\mu_0^3(r)$ and the standard deviation $\sigma_0^3(r)$ and the cost of the system singular renovation is k_{nig}^3.

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

$$\boldsymbol{K}_{nig}^3(\theta) \cong \sum_{l=1}^{w} q_l \sum_{i=1}^{n} k_i^3(\theta,l) + k_{nig}^3 \; \overline{\overline{H}}^3(\theta,r), \; \theta \geq 0, \quad (67)$$

where q_l, $l = 1,2,...w,$ are the transient probabilities defined by (1)-(2) and $\overline{\overline{H}}^3(\theta,r)$ 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 $H^3(\theta,r)$ and $\overline{\overline{H}}^3(\theta,r)$ for the repairable systems with ignored and non-ignored renovation times existing in the formulae (66) and (67), 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.

5. Cost analysis of port oil piping transportation system impacted by climate-weather change 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 climate-weather states c_l, $l = 1,2,...,7,$ amount

$$k_i^3(\theta,l) \cong 9.6 \text{ PLN}, \; l = 1,2,...,7, \; i = 1,2,...,2880$$

and it is equal to 0 in the component is not used.

Thus, according to (65), 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 cost during the operation time θ = 1 year is approximately given by

$$\boldsymbol{K}^3(1) \cong \sum_{l=1}^{7} q_l \sum_{i=1}^{n} k_i^3(1) \cong 0.403 \cdot 1086 \cdot 9.6$$
$$+ 0.055 \cdot 1086 \cdot 9.6 + 0.003 \cdot 1794 \cdot 9.6$$
$$+ 0.002 \cdot 2880 \cdot 9.6 + 0.199 \cdot 1794 \cdot 9.6$$
$$+ 0.057 \cdot 2880 \cdot 9.6 + 0.281 \cdot 1086 \cdot 9.6$$
$$= 12814.68 \text{ PLN.} \quad (68)$$

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

$$k_{ig}^3 = 88\,500 \text{ PLN.}$$

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

$$H^3(1,1) = 1/56.7545 = 0.01762,$$

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

$$\boldsymbol{K}_{ig}^3(1) \cong \sum_{l=1}^{7} q_l \sum_{i=1}^{n} k_i^3(1) + k_{ig}^1 H^3(1,1) = 12\,814.68$$
$$+ 88\,500 \cdot 0.01762 = 12\,814.68 + 1\,559.37$$
$$\cong 14\,374 \text{ PLN.} \quad (69)$$

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

$$\mu_0^3(1) = 0.2 \text{ year}$$

and the cost of the system singular renovation is

$$k_{nig}^3 = 90\,000 \text{ PLN}$$

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

$$\overline{\overline{H}}^3(1,1) = 1/(56.7545 + 0.2) = 0.01756,$$

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

$$\boldsymbol{K}_{nig}^3(1) \cong \sum_{l=1}^{7} q_l \sum_{i=1}^{n} k_i^3(1) + k_{nig}^3 \, \overline{\overline{H}}^3(1,1) = 12\,814.68$$
$$+ 90\,000 \cdot 0.01756 = 12\,814.68 + 1580.4$$
$$\cong 14395 \text{ PLN.} \quad (70)$$

6. Conclusions

The proposed in [EU-CIRCLE Report D3.3-Part 3, 2017] Model 3 of critical infrastructure safety was applied to safety analysis of the port oil piping transportation system related to climate-weather change process. 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 related to climate-weather change, in the next part of the series of 4 papers concerned with the EU-CIRCLE project Case Study 2, Storm and Sea Surge at Baltic Sea Port.

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