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Consequences of Maritime Critical Infrastructure Accidents with Chemical Releases

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ABSTRACT: The probabilistic general model of critical infrastructure accident consequences including three models of the process of the initiating events generated by a critical infrastructure accident, the process of the environment threats and the process of environment degradation is created and adopted to the maritime transport critical infrastructure understood as a ship network operating at the sea waters and then applied to accident consequences modeling, identification and to these consequences optimization and mitigation.

1 INTRODUCTION

The general semi-Markov model of critical infrastructure accident consequences including the superposition of three models, the process of the initiating events generated by a critical infrastructure accident, the process of the environment threats and the process of environment degradation, is designed and then adopted to the maritime transport critical infrastructure. The proposed model, methods and tools are applied to this critical infrastructure accident with chemical release consequences modeling and identification, on the basis of the statistical data coming from reports of chemical accidents at the Baltic Sea and world sea waters, and prediction. The model also includes the cost analysis of losses associated with those consequences of chemical releases. Further, under the assumption of the stress of weather influence on the ship operation condition in the form of maritime storm and/or other hard sea conditions existence, critical infrastructure accident consequences are examined and the results are compared with the previous ones. Finally, the critical infrastructure accident losses optimization is performed and practical suggestions and procedures of these losses mitigation are given.

2 GENERAL MODEL OF CRITICAL INFRASTRUCTURE ACCIDENT CONSEQUENCES

The general model of a critical infrastructure accident consequences including the process of initiating events, the process of environment threats and the process of environment degradation is designed and described in detail in (Bogalecka & Kołowrocki 2016, 2017d, 2018a).

2.1 *Process of initiating events*

We assume, as in (Bogalecka & Kołowrocki 2017a, d) that the process of initiating events is taking ω, $\omega \in N$, different initiating events states $e^1, e^2, \ldots, e^{\omega}$. Next, we mark by $E(t)$, $t \in \langle 0,+\infty)$, the process of initiating events, that is a function of a continuous variable t, taking discrete values in the set $\{e^1, e^2, \ldots, e^{\omega}\}$ of the initiating events states. We assume a semi-Markov model (Grabski 2015, Kołowrocki 2014, Kołowrocki & Soszyńska-Budny 2011, Limnios & Oprisan 2005, Macci 2008, Mercier 2008) of the process of initiating events $E(t)$, and we mark by θ^{lj} its random conditional sojourn times at the initiating events states e^l, when its next initiating events state is e^j, $l, j = 1,2,\ldots,\omega$, $l \neq j$.

Under these assumption, the process of initiating events may be described by the vector $[p^l(0)]_{1\times\omega}$ of probabilities of the process of initiating events staying at the particular initiating events states at the initial moment $t = 0$, the matrix $[p^{lj}(t)]_{\omega\times\omega}$ of probabilities of transitions between the initiating events states and the matrix $[H^{lj}(t)]_{\omega\times\omega}$ of the distribution functions of the conditional sojourn times θ^{lj} of the process $E(t)$ at the initiating events states or equivalently by the matrix $[h^{lj}(t)]_{\omega\times\omega}$ of the density functions of the conditional sojourn times θ^{lj}, $l, j = 1,2,\ldots,\omega$, $l \neq j$ of the process of initiating events at the initiating events states.

The approximate limit values of transient probabilities p^l, $l = 1,2,\ldots,\omega$ at the particular states of the process of initiating events given by (3) in (Bogalecka & Kołowrocki 2017d) can be either calculated analytically using the above parameters of the process of initiating events or evaluated approximately by experts (Bogalecka & Kołowrocki 2017a, 2018a).

2.2 *Process of environment threats*

We assume, as in (Bogalecka & Kołowrocki 2017b, d) that the process of environment threats of the sub-region D_k, $k = 1,2,\ldots,n_3$, is taking υ_k, $\upsilon_k \in N$, different states of environment threats $s^1_{(k)}, s^2_{(k)},\ldots, s^{\upsilon_k}_{(k)}$. Next, we mark by $S_{(k/l)}(t)$, $t\in<0,+\infty)$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$, the process of environment threats of the sub-region D_k, $k = 1,2,\ldots,n_3$ while the process of initiating events $E(t)$ is at the state e^l, $l = 1,2,\ldots,\omega$. The process $S_{(k/l)}(t)$ is a function defined on the time interval $t \in <0,+\infty)$ depending on the states of the process of initiating events $E(t)$ and taking discrete values in the set $\{s^1_{(k/l)}, s^2_{(k/l)},\ldots, s^{\upsilon_k}_{(k/l)}\}$ of the environment threats states. We assume a semi-Markov model (Grabski 2015, Kołowrocki 2014, Kołowrocki & Soszyńska-Budny 2011, Limnios & Oprisan 2005, Macci 2008, Mercier 2008) of the process of environment threats $S_{(k/l)}(t)$ and we mark by $\eta^{ij}_{(k/l)}$ its random conditional sojourn times at the states $s^i_{(k/l)}$, when its next state is $s^j_{(k/l)}$, $i, j = 1,2,\ldots,\upsilon_k$, $i \neq j$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$.

Under these assumption, the process of environment threats $S_{(k/l)}(t)$, for each sub-region D_k, $k = 1,2,\ldots,n_3$, may be described by the vector $[p^i_{(k/l)}(0)]_{1\times\upsilon_k}$ of initial probabilities of the process of environment threats staying at particular environment threats states at the initial moment $t = 0$, the matrix $[p^{ij}_{(k/l)}]_{\upsilon_k\times\upsilon_k}$ of probabilities of transitions between the environment threats states $s^i_{(k/l)}$ and $s^j_{(k/l)}$, and the matrix $[H^{ij}_{(k/l)}(t)]_{\upsilon_k\times\upsilon_k}$ of the distribution functions of the conditional sojourn times $\eta^{ij}_{(k/l)}$ of the process $S_{(k/l)}(t)$ at the environment threats states or equivalently by the matrix $[h^{ij}_{(k/l)}(t)]_{\upsilon_k\times\upsilon_k}$ of the density functions of the conditional sojourn times $\eta^{ij}_{(k/l)}$, $i, j = 1,2,\ldots,\upsilon_k$, $i \neq j$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$ of the process of environment threats at the environment threats states.

The following characteristics of the process of environment threats $S_{(k/l)}(t)$ can be either calculated analytically using the above parameters of the conditional sub-process of environment threats or evaluated approximately by experts (Bogalecka & Kołowrocki 2017b, 2018a):

- approximate limit values of transient probabilities $p^i_{(k/l)}$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$ at the particular states of the process of environment threats given by (8) in (Bogalecka & Kołowrocki 2017d),
- limit forms of total probabilities $p^i_{(k)}$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$ of the joined process of environment threats and process of initiating events (Bogalecka & Kołowrocki 2017d)

$$p^i_{(k)} = \sum_{l=1}^{\omega} p^l \cdot p^i_{(k/l)}, \quad i = 1,2,\ldots,\upsilon_k,\ k = 1,2,\ldots,n_3. \tag{1}$$

2.3 *Process of environment degradation*

We assume, as in (Bogalecka & Kołowrocki 2017c, d) that the process of environment degradation of the sub-region D_k, $k = 1,2,\ldots,n_3$ is taking ℓ_k, $\ell_k \in N$ different environment degradation states $r^1_{(k)}, r^2_{(k)},\ldots, r^{\ell_k}_{(k)}$. Next, we mark by $R_{(k/\upsilon)}(t)$, $t \in <0,+\infty)$, $k = 1,2,\ldots,n_3$, $\upsilon = 1,2,\ldots,\upsilon_k$, the process of the environment degradation of the sub-region D_k, $k = 1,2,\ldots,n_3$ while the process of environment threats $S_{(k)}(t)$ of the sub-region D_k is in the state $s^{\upsilon}_{(k)}$, $\upsilon = 1,2,\ldots,\upsilon_k$. The process $R_{(k/\upsilon)}(t)$ is a function defined on the time interval $t \in <0,+\infty)$, depending on the states of the process of environment threats $S_{(k)}(t)$ and taking discrete values in the set $\{r^1_{(k/\upsilon)}, r^2_{(k/\upsilon)},\ldots, r^{\ell_k}_{(k/\upsilon)}\}$ of the environment degradation states. We assume a semi-Markov model (Grabski 2015, Kołowrocki 2014, Kołowrocki & Soszyńska-Budny 2011, Limnios & Oprisan 2005, Macci 2008, Mercier 2008) of the process of environment degradation $R_{(k/\upsilon)}(t)$ and we mark by $\zeta^{ij}_{(k/\upsilon)}$ its random conditional sojourn times at the states $r^i_{(k/\upsilon)}$ when its next state is $r^j_{(k/\upsilon)}$, $i, j = 1,2,\ldots, \ell_k$, $i \neq j$, $k = 1,2,\ldots,n_3$, $\upsilon = 1,2,\ldots,\upsilon_k$.

Under these assumption, the process of environment degradation $R_{(k/\upsilon)}(t)$ for each sub-region D_k, $k = 1,2,\ldots,n_3$ may be described by the vector $[q^i_{(k/\upsilon)}(0)]_{1\times\ell_k}$ of initial probabilities of the process of environment degradation staying at particular environment degradation states at the initial moment $t = 0$, the matrix $[q^{ij}_{(k/\upsilon)}]_{\ell_k\times\ell_k}$ of probabilities of transitions between the environment degradation states $r^i_{(k/\upsilon)}$ and $r^j_{(k/\upsilon)}$, and the matrix $[G^{ij}_{(k/\upsilon)}(t)]_{\ell_k\times\ell_k}$ of the distribution functions of the conditional sojourn times $\zeta^{ij}_{(k/\upsilon)}$ of the process $R_{(k/\upsilon)}(t)$ at the environment degradation states or equivalently by the matrix $[g^{ij}_{(k/\upsilon)}(t)]_{\ell_k\times\ell_k}$ of the density functions of the conditional sojourn times $\zeta^{ij}_{(k/\upsilon)}$, $i, j = 1,2,\ldots, \ell_k$, $i \neq j$, $k = 1,2,\ldots,n_3$, $\upsilon = 1,2,\ldots,\upsilon_k$ of the process of environment degradation at the environment degradation states.

The following characteristics of the process of environment degradation $R_{(k/\upsilon)}(t)$ can be either calculated analytically using the above parameters of the process of environment degradation or evaluated approximately by experts (Bogalecka & Kołowrocki 2017c, 2018a):

- approximate limit values of transient probabilities $q^i_{(k/\upsilon)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$, $\upsilon = 1,2,\ldots,\upsilon_k$ at the particular states of the process of environment degradation given by (16) in (Bogalecka & Kołowrocki 2017d),
- limit forms of total probabilities $q^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$ of the joined process of environment degradation, the process of environment threats and the process of initiating events (Bogalecka & Kołowrocki 2017d)

$$q^i_{(k)} \cong \sum_{\upsilon=1}^{\upsilon_k} p^{\upsilon}_{(k)} \cdot q^i_{(k/\upsilon)} = \sum_{\upsilon=1}^{\upsilon_k} [\sum_{l=1}^{\omega} p^l \cdot p^{\upsilon}_{(k/l)}] q^i_{(k/\upsilon)} \quad (2)$$

for $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$.

3 CRITICAL INFRASTRUCTURE ACCIDENT LOSSES

We denote by (Bogalecka & Kołowrocki 2017d, 2018c)

$$L^i_{(k)}(t),\ \ i = 1,2,\ldots,\ell_k,\ \ k = 1,2,\ldots,n_3, \quad (3)$$

the losses associated with the process of the environment degradation $R_{(k)}(t)$, $t \in <0,+\infty)$, $k = 1,2,\ldots,n_3$, in the sub-region D_k, $k = 1,2,\ldots,n_3$ at the environment degradation state $r^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$ in the time interval $<0,t>$. Thus, the approximate expected value of the losses in the time interval $<0,t>$, associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-region D_k can be defined by

$$L_{(k)}(t) \cong \sum_{i=1}^{\ell_k} q^i_{(k)} \cdot L^i_{(k)}(t) \quad \text{for } k = 1,2,\ldots,n_3, \quad (4)$$

where $q^i_{(k)}$ mean the limit transient probabilities of the unconditional process of the environment degradation at its particular states and are given by (2), and $L^i_{(k)}(t)$, $t \in <0,+\infty)$ are defined by (3).

The losses associated with particular environment degradation states are involved with negative consequences in the accident area. The types of consequences are various for different kinds of accident and accident area. For instance, in the shipping, the closure of port, closure of fishery area and people death can be considered as the negative consequences. The losses can be expressed by the cost of the negative consequences in case like the closure of port, closure of fishery area (Etkin 1999, Goldstein & Ritterling 2001, Kontovas et al. 2011, Psaraftis 2008). In the case of negative consequences like people death, the losses can be expressed as the number of loss of life. In the paper we only consider the accident consequences that can be expressed by cost.

Under these assumption, if we fix the number of kinds of accident consequences by ξ and the cost function of this consequence lasting t

$$[K^i_{(k)}(t)]^{(j)},\ \ j = 1,2,\ldots,\xi,\ i = 1,2,\ldots,\ell_k,\ \ k = 1,2,\ldots,n_3 \quad (5)$$

than the loss for the sub-region D_k is expressed by the total cost of all consequences lasting t in the sub-region D_k, and is given by

$$L^i_{(k)}(t) \cong \sum_{j=1}^{\xi} [K^i_{(k)}(t)]^{(j)},\ \ i = 1,2,\ldots,\ell_k,\ \ k = 1,2,\ldots,n_3. \quad (6)$$

Hence, according to (4), losses associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-region D_k are given by

$$L_{(k)}(t) \cong \sum_{i=1}^{\ell_k} q^i_{(k)} \left[\sum_{j=1}^{\xi} [K^i_{(k)}(t)]^{(j)} \right],\ \ k = 1,2,\ldots,n_3. \quad (7)$$

Furthermore, the total expected value of the losses for the fixed time φ, $\varphi \geq 0$, associated with the process of the environment degradation $R(t)$ in all sub-regions of the considered critical infrastructure operating environment region D, can be evaluated by

$$L(\varphi) \cong \sum_{k=1}^{n_3} L_{(k)}(\varphi), \quad (8)$$

where $L_{(k)}(\varphi)$ are given by (7) for $t = \varphi$.

4 CRITICAL INFRASTRUCTURE ACCIDENT LOSSES WITH CONSIDERING CLIMATE-WEATHER CHANGE PROCESS IMPACT

4.1 *Critical infrastructure accident area climate-weather change process*

The critical infrastructure accident area climate-weather change process parameters are (Kołowrocki et al. 2017): the number of climate-weather states w, the vector $[q_b(0)]_{1\times w}$ of the initial probabilities of the climate-weather change process $C(t)$ staying at particular climate-weather states c_b at the moment $t = 0$, the matrix $[q_{bl}]_{w\times w}$ of the probabilities of transitions q_{bl}, $b, l = 1,2,\ldots,w$, $b \neq l$ of the climate-weather change process $C(t)$ from the climate-weather state c_b to c_l; and the matrix $[N_{bl}]_{w\times w}$ of the mean values $N_{bl} = E[C_{bl}]$, $b, l = 1,2,\ldots,w$, $b \neq l$ of the climate-weather change process $C(t)$ conditional sojourn times C_{bl} at the climate-weather states c_b when its next climate-weather state is c_l.

The critical infrastructure operating area climate-weather change process characteristic is (Kołowrocki et al. 2017) the vector

$$[q_b]_{1\times w} = [q_1, q_2, \ldots, q_w] \quad (9)$$

of the limit values of transient probabilities

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

of the climate-weather change process $C(t)$ at the particular operation states c_b.

We consider that the climate-weather change process affects the losses associated with the process of the environment degradation (Bogalecka & Kołowrocki 2017e). We suppose that there are $w = 6$

climate-weather states c_b, $b = 1,2,\ldots,w$ dependent on the wave height and the wind speed, distinguished for the ship operating area at the Baltic Sea open and restricted waters and also $w = 6$ climate-weather states c_b, $b = 1,2,\ldots,w$ dependent on the wind speed and the wind direction, distinguished for the ship operating area at the Baltic Sea port waters. These climate-weather states c_b, $b = 1,2,\ldots,w$ are detailed defined in (Kuligowska 2017).

4.2 *Critical infrastructure accident losses related to climate-weather impact*

We denote the losses associated with the process of the environment degradation $R_{(k)}(t)$, $t \in <0,+\infty)$, $k = 1,2,\ldots,n_3$, in the sub-region D_k, $k = 1,2,\ldots,n_3$, at the environment degradation state $r^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$, in the time interval $<0,t>$ while the climate-weather change process $C(t)$ at the critical infrastructure accident area is at the climate-weather state c_b, $b = 1,2,\ldots,w$, by (Bogalecka & Kołowrocki 2017e)

$$[L^i_{(k)}(t)]^{(b)}, \tag{10}$$

$t \in <0,+\infty)$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$, $b = 1,2,\ldots,w$.

The losses $[L^i_{(k)}(t)]^{(b)}$ are the conditional losses while the climate-weather change process $C(t)$ is at the climate-weather state c_b, $b = 1,2,\ldots,w$, defined by

$$[L^i_{(k)}(t)]^{(b)} = [\rho^i_{(k)}]^{(b)} \cdot L^i_{(k)}(t), \tag{11}$$

$t \in <0,+\infty)$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$, $b = 1,2,\ldots,w$,

where

$$[\rho^i_{(k)}]^{(b)}, \quad i = 1,2,\ldots,\ell_k, \quad k = 1,2,\ldots,n_3, \; b = 1,2,\ldots,w, \tag{12}$$

are the coefficients of the climate-weather change process impact on the losses associated with the process of the environment degradation in the sub-region D_k, $k = 1,2,\ldots,n_3$, at the environment degradation state $r^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$, in the time interval $<0,t>$ while the climate-weather change process $C(t)$ at the critical infrastructure accident area is at the climate-weather state c_b, $b = 1,2,\ldots,w$. Thus, by (7) and (11) the conditional approximate expected value of the losses in the time interval $<0,t>$, associated with the process of the environment degradation $R_{(k)}(t)$, of the sub-region D_k while the climate-weather change process $C(t)$ is at the climate-weather state c_b, $b = 1,2,\ldots,w$, can be defined by

$$[L_{(k)}(t)]^{(b)} \cong \sum_{i=1}^{\ell_k} q^i_{(k)} \cdot [L^i_{(k)}(t)]^{(b)} \tag{13}$$

for $k = 1,2,\ldots,n_3$, $b = 1,2,\ldots,w$, where $q^i_{(k)}$ are given by (2) and $[L^i_{(k)}(t)]^{(b)}$, $t \in <0,+\infty)$ are defined by (11)-(12).

Further, applying the formula for total probability, the unconditional approximate expected value of the losses, impacted by the climate-weather change process $C(t)$, in the time interval $<0,t>$, associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-region D_k, can be expressed by

$$\overline{L}_{(k)}(t) \cong \sum_{b=1}^{w} q_b \cdot [L_{(k)}(t)]^{(b)}, \quad k = 1,2,\ldots,n_3, \tag{14}$$

where q_b are given by (9) and $[L_{(k)}(t)]^{(b)}$, $t \in <0,+\infty)$ are determined by (13).

Hence, according to (13), we have

$$\overline{L}_{(k)}(t) \cong \sum_{b=1}^{w}\sum_{i=1}^{\ell_k} q_b \cdot q^i_{(k)} \cdot [L^i_{(k)}(t)]^{(b)}, \quad k = 1,2,\ldots,n_3. \tag{15}$$

Finally, the total expected value of losses, impacted by the climate-weather change process $C(t)$, in the fixed time interval $<0,\varphi>$, associated with the process of the environment degradation $R(t)$, in all sub-regions of the considered critical infrastructure operating environment region D, can be evaluated by

$$\overline{L}(\varphi) \cong \sum_{k=1}^{n_3} \overline{L}_{(k)}(\varphi), \tag{16}$$

where $\overline{L}_{(k)}(\varphi)$ are given by (14) for $t = \varphi$.

Thus, considering (11), the coefficient of the climate-weather change process impact on the losses associated with the process of the environment degradation in the sub-region D_k, $k = 1,2,\ldots,n_3$, in the time interval $<0,\varphi>$, may be defined as

$$\rho_{(k)} = \overline{L}_{(k)}(\varphi)/L_{(k)}(\varphi), \; \varphi \in <0,+\infty), \; k = 1,2,\ldots,n_3, \tag{17}$$

where $\overline{L}_{(k)}(\varphi)$ are the losses related to the climate-weather impact, determined by (14) and $L_{(k)}(\varphi)$ are the losses without considering climate-weather impact, determined by (4).

Similarly, the coefficient of the climate-weather change process impact on the total losses associated with the process of the environment degradation in the entire considered region D, in the time interval $<0,\varphi>$, may be defined as

$$\rho = \overline{L}(\varphi)/L(\varphi), \; \varphi \in <0,+\infty), \tag{18}$$

where $\overline{L}(\varphi)$ are the total losses related to the climate-weather impact determined by (16) and $L(\varphi)$ are the total losses without considering climate-weather impact determined by (8).

Other practically interesting characteristics of the environment degradation caused by critical infrastructure accident consequences related to the climate-weather are the indicators of the environment of the sub-regions D_k, $k = 1,2,\ldots,n_3$ resilience to the losses associated with the critical infrastructure accident related to the climate-weather change that are proposed to be defined by

$$RI_{(k)}(\varphi) = 1/\rho_{(k)}, \; \varphi \in <0,+\infty), \; k = 1,2,\ldots,n_3, \tag{19}$$

where $\rho_{(k)}$ are determined by (17) and the indicator of the environment of the entire region D resilience to the total losses associated with the critical infrastructure accident consequences related to the climate-weather change that are proposed to be defined by

$$RI(\varphi) = 1/\rho,\ \varphi \in <0,+\infty), \tag{20}$$

where ρ is determined by (18).

5 APPLICATION TO THE DYNAMIC SHIP CRITICAL INFRASTRUCTURE NETWORK OPERATING AT THE BALTIC SEA WATERS

On the basis of the statistical data, using the procedures given in (Bogalecka & Kołowrocki 2016, 2017a, b, c, d, 2018a) we identify and predict the process of environment degradation for the Baltic Sea waters. Namely, we calculate unconditional approximate transient probabilities $q^i_{(k)}$, $k = 1,2,\dots,5$, $i = 1,2,\dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ at the particular states of the process of environment degradation given by (2), for particular sub-regions D_k, $k = 1,2,\dots,5$ that are as follows (the probabilities of transitions that are not equal to 0 are presented only):

$$q^1_{(1)} = 0.999872179003445,\ q^2_{(1)} = 0.000000005069726,$$
$$q^6_{(1)} = 0.000054820128704,\ q^{11}_{(1)} = 0.000072995798125;$$
$$q^1_{(2)} = 0.999871085266778,\ q^6_{(2)} = 0.000016170471066,$$
$$q^{12}_{(2)} = 0.000032213681563,\ q^{16}_{(2)} = 0.000042280457051,$$
$$q^{21}_{(2)} = 0.000032213681563,\ q^{25}_{(2)} = 0.000003353578877,$$
$$q^{27}_{(2)} = 0.000002682863102;\ q^1_{(3)} = 0.999871085266778,$$
$$q^6_{(3)} = 0.000016170471066,\ q^{12}_{(3)} = 0.000032213681563,$$
$$q^{16}_{(3)} = 0.000042280457051,\ q^{21}_{(3)} = 0.000032213681563,$$
$$q^{25}_{(3)} = 0.000003353578877,\ q^{27}_{(3)} = 0.000002682863102;$$
$$q^1_{(4)} = 0.999871139828532,\ q^{12}_{(4)} = 0.000036818375059,$$
$$q^{16}_{(4)} = 0.000048324117265,\ q^{21}_{(4)} = 0.000036818375059,$$
$$q^{28}_{(4)} = 0.000003832946714,\ q^{30}_{(4)} = 0.000003066357371;$$
$$q^1_{(5)} = 1. \tag{21}$$

The general model of critical infrastructure accident consequences is applied to cost analysis of losses associated with consequences generated by the critical infrastructure defined as a ship operating at the Baltic Sea (Bogalecka & Kołowrocki 2018c). Considering (21), according to (6)-(7) and the information coming from experts, the losses associated with the process of the environment degradation $R_{(k)}(t)$ of the particular sub-region D_k, $k = 1,2,\dots,5$, during the time $t = 1$ hour, amount (in PLN):

– at the open and restricted waters

$$L_{(1)}(1) \cong 0.785,\ L_{(2)}(1) \cong 2.467,\ L_{(3)}(1) \cong 3.091,$$
$$L_{(4)}(1) \cong 3.072,\ L_{(5)}(1) = 0; \tag{22}$$

– at Gdynia and Karlskrona ports

$$L_{(1)}(1) \cong 1.457,\ L_{(2)}(1) \cong 3.145,\ L_{(3)}(1) \cong 3.769,$$
$$L_{(4)}(1) \cong 3.750,\ L_{(5)}(1) = 0. \tag{23}$$

Considering the above results, after applying (8), the total expected value of losses associated with the process of the environment degradation $R(t)$ in all sub-regions of the considered critical infrastructure operating environment region D, during the time $t = 1$ hour, amounts (in PLN)

– at the open and restricted waters:

$$L(1) = 9.415; \tag{24}$$

– at Gdynia and Karlskrona ports:

$$L(1) = 12.121. \tag{25}$$

Moreover, the losses of critical infrastructure accident consequences impacted by the climate-weather change process are calculated.

The approximate limit values of transient probabilities q_b, $b = 1,2,\dots,6$ of the climate-weather change process, at the climate-weather states for the operating area (GMU Safety Interactive Platform 2018) amount

– at the open waters:

$$q_1 = 0.834,\ q_2 = 0.149,\ q_3 = 0,$$
$$q_4 = 0,\ q_5 = 0.015,\ q_6 = 0.002; \tag{26}$$

– at the restricted waters:

$$q_1 = 0.827,\ q_2 = 0.155,\ q_3 = 0.004,$$
$$q_4 = 0,\ q_5 = 0.007,\ q_6 = 0.007; \tag{27}$$

– at the Gdynia Port:

$$q_1 = 0.394,\ q_2 = 0.010,\ q_3 = 0.473,$$
$$q_4 = 0.006,\ q_5 = 0.017,\ q_6 = 0; \tag{28}$$

– at the Karlskrona Port:

$$q_1 = 0.364,\ q_2 = 0.005,\ q_3 = 0.417,$$
$$q_4 = 0.016,\ q_5 = 0.197,\ q_6 = 0.001. \tag{29}$$

According to the information coming from experts, the coefficients $[\rho^i_{(k)}]^{(b)}$, $b = 1,2,\dots,6$, $k = 1,2,\dots,5$, $i = 1,2,\dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ of the climate-weather impact on losses at the climate-weather change process states c_b, $b = 1,2,\dots,6$ are

– at the open and restricted sea waters area:

$$[\rho^i_{(1)}]^{(b)} = 1.0,\ b = 1,2,3,\ i = 1,2,\dots 30,$$
$$[\rho^i_{(1)}]^{(b)} = 2.0,\ b = 4,5,6,\ i = 1,2,\dots 30,$$
$$[\rho^i_{(2)}]^{(b)} = 1.0,\ b = 1,\ i = 1,2,\dots 28,$$
$$[\rho^i_{(2)}]^{(b)} = 2.0,\ b = 2,\ i = 1,2,\dots 28,$$
$$[\rho^i_{(2)}]^{(b)} = 2.5,\ b = 3,5,\ i = 1,2,\dots 28,$$
$$[\rho^i_{(2)}]^{(b)} = 1.8,\ b = 4,\ i = 1,2,\dots 28,$$

$[\rho^i_{(2)}]^{(b)} = 3.0,\ b = 6,\ i = 1,2,\ldots 28,$

$[\rho^i_{(3)}]^{(b)} = 1.0,\ b = 1,4,\ i = 1,2,\ldots 28,$

$[\rho^i_{(3)}]^{(b)} = 2.0,\ b = 2,5,\ i = 1,2,\ldots 28,$

$[\rho^i_{(3)}]^{(b)} = 3.0,\ b = 3,6,\ i = 1,2,\ldots 28,$

$[\rho^i_{(4)}]^{(b)} = 1.0,\ b = 1,2,\ldots,6,\ i = 1,2,\ldots 31,$

$[\rho^i_{(5)}]^{(b)} = 1.0,\ b = 1,2,\ldots,6,\ i = 1,2,\ldots 23;$ (30)

– at the Gdynia and Karlskrona ports:

$[\rho^i_{(1)}]^{(b)} = 1.0,\ b = 1,3,5,\ i = 1,2,\ldots 30,$

$[\rho^i_{(1)}]^{(b)} = 2.0,\ b = 2,4,6,\ i = 1,2,\ldots 30,$

$[\rho^i_{(2)}]^{(b)} = 1.0,\ b = 1,3,5\ i = 1,2,\ldots 28,$

$[\rho^i_{(2)}]^{(b)} = 2.0,\ b = 2,4,6,\ i = 1,2,\ldots 28,$

$[\rho^i_{(3)}]^{(b)} = 1.0,\ b = 1,3,5,\ i = 1,2,\ldots 28,$

$[\rho^i_{(3)}]^{(b)} = 2.0,\ b = 2,4,6,\ i = 1,2,\ldots 28,$

$[\rho^i_{(4)}]^{(b)} = 1.0,\ b = 1,2,\ldots,6,\ i = 1,2,\ldots 31,$

$[\rho^i_{(5)}]^{(b)} = 1.0,\ b = 1,2,\ldots,6,\ i = 1,2,\ldots 23.$ (31)

Hence, according to (11) and (13)-(15), the unconditional approximate expected value of the environmental losses $\overline{L}_{(k)}(t)$, during the time $t = 1$ hour, associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-region D_k, $k = 1,2,\ldots,5$ while the climate-weather change process $C(t)$ is at the climate-weather state c_b, $b = 1,2,\ldots,6$, are as follows (in PLN)

– at the open sea waters:

$$\overline{L}_{(1)}(1) \cong 0.798,\ \overline{L}_{(2)}(1) \cong 2.900,\ \overline{L}_{(3)}(1) \cong 3.611,$$
$$\overline{L}_{(4)}(1) \cong 3.072,\ \overline{L}_{(5)}(1) = 0; \quad (32)$$

– at the restricted sea waters:

$$\overline{L}_{(1)}(1) \cong 0.796,\ \overline{L}_{(2)}(1) \cong 2.925,\ \overline{L}_{(3)}(1) \cong 3.660,$$
$$\overline{L}_{(4)}(1) \cong 3.072,\ \overline{L}_{(5)}(1) = 0; \quad (33)$$

– at the Gdynia Port:

$$\overline{L}_{(1)}(1) \cong 1.481,\ \overline{L}_{(2)}(1) \cong 3.195,\ \overline{L}_{(3)}(1) \cong 3.800,$$
$$\overline{L}_{(4)}(1) \cong 3.750,\ \overline{L}_{(5)}(1) = 0; \quad (34)$$

– at the Karlskrona Port:

$$\overline{L}_{(1)}(1) \cong 1.489,\ \overline{L}_{(2)}(1) \cong 3.214,\ \overline{L}_{(3)}(1) \cong 3.811,$$
$$\overline{L}_{(4)}(1) \cong 3.750,\ \ \overline{L}_{(5)}(1) = 0. \quad (35)$$

Considering (32)-(35) respectively and applying (16), the total expected value of the losses $\overline{L}(t)$, impacted by the climate-weather change process $C(t)$, during the time $t = 1$ hour, associated with the process of the environment degradation $R(t)$ in all sub-regions of the considered critical infrastructure operating environment region D, amounts (in PLN)

– at the open sea waters:

$\overline{L}(1) \cong 10.381;$ (36)

– at the restricted sea waters:

$\overline{L}(1) \cong 10.453;$ (37)

– at the Gdynia Port:

$\overline{L}(1) \cong 12.226;$ (38)

– at the Karlskrona Port:

$\overline{L}(1) \cong 12.264.$ (39)

Thus, considering (22)-(23) and (32)-(35) respectively, and according to (17) and (19), the indicators $RI_{(k)}(t)$ of the environment of the sub-regions D_k, $k = 1,2,\ldots,5$, resilience to the losses associated with the critical infrastructure accident related to the climate-weather change are

– at the open sea waters:

$RI_{(1)}(1) = 98.4\%$, $RI_{(2)}(1) = 85.1\%$,
$RI_{(3)}(1) = 85.6\%$, $RI_{(4)}(1) = 100\%$,
$RI_{(5)}(1)$ – n/a as $L_{(5)}(1) = 0$ and $\overline{L}_{(5)}(1) = 0$; (40)

– at the restricted sea waters:

$RI_{(1)}(1) = 98.6\%$, $RI_{(2)}(1) = 84.3\%$,
$RI_{(3)}(1) = 84.5\%$, $RI_{(4)}(1) = 100\%$,
$RI_{(5)}(1)$ – n/a as $L_{(5)}(1) = 0$ and $\overline{L}_{(5)}(1) = 0$; (41)

– at the Gdynia Port:

$RI_{(1)}(1) = 98.4\%$, $RI_{(2)}(1) = 98.4\%$,
$RI_{(3)}(1) = 99.2\%$, $RI_{(4)}(1) = 100\%$,
$RI_{(5)}(1)$ – n/a as $L_{(5)}(1) = 0$ and $\overline{L}_{(5)}(1) = 0$; (42)

– at the Karlskrona Port:

$RI_{(1)}(1) = 97.8\%$, $RI_{(2)}(1) = 97.8\%$,
$RI_{(3)}(1) = 98.9\%$, $RI_{(4)}(1) = 100\%$,
$RI_{(5)}(1)$ – n/a as $L_{(5)}(1) = 0$ and $\overline{L}_{(5)}(1) = 0$. (43)

Next, considering (24)-(25) and (36)-(39) respectively, and according to (18) and (20), the indicator $RI(t)$ of the environment of the entire region D resilience to the losses associated with the critical infrastructure accident related to the climate-weather change is

– at the open sea waters:

$RI(1) = 90.7\%$; (44)

– at the restricted sea waters:

$RI(1) = 90.1\%$; (45)

– at the Gdynia Port:

$$RI(1) = 99.1\%; \tag{46}$$

– at the Karlskrona Port:

$$RI(1) = 98.8\%. \tag{47}$$

The above results point the more significant impact of the climate-weather change process within the open and restricted waters than Gdynia and Karlskrona ports. The reason for this can be explained that the wave height and the wind speed are parameters considered in the state of the climate-weather change process at the open and restricted sea waters, whereas the wind speed and the wind direction are parameters considered in the state of the climate-weather change process at Gdynia and Karlskrona ports. It confirms that a wind direction that is consider in the states of the climate-weather change process only for Gdynia and Karlskrona ports has a little significant impact on a value of losses associated with the process of the environment degradation.

Finally, these results are applied to the accident consequences cost optimization through the accident losses minimizing. From the linear equation (4), we can see that the mean value of expected critical infrastructure accident losses $L_{(k)}(t)$, $t \in \langle 0,+\infty)$, associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-region D_k, $k = 1,2,\ldots,5$ is determined by the limit value of transient probabilities $q^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,5$ of the process of the environment degradation at the state $r^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,5$ and the mean value of the critical infrastructure accident losses $L^i_{(k)}(t)$ associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-region D_k, $k = 1,2,\ldots,5$, at the state $r^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,5$. Similarly, from the linear equation (15), we can see that the mean value of expected critical infrastructure accident losses $\bar{L}_{(k)}(t)$, $t \in \langle 0,+\infty)$, associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-region D_k, $k = 1,2,\ldots,5$, impacted by the climate-weather change process $C(t)$ is determined by the limit value of transient probabilities q_b, $b = 1,2,\ldots,6$ of the climate-weather change process $C(t)$ at the particular climate-weather state c_b, $b = 1,2,\ldots,6$, the limit value of transient probabilities $q^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,5$ of the process of the environment degradation at the state $r^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,5$ and by the mean value of the critical infrastructure accident losses $[L^i_{(k)}(t)]^b$ associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-region D_k, $k = 1,2,\ldots,5$ at the state $r^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,5$ impacted by the climate-weather change process $C(t)$.

Therefore, the optimization based on the linear programming (Kołowrocki & Soszyńska-Budny 2011, Klabjan & Adelman 2006, Vercellis 2009) of the critical infrastructure accident losses associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-region D_k, $k = 1,2,\ldots,5$ without and with considering the climate-weather change process $C(t)$ can be proposed. Namely, we may look for the corresponding optimal values $\dot{q}^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,5$ of the limit transient probabilities $q^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,5$ of the process of the environment degradation at the state $r^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,5$ to minimize the mean value of critical infrastructure accident losses $L_{(k)}(t)$ in the sub-region D_k, $k = 1,2,\ldots,5$ (Bogalecka & Kołowrocki 2018b) or optimal values $q_b\dot{q}^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $b = 1,2,\ldots,6$, $k = 1,2,\ldots,5$ of the limit transient probabilities $q_b q^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $b = 1,2,\ldots,6$, $k = 1,2,\ldots,5$ of the process of the environment degradation at the state $r^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,5$ to minimize the mean value of critical infrastructure accident losses $\bar{L}_{(k)}(t)$ impacted by the climate-weather change process $C(t)$ in the sub-region D_k, $k = 1,2,\ldots,5$ (Bogalecka & Kołowrocki 2018b). Now, we can obtain the optimal solution, using the procedure given in (Bogalecka & Kołowrocki 2018b). Namely, we can find the optimal values $\dot{q}^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,5$ of the limit transient probabilities $q^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,5$, or $q_b\dot{q}^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $b = 1,2,\ldots,6$, $k = 1,2,\ldots,5$ of the transient probabilities $q_b q^i_{(k)}$, $i = 1,2,\ldots,\ell_k$, $b = 1,2,\ldots,6$, $k = 1,2,\ldots,5$ that minimize the objective functions given by (4) and (15) respectively.

The inventory of losses associated with the shipping critical infrastructure accident without and with considering the climate-weather change impact and resilience indicators for these losses impacted by the climate-weather change, based on data collected at the Baltic Sea waters, before and after optimization are presented in Tables 1-4.

The performed comparison of values of losses associated with the shipping critical infrastructure accident without and with considering the climate-weather change impact and resilience indicators for these losses impacted by the climate-weather change confirms and justifies the reasonableness of the critical infrastructure accident losses optimization. It may be the basis of some suggestions on new strategy assuring lower environment losses concerned with chemical releases generated by an accident of ships operating within the shipping critical infrastructure network.

Table 1. Shipping critical infrastructure accident losses (in PLN) and resilience indicators for open sea waters before and after optimization

Before optimization			
	$L_{(1)}(1) = 0.785$	$\bar{L}_{(1)}(1) = 0.798$	$RI_{(1)} = 0.984$
	$L_{(2)}(1) = 2.467$	$\bar{L}_{(2)}(1) = 2.900$	$RI_{(2)} = 0.851$
	$L_{(3)}(1) = 3.091$	$\bar{L}_{(3)}(1) = 3.611$	$RI_{(3)} = 0.856$
	$L_{(4)}(1) = 3.072$	$\bar{L}_{(4)}(1) = 3.072$	$RI_{(4)} = 1.000$
	$L_{(5)}(1) = 0$	$\bar{L}_{(5)}(1) = 0$	n/a
total	$L(1) = 9.415$	$\bar{L}(1) = 10.381$	$RI = 0.907$
After optimization			
	$\dot{L}_{(1)}(1) = 0.570$	$\dot{\bar{L}}_{(1)}(1) = 0.575$	$\dot{RI}_{(1)} = 0.991$
	$\dot{L}_{(2)}(1) = 1.437$	$\dot{\bar{L}}_{(2)}(1) = 1.570$	$\dot{RI}_{(2)} = 0.915$
	$\dot{L}_{(3)}(1) = 1.980$	$\dot{\bar{L}}_{(3)}(1) = 2.141$	$\dot{RI}_{(3)} = 0.925$
	$\dot{L}_{(4)}(1) = 1.930$	$\dot{\bar{L}}_{(4)}(1) = 1.930$	$\dot{RI}_{(4)} = 1.000$
	$\dot{L}_{(5)}(1) = 0$	$\dot{\bar{L}}_{(5)}(1) = 0$	n/a
total	$\dot{L}(1) = 5.917$	$\dot{\bar{L}}(1) = 6.216$	$\dot{RI} = 0.952$

Table 2. Shipping critical infrastructure accident losses (in PLN) and resilience indicators for restricted sea waters before and after optimization

Before optimization			
	$L_{(1)}(1) = 0.785$	$\bar{L}_{(1)}(1) = 0.796$	$RI_{(1)} = 0.986$
	$L_{(2)}(1) = 2.467$	$\bar{L}_{(2)}(1) = 2.925$	$RI_{(2)} = 0.844$
	$L_{(3)}(1) = 3.091$	$\bar{L}_{(3)}(1) = 3.660$	$RI_{(3)} = 0.845$
	$L_{(4)}(1) = 3.072$	$\bar{L}_{(4)}(1) = 3.072$	$RI_{(4)} = 1.000$
	$L_{(5)}(1) = 0$	$\bar{L}_{(5)}(1) = 0$	n/a
total	$L(1) = 9.415$	$\bar{L}(1) = 10.453$	$RI = 0.901$
After optimization			
	$\dot{L}_{(1)}(1) = 0.570$	$\dot{\bar{L}}_{(1)}(1) = 0.570$	$\dot{RI}_{(1)} = 1.000$
	$\dot{L}_{(2)}(1) = 1.437$	$\dot{\bar{L}}_{(2)}(1) = 1.577$	$\dot{RI}_{(2)} = 0.911$
	$\dot{L}_{(3)}(1) = 1.980$	$\dot{\bar{L}}_{(3)}(1) = 2.157$	$\dot{RI}_{(3)} = 0.918$
	$\dot{L}_{(4)}(1) = 1.930$	$\dot{\bar{L}}_{(4)}(1) = 1.930$	$\dot{RI}_{(4)} = 1.000$
	$\dot{L}_{(5)}(1) = 0$	$\dot{\bar{L}}_{(5)}(1) = 0$	n/a
total	$\dot{L}(1) = 5.917$	$\dot{\bar{L}}(1) = 6.234$	$\dot{RI} = 0.949$

Table 3. Shipping critical infrastructure accident losses (in PLN) and resilience indicators for Gdynia Port before and after optimization

Before optimization			
	$L_{(1)}(1) = 1.457$	$\bar{L}_{(1)}(1) = 1.481$	$RI_{(1)} = 0.984$
	$L_{(2)}(1) = 3.145$	$\bar{L}_{(2)}(1) = 3.195$	$RI_{(2)} = 0.884$
	$L_{(3)}(1) = 3.769$	$\bar{L}_{(3)}(1) = 3.800$	$RI_{(3)} = 0.992$
	$L_{(4)}(1) = 3.750$	$\bar{L}_{(4)}(1) = 3.750$	$RI_{(4)} = 1.000$
	$L_{(5)}(1) = 0$	$\bar{L}_{(5)}(1) = 0$	n/a
total	$L(1) = 12.122$	$\bar{L}(1) = 12.225$	$RI = 0.992$
After optimization			
	$\dot{L}_{(1)}(1) = 1.149$	$\dot{\bar{L}}_{(1)}(1) = 1.155$	$\dot{RI}_{(1)} = 0.994$
	$\dot{L}_{(2)}(1) = 2.016$	$\dot{\bar{L}}_{(2)}(1) = 2.031$	$\dot{RI}_{(2)} = 0.992$
	$\dot{L}_{(3)}(1) = 2.559$	$\dot{\bar{L}}_{(3)}(1) = 2.568$	$\dot{RI}_{(3)} = 0.996$
	$\dot{L}_{(4)}(1) = 2.509$	$\dot{\bar{L}}_{(4)}(1) = 2.509$	$\dot{RI}_{(4)} = 1.000$
	$\dot{L}_{(5)}(1) = 0$	$\dot{\bar{L}}_{(5)}(1) = 0$	n/a
total	$\dot{L}(1) = 8.231$	$\dot{\bar{L}}(1) = 8.262$	$\dot{RI} = 0.952$

Table 4. Shipping critical infrastructure accident losses (in PLN) and resilience indicators for Karlskrona Port before and after optimization

Before optimization			
	$L_{(1)}(1) = 1.457$	$\bar{L}_{(1)}(1) = 1.489$	$RI_{(1)} = 0.978$
	$L_{(2)}(1) = 3.145$	$\bar{L}_{(2)}(1) = 3.214$	$RI_{(2)} = 0.978$
	$L_{(3)}(1) = 3.769$	$\bar{L}_{(3)}(1) = 3.811$	$RI_{(3)} = 0.989$
	$L_{(4)}(1) = 3.750$	$\bar{L}_{(4)}(1) = 3.750$	$RI_{(4)} = 1.000$
	$L_{(5)}(1) = 0$	$\bar{L}_{(5)}(1) = 0$	n/a
total	$L(1) = 12.122$	$\bar{L}(1) = 12.225$	$RI = 0.988$
After optimization			
	$\dot{L}_{(1)}(1) = 1.149$	$\dot{\bar{L}}_{(1)}(1) = 1.157$	$\dot{RI}_{(1)} = 0.992$
	$\dot{L}_{(2)}(1) = 2.016$	$\dot{\bar{L}}_{(2)}(1) = 2.037$	$\dot{RI}_{(2)} = 0.989$
	$\dot{L}_{(3)}(1) = 2.559$	$\dot{\bar{L}}_{(3)}(1) = 2.572$	$\dot{RI}_{(3)} = 0.995$
	$\dot{L}_{(4)}(1) = 2.509$	$\dot{\bar{L}}_{(4)}(1) = 2.509$	$\dot{RI}_{(4)} = 1.000$
	$\dot{L}_{(5)}(1) = 0$	$\dot{\bar{L}}_{(5)}(1) = 0$	n/a
total	$\dot{L}(1) = 8.231$	$\dot{\bar{L}}(1) = 8.275$	$\dot{RI} = 0.995$

From the performed analysis of the results of the chemical spills at sea consequences optimization it can be suggested to modify the process of accident initiating events and the process of environment threats, and the process of environment degradation in the way that causes the replacing (approximately) the conditional mean sojourn times of the environment degradation process at its particular states before the optimization by their optimal values after the optimization.

Instead of this practically difficult modification it seems to be easier to change the process of accident initiating events and the process of environment threats characteristics that results in replacing (approximately) the unconditional mean sojourn times of the environment degradation process at its particular states before the optimization by their optimal values after the optimization. The easiest way of these two processes modification is that leading to the replacing (approximately) the total sojourn times of the process of accident initiating events and the process of environment threats at their particular states during the fixed time before the optimization by their optimal values after the optimization. Coming directly from the practice suggestions on the way of minimizing the environment losses are the basis for creating the general procedures and new strategies assuring the critical infrastructures accident consequences decreasing the environment losses. In practice it includes the following proactive and reactive strategies (HELCOM 2002, IMO 2002, Kristiansen 2005, Mamaca et al. 2009):

- prevention measures to elimination or reduction accidents at sea (establish and revision of national laws and regulations, IMO conventions and resolutions, inspection, certification and auditing, maintenance of the ship and equipment, reduction traffic congestion),
- investigation of accidents and learn from experience (identify causes and potential measures that will reduce the threats and degradation effects of similar accident in the future),
- identification of hazard and possible events that may cause threats and result in severity of degradation effects,
- emergency preparedness (preparation and revision of emergency action plan, high quality equipment for combating released substances, rescuers training),
- reduction the time of emergency response process, quickly undertaking a proper decision and action, selection the best response method (recommendation for decision-making, decision support, cooperation with external parties and exchange of information, tools for forecasting and equipment for monitoring the spread or drift of released substances).

6 CONCLUSION

Presented in the paper model, methods, procedures and tools are supposed to be very useful in the critical infrastructure accident consequences modeling, identification, prediction, optimization and mitigation the losses associated with these consequences. The constructed model is applied to the maritime critical infrastructure accident consequences caused by the ship operating at the sea waters and chemical releases. The papers contains results obtained when the model was applied to the critical infrastructure accident consequences caused by the ship operating at the Baltic Sea. However, the proposed general model of critical infrastructure accident consequences is a universal tool that can have wide applications in various industrial sectors. In spite of the model has been designed for the maritime critical infrastructure, it can be applied to identification, prediction, optimization and mitigation of the losses associated with chemical releases generated by any other critical infrastructures, industrial installations and systems. Next, based on the results, a new strategy assuring low consequences of any critical infrastructure accident can be created through the initiating events, environment threats and environment degradation processes modification related to minimizing critical infrastructure accident losses.

REFERENCES

Bogalecka, M. & Kołowrocki, K. 2016. Modelling critical infrastructure accident consequences – an overall approach. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 7(1): 1-13.

Bogalecka, M. & Kołowrocki, K. 2017a. General model of critical infrastructure accident consequences application to chemical spill consequences generated by dynamic ship critical infrastructure network operating at the Baltic Sea waters. Part 1. Process of initiating events. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 8(3): 117-121.

Bogalecka, M. & Kołowrocki, K. 2017b. General model of critical infrastructure accident consequences application to chemical spill consequences generated by dynamic ship critical infrastructure network operating at the Baltic Sea waters. Part 2. Process of environment threats. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 8(3): 123-129.

Bogalecka, M. & Kołowrocki, K. 2017c. General model of critical infrastructure accident consequences application to chemical spill consequences generated by dynamic ship critical infrastructure network operating at the Baltic Sea waters. Part 3. Process of environment degradation. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 8(3): 131-138.

Bogalecka, M. & Kołowrocki, K. 2017d. Integrated model of critical infrastructure accident consequences. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 8(3): 43-52.

Bogalecka, M. & Kołowrocki, K. 2017e. Integrated impact model on critical infrastructure accident consequences related to climate-weather change process. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 8(4): 67-75.

Bogalecka, M. & Kołowrocki, K. 2018a. Chemical spill due to extreme sea surges critical infrastructure chemical accident (spill) consequences related to climate-weather change. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars*, 9(2): 65-77.

Bogalecka, M. & Kołowrocki, K. 2018b. Optimization of critical infrastructure accident consequences related to climate-weather change process influence – losses minimizing. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 9(1): 11-16.

Bogalecka, M. & Kołowrocki, K. 2018c. Prediction of critical infrastructure accident losses of chemical releases impacted by climate-weather change. *Proceedings of 2018 IEEE International Conference on Industrial Engineering and Engineering Management* 788-792.

Etkin, D.S. 1999. Estimating cleanup costs for oil spills. *1999 International oil spill conference proceedings* paper 168.

GMU Safety Interactive Platform. http://gmu.safety.umg.edu. pl. Accessed 13 Dec 2018.

Goldstein, M. & Ritterling, J. 2001. A practical guide to estimating cleanup costs. *U.S. EPA Papers* paper 30.

Grabski, F. 2015. *Semi-Markov processes: applications in system reliability and maintenance*. Amsterdam, Boston, Heidelberd, London, New York, Oxford, Paris, San Diego, San Francisco, Sidney, Tokyo: Elsevier.

HELCOM. 2002. *Manual on co-operation in response to marine pollution within the framework of the convention on the protection of the marine environment of the Baltic Sea area*. Helsinki.

IMO. 2002. *International convention on oil pollution preparedness, response and co-operation 1990 with protocol on preparedness, response and co-operation to pollution incidents by hazardous and noxious substances 2000*. London: IMO Publishing.

Klabjan, D. & Adelman, D. 2006. Existence of optimal policies for semi-Markov decision processes using duality for infinite linear programming. *SIAM Journal on Control and Optimization* 44(6): 2104-2122.

Kołowrocki, K. 2014. *Reliability of large and complex systems*. Amsterdam, Boston, Heidelberd, London, New York, Oxford, Paris, San Diego, San Francisco, Singapore, Sidney, Tokyo: Elsevier.

Kołowrocki K. & Soszyńska-Budny, J. 2011. *Reliability and safety of complex technical systems and processes: modeling – identification – prediction – optimization*. London, Dordrecht, Heildeberg, New York: Springer.

Kołowrocki, K., Soszyńska-Budny, J. & Torbicki, M. 2017 Critical infrastructure operating area climate-weather change process including extreme weather hazards. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 8(2): 15-24.

Kontovas, C.A., Ventikos, N.P. & Psaraftis, H.N. 2011 Estimating the consequences costs of oil spills from tankers. *Proceedings of SNAME 2011 Annual Meeting*. Houston.

Kristiansen, S. 2005 *Maritime transportation: safety management and risk analysis*. Amsterdam, Boston, Heidelberd, London, New York, Oxford, Paris, San Diego, San Francisco, Singapore, Sidney, Tokyo: Elsevier.

Kuligowska, E. 2017. Identification and prediction of climate-weather change process for maritime ferry operating area. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 8(2): 129-134.

Limnios N. & Oprisan, G. 2005. *Semi-Markov processes and reliability*. Boston: Birkhauser.

Macci, C. 2008. Large deviations for empirical estimators of the stationary distribution of a semi-Markov process with finite state space. *Communications in Statistics-Theory and Methods* 37(9): 3077-3089.

Mamaca, E., Girin, M., le Floch, S. & el Zir R. 2009. Review of chemical spills at sea and lessons learnt. *Proceedings of Interspill conference & exhibition*. Marseille.

Mercier, S. 2008. Numerical bounds for semi-Markovian quantities and application to reliability. *Methodology and Computing in Applied Probability* 10(2): 179-198.

Psaraftis, H.N. 2008. Environmental risk evaluation criteria. *Proceedings of 2nd international workshop of risk-based approaches to the maritime industry*. Glasgow.

Vercellis, S. 2009. *Data mining and optimization for decision making*. John Wiley & Sons Ltd.