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MODELLING CONSEQUENCES OF MARITIME CRITICAL INFRASTRUCTURE ACCIDENTS

Modelowanie konsekwencji wypadków morskiej infrastruktury krytycznej

Abstract: *The probabilistic general model of critical infrastructure accident consequences including the superposition of three models of the process of initiating events, the process of environment threats and the process of environment degradation is adopted to the maritime transport critical infrastructure. The general model is applied to this critical infrastructure accident with chemical release consequences identification and prediction. The model also includes the cost analysis of losses associated with these chemical releases. Further, under the assumption of the stress of weather influence on the ship operation condition, critical infrastructure accident losses are examined and the results are compared with the previous ones. Finally, the method of optimization are practically tested to the minimizing these losses and the procedures and the new strategy assuring lower environment losses of the considered critical infrastructure accidents are proposed.*

Keywords: maritime transport, environment degradation, cost of losses, climate-weather change impact, optimization

Streszczenie: *Probabilistyczny model konsekwencji wypadków infrastruktury krytycznej łączący trzy modele: procesu zdarzeń inicjujących, procesu zagrożeń środowiska oraz procesu degradacji środowiska został zaadaptowany do morskiej infrastruktury krytycznej. Model zastosowano do identyfikacji i prognozowania konsekwencji uwolnienia substancji chemicznych podczas wypadków morskiej infrastruktury krytycznej. Model zawiera także analizę kosztów wynikających z uwolnienia tych substancji. Dodatkowa analiza strat uwzględnia wpływ warunków pogodowych na stan eksploatacyjny statku, który uległ wypadkowi. Ponadto przetestowano metodę optymalizacji w celu zmniejszenia tych strat oraz przedstawiono procedury i nowe rozwiązania zapewniające mniejsze straty w środowisku, wynikające z wypadków omawianej infrastruktury krytycznej.*

Słowa kluczowe: transport morski, degradacja środowiska, koszt strat, wpływ zmian klimatyczno-pogodowych, optymalizacja

1. Introduction

The critical infrastructure accident is understood as an event that causes changing the critical infrastructure safety state into the safety state worse than the critical safety state that is dangerous for the critical infrastructure itself, its operating environment and as well has disastrous influence on the human health and activity. Each critical infrastructure accident can generate the initiating events causing dangerous situations in the critical infrastructure operating surroundings. The process of these initiating events can result in this environment threats and lead to the environment dangerous degradations. Thus, the probabilistic general model of critical infrastructure accident consequences includes the superposition of three models of the process of initiating events generated either by the critical infrastructure accident or by its loss of safety critical level, the process of environment threats and the process of environment degradation [2].

2. Research problem and research methodology

The designed general semi-Markov model [7], [15] of critical infrastructure accident consequences is adopted to the maritime transport critical infrastructure understood as a ship network operating at the sea waters [1]. The proposed models, methods and tools are applied to this critical infrastructure accident with chemical release consequences modelling, identification, and prediction.

2.1. Modelling process of initiating events

To model the process of initiating events, we fix the time interval $t \in <0, +\infty)$ as the time of a critical infrastructure operation and we distinguish $n_1, n_1 \in N$ events initiating the dangerous situation for the critical infrastructure operating environment and mark them by $E_1, E_2, \dots, E_{n_1}$. Further, we introduce the set of vectors

$$E = \{e: e = [e_1, e_2, \dots, e_{n_1}], e_i \in \{0, 1\}\}, \quad (1)$$

where

$$e_i = \begin{cases} 1, & \text{if the initiating event } E_i \text{ occurs,} \\ 0, & \text{if the initiating event } E_i \text{ does not occur,} \end{cases} \quad (2)$$

for $i = 1, 2, \dots, n_1$. We call vectors (1) the initiating events state. We may eliminate vectors that cannot occur and we number the remaining states of the set E from $l = 1$ up to ω , $\omega \in N$, where ω is the number of different elements of the set

$$E = \{e^1, e^2, \dots, e^\omega\}, \quad (3)$$

where $e^l = [e_1^l, e_2^l, \dots, e_{n_1}^l]$, $l = 1, 2, \dots, \omega$ and $e_i^l \in \{0, 1\}$, $i = 1, 2, \dots, n_1$. Next, we can define the process of initiating events $E(t)$ on the time interval $t \in (0, +\infty)$ with its discrete states from the set (3).

There are $n_1 = 7$ initiating events E_i generating dangerous situations for the sea environment as follows: E_1 – collision (a ship striking another ship), E_2 – grounding (a ship striking the sea bottom, shore or underwater wreck), E_3 – contact (a ship striking an external object e.g. pier or floating object), E_4 – fire or explosion on board, E_5 – shipping without control or missing of ship, E_6 – capsizing or listing of ship and E_7 – movement of cargo in the ship. Hence, and considering (1)-(2) there are fixed $\omega = 16$ states of initiating events that are given in Section 2.3 in [3]. The identification and prediction of the process of initiating events allow to estimate inter alia a limit value of transient probabilities p^l , $l = 1, 2, \dots, 16$ at particular states of the process of initiating events given by (3) in [2].

2.2. Modelling process of environment threats

To construct the model of the environment threats caused by the process of the initiating events generated by the critical infrastructure loss of required safety critical level, we distinguish the set of n_2 , $n_2 \in N$ kinds of threats as the consequences of initiating events that may cause the environment degradation and denote them by $H_1, H_2, \dots, H_{n_2}$. We also distinguish n_3 , $n_3 \in N$ environment sub-areas $D_1, D_2, \dots, D_{n_3}$ of the considered critical infrastructure operating in the environment area $D = D_1 \cup D_2 \cup \dots \cup D_{n_3}$ that may be degraded by the environment threats H_i , $i = 1, 2, \dots, n_2$. We assume that the operating environment area D can be affected by some of threats H_i , $i = 1, 2, \dots, n_2$ and that a particular environment threat H_i , $i = 1, 2, \dots, n_2$ can be characterised by the parameter f^i , $i = 1, 2, \dots, n_2$. Moreover, we assume that the scale of the threat H_i , $i = 1, 2, \dots, n_2$ influence on area D depends on the range of its parameter value and for particular parameter f^i , $i = 1, 2, \dots, n_2$ we distinguish l^i ranges $f^{i1}, f^{i2}, \dots, f^{il^i}$ of its values. After that, we introduce the set of vectors

$$S = \{s : s = [f^1, f^2, \dots, f^{n_2}]\}, \quad (4)$$

where

$$f^i = \begin{cases} 0, & \text{if a threat } H_i \text{ does not appear in the area } D, \\ f^{ij}, & \text{if a threat } H_i \text{ appears in the area } D \\ & \text{and its parameter is at the range } f^{ij}, j = 1, 2, \dots, l^i, \end{cases}$$

for $i = 1, 2, \dots, n_2$. We call vectors (4) the environment threat state in the area D .

Simultaneously, we proceed for the particular sub-areas D_k , $k = 1, 2, \dots, n_3$. The vector

$$s_{(k)} = [f_{(k)}^1, f_{(k)}^2, \dots, f_{(k)}^{n_2}], \quad k = 1, 2, \dots, n_3, \quad (5)$$

where

$$f_{(k)}^i = \begin{cases} 0, & \text{if a threat } H_i \text{ does not appear in the area } D_k, \\ f_{(k)}^{ij}, & \text{if a threat } H_i \text{ appears in the area } D_k \text{ and its parameter} \\ & \text{is at the range } f_{(k)}^{ij}, j = 1, 2, \dots, l^i, \end{cases} \quad (6)$$

for $i = 1, 2, \dots, n_2$, $k = 1, 2, \dots, n_3$ is called the environment threat state in the sub-area D_k . Further, we number the sub-area environment threat states defined by (5) and (6) and mark them by $s_{(k)}^\nu$ for $\nu = 1, 2, \dots, \nu_k$, $k = 1, 2, \dots, n_3$, and form the set

$$S_{(k)} = \{s_{(k)}^\nu, \quad \nu = 1, 2, \dots, \nu_k\}, \quad k = 1, 2, \dots, n_3, \quad (7)$$

where $s_{(k)}^i \neq s_{(k)}^j$ for $i \neq j$, $i, j \in \{1, 2, \dots, \nu_k\}$. The set (7) is called the set of the environment threat states in the sub-area D_k , $k = 1, 2, \dots, n_3$ while a number ν_k is called the number of the environment threat states of this sub-area. A function $S_{(k)}(t)$, $k = 1, 2, \dots, n_3$, defined on the time interval $t \in <0, +\infty)$ and having values in the environment threat states set (7) is called the process of the environment threats in the sub-area D_k , $k = 1, 2, \dots, n_3$.

Next, to involve the process of environment threats in the sub-area D_k , $k = 1, 2, \dots, n_3$ with the process of initiating events, we introduced the function $S_{(k/l)}(t)$, $k = 1, 2, \dots, n_3$, $l = 1, 2, \dots, 16$, defined on the time interval $t \in <0, +\infty)$ depending on the states e^l , $l = 1, 2, \dots, 16$ of the process of initiating events $E(t)$ and taking its values in the set of the environment threat states $S_{(k)}$, $k = 1, 2, \dots, n_3$. This function is called the conditional process of environment threats in the sub-area D_k ,

$k = 1, 2, \dots, n_3$ while the process of initiating events $E(t)$ is at the state e^l , $l = 1, 2, \dots, 16$.

There are distinguished $n_3 = 5$ sub-areas that may be degraded by the environment threats as follows: D_1 – air, D_2 – water surface, D_3 – water column, D_4 – sea floor and D_5 – coast (shoreline). Based on the analysis of chemical substances properties, $n_2 = 6$ possible environment threats caused by released substances within the neighbourhood area of the ship accident area are distinguished. There are as follows: H_1 – explosion of the chemical substance in the accident area, H_2 – fire of the chemical substance in the accident area, H_3 – toxic chemical substance presence in the accident area, H_4 – corrosive chemical substance presence in the accident area, H_5 – bioaccumulative substance presence in the accident area and H_6 – other dangerous chemical substances presence in the accident area. Each environment threat is characterised by one parameter as follows: f^1 – explosiveness range of the substance causing the explosion, f^2 – flashpoint of the substance causing the fire, f^3 – toxicity of the chemical substance, f^4 – time of corrosive substance causing the skin necrosis, f^5 – ability to bioaccumulation in living organisms and f^6 – ability to cause other threats. These parameters are expressed in the rising from 0 scale (l^i ranges). Hence, and considering (5)-(6) there are fixed $\nu_1 = 35$, $\nu_2 = 33$, $\nu_3 = 29$, $\nu_4 = 29$, $\nu_5 = 29$ states of environment threats for particular sub-areas that are given in Section 3.3 in [3].

The identification and prediction of the process of environment threats allow to estimate inter alia:

- approximate limit value of transient probabilities $p_{(k/l)}^i$, $i = 1, 2, \dots, \nu_k$, $k = 1, 2, \dots, 5$, $\nu_1 = 35$, $\nu_2 = 33$, $\nu_3 = 29$, $\nu_4 = 29$, $\nu_5 = 29$, $l = 1, 2, \dots, 16$ at particular states of the process of environment threats in the sub-area D_k while the process of initiating events is in the state e^l , given by (8) in [2],
- limit forms of total probabilities $p_{(k)}^i$, $i = 1, 2, \dots, \nu_k$, $k = 1, 2, \dots, 5$, $\nu_1 = 35$, $\nu_2 = 33$, $\nu_3 = 29$, $\nu_4 = 29$, $\nu_5 = 29$ of the joint process of environment threats and the process of initiating events [2]

$$p_{(k)}^i = \sum_{l=1}^{16} p^l \cdot p_{(k/l)}^i, \quad (8)$$

for $i = 1, 2, \dots, \nu_k$, $k = 1, 2, \dots, 5$, $\nu_1 = 35$, $\nu_2 = 33$, $\nu_3 = 29$, $\nu_4 = 29$, $\nu_5 = 29$.

2.3. Modelling process of environment degradation

The particular states of the process of the environment threats $S_{(k)}(t)$ in the sub-area D_k , $k = 1, 2, \dots, 5$ may lead to dangerous effects degrading the environment at

this sub-area. Thus, we assume that there are m_k different dangerous degradation effects for the environment sub-area D_k , $k = 1, 2, \dots, 5$ and we mark them by $R_{(k)}^1, R_{(k)}^2, \dots, R_{(k)}^{m_k}$. This way the set $R_{(k)} = \{R_{(k)}^1, R_{(k)}^2, \dots, R_{(k)}^{m_k}\}$, $k = 1, 2, \dots, 5$ is the set of degradation effects for the environment in the sub-area D_k . These degradation effects may attain different levels. Namely, the degradation effect $R_{(k)}^m$, $m = 1, 2, \dots, m_k$, $k = 1, 2, \dots, 5$ may reach $\nu_{(k)}^m$ levels $R_{(k)}^{m1}, R_{(k)}^{m2}, \dots, R_{(k)}^{m\nu_{(k)}^m}$, $m = 1, 2, \dots, m_k$, $k = 1, 2, \dots, 5$ that are called the states of this degradation effect. The set

$$R_{(k)}^m = \{R_{(k)}^{m1}, R_{(k)}^{m2}, \dots, R_{(k)}^{m\nu_{(k)}^m}\}, \quad (9)$$

for $m = 1, 2, \dots, m_k$, $k = 1, 2, \dots, 5$ is called the set of states of the degradation effect $R_{(k)}^m$, $m = 1, 2, \dots, m_k$, $k = 1, 2, \dots, 5$ for the environment in the sub-area D_k , $k = 1, 2, \dots, 5$.

Under the above assumptions, we can introduce the environment sub-area degradation process as a vector

$$R_{(k)}(t) = [R_{(k)}^1(t), R_{(k)}^2(t), \dots, R_{(k)}^{m_k}(t)], \quad (10)$$

where $R_{(k)}^m(t)$, $t \in <0, +\infty)$, $m = 1, 2, \dots, m_k$, $k = 1, 2, \dots, 5$ are the processes of degradation effects for the environment in the sub-area D_k , $k = 1, 2, \dots, 5$ defined on the time interval $t \in <0, +\infty)$ and having their values in the degradation effect state sets (9).

The vector

$$r_{(k)}^m = [d_{(k)}^1, d_{(k)}^2, \dots, d_{(k)}^{m_k}], \quad k = 1, 2, \dots, 5, \quad (11)$$

where

$$d_{(k)}^m = \begin{cases} 0, & \text{if a degradation effect } R_{(k)}^m \text{ does not appear} \\ & \text{in the sub-area } D_k, \\ R_{(k)}^{mj}, & \text{if a degradation effect } R_{(k)}^m \text{ appears in the sub-area } D_k \\ & \text{and its level is equaled to } R_{(k)}^{mj}, j = 1, 2, \dots, \nu_{(k)}^m, \end{cases} \quad (12)$$

for $m = 1, 2, \dots, m_k$, $k = 1, 2, \dots, 5$ is called the degradation state in the sub-area D_k , $k = 1, 2, \dots, 5$. Further, we number the sub-area degradation states defined by (11)-(12), and mark them by $r_{(k)}^\ell$ for $\ell = 1, 2, \dots, \ell_k$, $k = 1, 2, \dots, 5$, and form the set of degradation states

$$R_{(k)} = \{r_{(k)}^\ell, \ell = 1, 2, \dots, \ell_k\}, k = 1, 2, \dots, 5 \quad (13)$$

where $r_{(k)}^i \neq r_{(k)}^j$ for $i \neq j$, $i, j \in \{1, 2, \dots, \ell_k\}$. The set (13) is called the set of the environment degradation states in the sub-area D_k , $k = 1, 2, \dots, 5$ while a number ℓ_k is called the number of the environment degradation states of this sub-area. A function $R_{(k)}(t)$, $k = 1, 2, \dots, 5$ defined on the time interval $t \in <0, +\infty)$ and having values in the environment degradation states set (13) is called the process of the environment degradation in the sub-area D_k , $k = 1, 2, \dots, 5$.

Next, to involve the process of environment degradation with the process of the environment threats, we define the conditional process of environment degradation $R_{(k/v)}(t)$ while the process of the environment threats $S_{(k)}(t)$ in the sub-area D_k , $k = 1, 2, \dots, 5$ is at the state $s_{(k)}^\nu$, $\nu = 1, 2, \dots, \nu_k$, $k = 1, 2, \dots, 5$, $\nu_1 = 35$, $\nu_2 = 33$, $\nu_3 = 29$, $\nu_4 = 29$, $\nu_5 = 29$ as a vector $R_{(k/v)}(t) = [R_{(k/v)}^1(t), R_{(k/v)}^2(t), \dots, R_{(k/v)}^{m_k}(t)]$, where $R_{(k/v)}^m(t)$, $m = 1, 2, \dots, m_k$, $k = 1, 2, \dots, 5$, $\nu = 1, 2, \dots, \nu_k$, $\nu_1 = 35$, $\nu_2 = 33$, $\nu_3 = 29$, $\nu_4 = 29$, $\nu_5 = 29$ defined on the time interval $t \in <0, +\infty)$ and having values in the degradation effect states set $R_{(k)}^m$, $m = 1, 2, \dots, m_k$, $k = 1, 2, \dots, 5$. The above definition means that the conditional process of environment degradation $R_{(k/v)}(t)$, $t \in <0, +\infty)$ also takes the degradation states from the set $R_{(k)}$ of the unconditional process of environment degradation $R_{(k)}(t)$, $t \in <0, +\infty)$ defined by (10).

There are $m_k = 5$ possible environment degradation effects in the neighbourhood area of the ship accident area. There are as follows: R_1 – the increase of temperature in the accident area, R_2 – the decrease of oxygen concentration, R_3 – the disturbance of the air pH regime, R_4 – the aesthetic nuisance (caused by smells, fume, discoloration etc.) in the accident area and R_5 – pollution in the accident area. Each environment degradation effect may reach 1 of 3 levels. For instance, the air temperature in the accident area can increase the value from 1 of 3 intervals: $(0^\circ\text{C}, 10^\circ\text{C}]$, $(10^\circ\text{C}, 20^\circ\text{C}]$ and $(20^\circ\text{C}, +\infty)$. Similarly, the remaining environment degradation effects for particular sub-areas are expressed in the scale from 1 (slight) up to 3 (extreme). Additionally, 0 means there are no degradation effects. Hence, and considering (11)-(12) there are fixed $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ states of environment degradation for particular sub-areas that are given in Section 4.3 in [3].

The identification and prediction of the process of environment degradation allow to estimate inter alia:

- approximate limit value of transient probabilities $q_{(k/v)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$, $v = 1, 2, \dots, v_k$, $v_1 = 35$, $v_2 = 33$, $v_3 = 29$, $v_4 = 29$, $v_5 = 29$ at particular states of the process of environment degradation in the sub-area D_k while the process of environment threats is in the state $s_{(k)}^\nu$, given by (16) in [2],
- limit forms of total probabilities $q_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ of the joint process of environment degradation, process of environment threats and process of initiating events [2]

$$q_{(k)}^i \cong \sum_{v=1}^{v_k} p_{(k)}^\nu \cdot q_{(k/v)}^i = \sum_{v=1}^{v_k} \left[\sum_{l=1}^{16} p^l \cdot p_{(k/l)}^\nu \right] q_{(k/v)}^i, \quad (14)$$

where $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$, $v_1 = 35$, $v_2 = 33$, $v_3 = 29$, $v_4 = 29$, $v_5 = 29$.

2.4. Modelling critical infrastructure accident losses

The general model of critical infrastructure accident consequences also includes the cost analysis of losses associated with those consequences of chemical releases. 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. The losses can be expressed by the cost of the negative consequences. In the case of negative consequences like people death, the losses can be expressed as the number of loss of life [2]. The accident consequences that can be expressed by cost – K^i are only considered in the paper. In the shipping, there are distinguished $\xi = 7$ following negative consequences of critical infrastructure accident within the sea waters area: K^1 – closure of fishery area, K^2 – closure of beaches, K^3 – closure of hotels, K^4 – closure of port, K^5 – hold up shipping, K^6 – evacuation of people and K^7 – cleanup of accident area. Thus, a single loss $L_{(k)}^i(t)$ for the sub-area D_k is expressed by the total cost of all consequences lasting t in the sub-area D_k [5]

$$L_{(k)}^i(t) \cong \sum_{j=1}^{\xi} [K_{(k)}^i(t)]^{(j)}, \quad t \in <0, +\infty), \quad (15)$$

where $j = 1, 2, \dots, 7$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$. The expected value of the losses $L_{(k)}(t)$ associated with the process of the environment degradation of the sub-area D_k is defined by [5]

$$L_{(k)}(t) \cong \sum_{i=1}^{\ell_k} q_{(k)}^i \cdot L_{(k)}^i(t), \quad t \in <0, +\infty), \quad (16)$$

where $k = 1, 2, \dots, 5$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ and finally, a sum of losses given by (16) expresses total losses $L(t)$ in all sub-areas of the considered critical infrastructure operating environment area that is given in [5]

$$L(t) \cong \sum_{k=1}^5 L_{(k)}(t), \quad t \in <0, +\infty), \quad (17)$$

Further, under the assumption of the stress of weather influence on the ship operation condition, critical infrastructure accident losses are examined and the results are compared with the previous ones. Thus, we consider critical infrastructure accident losses with the climate-weather change process $C(t)$ impact [5], [12]. This process characteristic is the vector $[q_b]_{1 \times w}$ of limit values of transient probabilities $q_b(t) = P(C(t) = c_b)$, $t \in <0, +\infty)$, $b = 1, 2, \dots, w$ of the process $C(t)$ at the particular climate-weather states c_b . There are $w = 6$ climate-weather states c_b , $b = 1, 2, \dots, w$, dependent on the wave height and the wind speed, distinguished for the ship operating area at the Baltic Sea open waters [14]. The environmental losses, impacted by the process $C(t)$ [12], in the considered sub-area D_k , are defined by [5]

$$[L_{(k)}^i(t)]^{(b)} = [\rho_{(k)}^i(t)]^{(b)} \cdot L_{(k)}^i(t), \quad (18)$$

where $t \in <0, +\infty)$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$, $b = 1, 2, \dots, 6$ and are understood as losses without considering climate-weather impact determined by (15) and coefficient, given by (14) in [5], expresses the climate-weather change process impact on these losses.

Moreover, by (15) and (18) the conditional expected value of the losses associated with the process of the environment degradation of the sub-area D_k , impacted by the process $C(t)$ is expressed by [5]

$$[L_{(k)}(t)]^{(b)} \cong \sum_{i=1}^{\ell_k} q_{(k)}^i \cdot [L_{(k)}^i(t)]^{(b)}, \quad (19)$$

where $t \in <0, +\infty)$, $k = 1, 2, \dots, 5$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$, $b = 1, 2, \dots, 6$.

The unconditional approximate expected value of the environmental losses, impacted by the process $C(t)$, associated with the process of the environment degradation of the sub-area D_k , is expressed by [5]

$$\bar{L}_{(k)}(t) \cong \sum_{b=1}^6 q_b \cdot [L_{(k)}(t)]^{(b)}, \quad t \in <0, +\infty), \quad k = 1, 2, \dots, 5. \quad (20)$$

Hence, according to (19), we have

$$\bar{L}_{(k)}(t) \cong \sum_{b=1}^6 \sum_{i=1}^{\ell_k} q_b \cdot q_{(k)}^i \cdot [L_{(k)}^i(t)]^{(b)}, \quad (21)$$

where $k = 1, 2, \dots, 5$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$.

Finally, a sum of losses given by (21) expresses the total losses $\bar{L}(t)$ impacted by the process $C(t)$ in all sub-areas of the considered critical infrastructure operating environment area that is given by [5]

$$\bar{L}(t) \cong \sum_{k=1}^5 \bar{L}_{(k)}(t), \quad t \in <0, +\infty). \quad (22)$$

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-areas D_k , $k = 1, 2, \dots, 5$ resilience to the losses associated with the critical infrastructure accident related to the climate-weather change that is given by [5]

$$RI_{(k)} = L_{(k)}(t) / \bar{L}_{(k)}(t), \quad t \in <0, +\infty), \quad k = 1, 2, \dots, 5, \quad (23)$$

and the indicator of the environment of the entire area D resilience to the total losses associated with the critical infrastructure accident consequences related to the climate-weather change that is given by [5]

$$RI = L(t) / \bar{L}(t), \quad t \in <0, +\infty). \quad (24)$$

Finally, the methods based on the results of the general model and the linear programming are proposed to the critical infrastructures accident losses optimization without and with considering the climate-weather impact. From the

linear equation (16), we can see that the mean value of expected critical infrastructure accident losses $L_{(k)}(t)$, $t \in <0, +\infty)$, associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-area D_k , $k = 1, 2, \dots, 5$ is determined by the limit value of transient probabilities $q_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ of the process of the environment degradation at the state $r_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ and the mean value of the critical infrastructure accident losses $L_{(k)}^i(t)$ associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-area D_k , $k = 1, 2, \dots, 5$ at the state $r_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$. Similarly, from the linear equation (21), we can see that the mean value of expected critical infrastructure accident losses $\bar{L}_{(k)}(t)$, $t \in <0, +\infty)$, associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-area D_k , $k = 1, 2, \dots, 5$, impacted by the process $C(t)$ is determined by the limit value of transient probabilities q_b , $b = 1, 2, \dots, 6$ of the process $C(t)$ at the particular climate-weather state c_b , $b = 1, 2, \dots, 6$, the limit value of transient probabilities $q_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ of the process of the environment degradation at the state $r_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ and by the mean value of the critical infrastructure accident losses $[L_{(k)}^i(t)]^b$ associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-area D_k , $k = 1, 2, \dots, 5$ at the state $r_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ impacted by the process $C(t)$. Therefore, the optimization based on the linear programming [4], [10], [11], [17] of the critical infrastructure accident losses associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-area D_k , $k = 1, 2, \dots, 5$ without and with considering the process $C(t)$ can be proposed. Namely, we may look for the corresponding optimal values $\dot{q}_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ of the limit transient probabilities $q_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ of the process of the environment degradation at the state $r_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ that minimize the mean value of critical infrastructure accident losses $L_{(k)}(t)$ in the sub-area D_k , $k = 1, 2, \dots, 5$. Similarly, we may look for the corresponding optimal values $q_b \dot{q}_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$, $b = 1, 2, \dots, 6$ of the limit transient probabilities $q_b q_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$,

$\ell_5 = 23, b = 1, 2, \dots, 6$ of the process of the environment degradation at the state $r_{(k)}^i$, $k = 1, 2, \dots, 5, i = 1, 2, \dots, \ell_k, \ell_1 = 30, \ell_2 = 28, \ell_3 = 28, \ell_4 = 31, \ell_5 = 23$ that minimize the mean value of critical infrastructure accident losses $\bar{L}_{(k)}(t)$ impacted by the process $C(t)$ in the sub-area $D_k, k = 1, 2, \dots, 5$. Namely, we can obtain the optimal solution, using the procedure given in [4] to minimize the objective functions given by (16) and (21) respectively.

3. Results

The constructed general model of critical infrastructure accident consequences is applied to the examination of the critical infrastructure accident consequences caused by the ship operating at the Baltic Sea open waters [1]. Nevertheless, there is lack of sufficient statistical data of ship accidents at the Baltic Sea. Thus, based on wider statistical data (coming from 1630 accidents happened within the world sea waters) and assuming that similar accidents can happened within the Baltic Sea area, the general model is applied to this area. The expected values of the total environment losses without and with considering the climate-weather impact, for the fixed time interval, are determined and compared each other.

Based on data coming from those 1630 accidents, we calculate the unconditional approximate limit transient probabilities $q_{(i)}^i, i = 1, 2, \dots, \ell_k, \ell_1 = 30, \ell_2 = 28, \ell_3 = 28, \ell_4 = 31, \ell_5 = 23$ at the particular states of the process of environment degradation, for the particular sub-areas $D_k, k = 1, 2, \dots, 5$. Namely, applying (14), we obtained the following results (the limit transient probabilities that are not equal to 0 are presented only):

$$\begin{aligned} q_{(1)}^1 &= 0.999758661877160, q_{(1)}^2 = 0.000000368024153, q_{(1)}^6 = 0.000234503153208, \\ q_{(1)}^8 &= 0.000000001135173, q_{(1)}^{10} = 0.000000003973106, q_{(1)}^{11} = 0.000000840669180, \\ q_{(1)}^{13} &= 0.000000001467634, q_{(1)}^{14} = 0.000000000146763, q_{(1)}^{15} = 0.000000002935267, \\ q_{(1)}^{17} &= 0.000000000557289, q_{(1)}^{18} = 0.000000000557289, q_{(1)}^{19} = 0.000000003343732, \\ q_{(1)}^{20} &= 0.000000009922697, q_{(1)}^{21} = 0.000000997227226, q_{(1)}^{22} = 0.000000058584258, \\ q_{(1)}^{23} &= 0.000000000118657, q_{(1)}^{24} = 0.000001349189777, q_{(1)}^{25} = 0.000000058263165, \\ q_{(1)}^{26} &= 0.000000000711942, q_{(1)}^{27} = 0.000002962351467, q_{(1)}^{28} = 0.000000146460645, \\ q_{(1)}^{29} &= 0.000000009776737, q_{(1)}^{30} = 0.000000019553475, q_{(2)}^1 = 0.999749861320829, \\ q_{(2)}^2 &= 0.000009984221534, q_{(2)}^5 = 0.000002264763052, q_{(2)}^6 = 0.000171309578824, \\ q_{(2)}^9 &= 0.000018475286439, q_{(2)}^{11} = 0.000013761858129, q_{(2)}^{12} = 0.000013550968354, \\ q_{(2)}^{13} &= 0.000000003353979, q_{(2)}^{14} = 0.000000001547990, q_{(2)}^{15} = 0.000000287361526, \end{aligned}$$

$$\begin{aligned}
 q_{(2)}^{16} &= 0.000010543199308, q_{(2)}^{18} = 0.000000001289992, q_{(2)}^{20} = 0.000000402306137, \\
 q_{(2)}^{21} &= 0.000007520323982, q_{(2)}^{22} = 0.000000057472305, q_{(2)}^{23} = 0.000000057472305, \\
 q_{(2)}^{25} &= 0.000001253387330, q_{(2)}^{27} = 0.000000664287985, q_{(3)}^1 = 0.999751944191735, \\
 q_{(3)}^2 &= 0.000016989451252, q_{(3)}^6 = 0.000146779291559, q_{(3)}^9 = 0.000042195540139, \\
 q_{(3)}^{11} &= 0.000008832641765, q_{(3)}^{12} = 0.000013146320356, q_{(3)}^{13} = 0.000000003835076, \\
 q_{(3)}^{14} &= 0.000000001770035, q_{(3)}^{15} = 0.000000492036938, q_{(3)}^{16} = 0.000009881825265, \\
 q_{(3)}^{18} &= 0.000000001475029, q_{(3)}^{20} = 0.000000688851714, q_{(3)}^{21} = 0.000007048574664, \\
 q_{(3)}^{22} &= 0.000000098407388, q_{(3)}^{23} = 0.000000098407388, q_{(3)}^{25} = 0.000001174762444, \\
 q_{(3)}^{27} &= 0.000000622617253, q_{(4)}^1 = 0.999756082711471, q_{(4)}^2 = 0.000000191913748, \\
 q_{(4)}^6 &= 0.000149222927982, q_{(4)}^9 = 0.000032783820854, q_{(4)}^{11} = 0.000008731753325, \\
 q_{(4)}^{12} &= 0.000008158556210, q_{(4)}^{13} = 0.000000004317380, q_{(4)}^{14} = 0.000000001992637, \\
 q_{(4)}^{16} &= 0.000006628826921, q_{(4)}^{18} = 0.000000001660531, q_{(4)}^{21} = 0.000004728254167, \\
 q_{(4)}^{24} &= 0.000000753977576, q_{(4)}^{25} = 0.000008313641854, q_{(4)}^{26} = 0.000023050878822, \\
 q_{(4)}^{28} &= 0.000000927108660, q_{(4)}^{30} = 0.000000417657862, q_{(5)}^1 = 0.999751426543813, \\
 q_{(5)}^5 &= 0.000003933082185, q_{(5)}^6 = 0.000084474766319, q_{(5)}^9 = 0.000046093518504, \\
 q_{(5)}^{11} &= 0.000114072089179.
 \end{aligned} \tag{25}$$

According to (15) and the information coming from experts, we determine the losses $L_{(k)}^i(t)$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ for the particular sub-areas D_k , $k = 1, 2, \dots, 5$ during the time $t = 1$ hour, expressed by the approximate costs of accident consequences associated with the particular environment degradation state $r_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ that amount (in PLN):

$$\begin{aligned}
 L_{(1)}^1(1) &= 0, L_{(1)}^2(1) = 5000, L_{(1)}^6(1) = 5000, L_{(1)}^8(1) = 6500, L_{(1)}^{10}(1) = 7500, \\
 L_{(1)}^{11}(1) &= 7000, L_{(1)}^{13}(1) = 10000, L_{(1)}^{14}(1) = 12000, L_{(1)}^{15}(1) = 12500, L_{(1)}^{17}(1) = 2000, \\
 L_{(1)}^{18}(1) &= 2500, L_{(1)}^{19}(1) = 3000, L_{(1)}^{20}(1) = 2000, L_{(1)}^{21}(1) = 2000, L_{(1)}^{22}(1) = 8000, \\
 L_{(1)}^{23}(1) &= 3000, L_{(1)}^{24}(1) = 4000, L_{(1)}^{25}(1) = 10000, L_{(1)}^{26}(1) = 3500, L_{(1)}^{27}(1) = 7000, \\
 L_{(1)}^{28}(1) &= 11000, L_{(1)}^{29}(1) = 2500, L_{(1)}^{30}(1) = 4000, L_{(2)}^1(1) = 0, L_{(2)}^2(1) = 7000, \\
 L_{(2)}^5(1) &= 5000, L_{(2)}^6(1) = 10000, L_{(2)}^9(1) = 8000, L_{(2)}^{11}(1) = 12000, L_{(2)}^{12}(1) = 15000, \\
 L_{(2)}^{13}(1) &= 15000, L_{(2)}^{14}(1) = 17000, L_{(2)}^{15}(1) = 18000, L_{(2)}^{16}(1) = 20000, L_{(2)}^{18}(1) = 22000, \\
 L_{(2)}^{20}(1) &= 24000, L_{(2)}^{21}(1) = 25000, L_{(2)}^{22}(1) = 25000, L_{(2)}^{23}(1) = 26000, L_{(2)}^{25}(1) = 27000, \\
 L_{(2)}^{27}(1) &= 30000, L_{(3)}^1(1) = 0, L_{(3)}^2(1) = 13000, L_{(3)}^6(1) = 15000, L_{(3)}^9(1) = 18000, \\
 L_{(3)}^{11}(1) &= 20000, L_{(3)}^{12}(1) = 20000, L_{(3)}^{13}(1) = 20000, L_{(3)}^{14}(1) = 23000, L_{(3)}^{15}(1) = 22000, \\
 L_{(3)}^{16}(1) &= 25000, L_{(3)}^{18}(1) = 30000, L_{(3)}^{20}(1) = 28000, L_{(3)}^{21}(1) = 30000, L_{(3)}^{22}(1) = 28000,
 \end{aligned}$$

$$\begin{aligned}
 L_{(3)}^{23}(1) &= 30000, L_{(3)}^{25}(1) = 30000, L_{(3)}^{27}(1) = 30000, L_{(4)}^1(1) = 0, L_{(4)}^2(1) = 12000, \\
 L_{(4)}^6(1) &= 13000, L_{(4)}^9(1) = 15000, L_{(4)}^{11}(1) = 18000, L_{(4)}^{12}(1) = 15000, L_{(4)}^{13}(1) = 15000, \\
 L_{(4)}^{14}(1) &= 17000, L_{(4)}^{16}(1) = 25000, L_{(4)}^{18}(1) = 28000, L_{(4)}^{21}(1) = 30000, L_{(4)}^{24}(1) = 25000, \\
 L_{(4)}^{25}(1) &= 28000, L_{(4)}^{26}(1) = 30000, L_{(4)}^{28}(1) = 30000, L_{(4)}^{30}(1) = 30000, L_{(5)}^1(1) = 0, \\
 L_{(5)}^5(1) &= 0, L_{(5)}^6(1) = 0, L_{(5)}^9(1) = 0, L_{(5)}^{11}(1) = 0.
 \end{aligned} \tag{26}$$

Hence, after applying (16) and considering (25), the losses $L_{(k)}(t)$ during the time $t = 1$ hour, associated with the process of the environment degradation $R_{(k)}(t)$ in the particular sub-areas D_k , $k = 1, 2, \dots, 5$ of the Baltic Sea open waters amount (in PLN):

$$L_{(1)}(1) \cong 1.211, L_{(2)}(1) \cong 2.781, L_{(3)}(1) \cong 4.170, L_{(4)}(1) \cong 4.005, L_{(5)}(1) = 0. \tag{27}$$

Considering the above results, after applying (17), the total expected value of losses $L(t)$ during the time $t = 1$ hour, associated with the process of the environment degradation $R(t)$ in the entire area D of the Baltic Sea open waters, amounts (in PLN):

$$L(1) = 12.167. \tag{28}$$

To analyse the climate-weather impact on the losses, we suppose that there are $w = 6$ climate-weather states c_b , $b = 1, 2, \dots, 6$ dependent on the wave height and the wind speed, distinguished for the ship operating area at the Baltic Sea open waters [6], [14]. According to the information coming from experts, the coefficients $[\rho_{(k)}^i]^{(b)}$, $b = 1, 2, \dots, 6$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ of the climate-weather impact on losses at the climate-weather change process states c_b , $b = 1, 2, \dots, 6$ at the Baltic Sea open waters are as follows:

$$\begin{aligned}
 [\rho_{(1)}^i]^{(b)} &= 1.0, \text{ for } b = 1, 2, 3, i = 1, 2, \dots, 30, \\
 [\rho_{(1)}^i]^{(b)} &= 2.0, \text{ for } b = 4, 5, 6, i = 1, 2, \dots, 30, [\rho_{(2)}^i]^{(b)} = 1.0, \text{ for } b = 1, i = 1, 2, \dots, 28, \\
 [\rho_{(2)}^i]^{(b)} &= 2.0, \text{ for } b = 2, i = 1, 2, \dots, 28, [\rho_{(2)}^i]^{(b)} = 2.5, \text{ for } b = 3, 5, i = 1, 2, \dots, 28, \\
 [\rho_{(2)}^i]^{(b)} &= 1.8, \text{ for } b = 4, i = 1, 2, \dots, 28, [\rho_{(2)}^i]^{(b)} = 3.0, \text{ for } b = 6, i = 1, 2, \dots, 28, \\
 [\rho_{(3)}^i]^{(b)} &= 1.0, \text{ for } b = 1, 4, i = 1, 2, \dots, 28, [\rho_{(3)}^i]^{(b)} = 2.0, \text{ for } b = 2, 5, i = 1, 2, \dots, 28, \\
 [\rho_{(3)}^i]^{(b)} &= 3.0, \text{ for } b = 3, 6, i = 1, 2, \dots, 28, \\
 [\rho_{(4)}^i]^{(b)} &= 1.0, \text{ for } b = 1, 2, \dots, 6, i = 1, 2, \dots, 31, \\
 [\rho_{(5)}^i]^{(b)} &= 1.0, \text{ for } b = 1, 2, \dots, 6, i = 1, 2, \dots, 23.
 \end{aligned} \tag{29}$$

Considering (26) and (29), after applying (18)-(19), we calculate the conditional approximate expected value of the losses $[L_{(k)}(t)]^{(b)}$, $b = 1, 2, \dots, 6$, $k = 1, 2, \dots, 5$ during the time $t = 1$ hour, associated with the process of the environment degradation $R_{(k)}(t)$ in the sub-area D_k , $k = 1, 2, \dots, 5$ of the Baltic Sea open waters while the process $C(t)$ is at the climate-weather state c_b , $b = 1, 2, \dots, 6$. The results are as follows (in PLN):

$$\begin{aligned} [L_{(1)}(1)]^{(b)} &\cong 1.211 \text{ for } b = 1, 2, 3, [L_{(1)}(1)]^{(b)} \cong 2.422 \text{ for } b = 4, 5, 6; \\ [L_{(2)}(1)]^{(b)} &\cong 2.781 \text{ for } b = 1, [L_{(2)}(1)]^{(b)} \cong 5.562 \text{ for } b = 2, \\ [L_{(2)}(1)]^{(b)} &\cong 6.953 \text{ for } b = 3, 5, [L_{(2)}(1)]^{(b)} \cong 5.006 \text{ for } b = 4, \\ [L_{(2)}(1)]^{(b)} &\cong 8.343 \text{ for } b = 6; [L_{(3)}(1)]^{(b)} \cong 4.170 \text{ for } b = 1, 4, \\ [L_{(3)}(1)]^{(b)} &\cong 8.340 \text{ for } b = 2, 5, [L_{(3)}(1)]^{(b)} \cong 12.510 \text{ for } b = 3, 6; \\ [L_{(4)}(1)]^{(b)} &\cong 4.005 \text{ for } b = 1, 2, \dots, 6; [L_{(5)}(1)]^{(b)} \cong 0 \text{ for } b = 1, 2, \dots, 6. \end{aligned} \quad (30)$$

Further, taking into account the approximate limit values of transient probabilities q_b , $b = 1, 2, \dots, 6$ of the process $C(t)$ at the climate-weather states c_b , $b = 1, 2, \dots, 6$ for the Baltic Sea open sea waters [6]

$$q_1 = 0.834, q_2 = 0.149, q_3 = 0, q_4 = 0, q_5 = 0.015, q_6 = 0.002, \quad (31)$$

and considering (30), and applying (20), we calculate the unconditional approximate expected value of the environmental losses $\bar{L}_{(k)}(t)$, during the time $t = 1$ hour, associated with the process of the environment degradation $R_{(k)}(t)$ in the sub-area D_k , $k = 1, 2, \dots, 5$ while the process $C(t)$ is at the climate-weather state c_b , $b = 1, 2, \dots, 6$ that for the Baltic Sea open waters are (in PLN):

$$\bar{L}_{(1)}(1) \cong 1.232, \bar{L}_{(2)}(1) \cong 3.269, \bar{L}_{(3)}(1) \cong 4.871, \bar{L}_{(4)}(1) \cong 4.005, \bar{L}_{(5)}(1) \cong 0. \quad (32)$$

Hence, applying (22), the total expected value of the losses $\bar{L}(t)$ 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 the entire area D of the Baltic Sea open waters amounts (in PLN):

$$\bar{L}(1) = 13.377. \quad (33)$$

Thus, considering (27), (32) and according to (23), the indicators $RI_{(k)}$ of the environment in the sub-areas D_k , $k = 1, 2, \dots, 5$ resilience to the losses associated with the critical infrastructure accident at the Baltic Sea open waters, related to the climate-weather change impact are:

$$RI_{(1)} = 0.983, RI_{(2)} = 0.851, RI_{(3)} = 0.856, RI_{(4)} = 1,$$

$$RI_{(5)} - \text{n/a as } L_{(5)}(1) = 0 \text{ and } \bar{L}_{(5)}(1) = 0, \quad (34)$$

and considering (28), (33) and according to (24), the indicator RI of the environment of the entire area D resilience to the losses associated with the critical infrastructure accident at the Baltic Sea open waters, related to the climate-weather change impact is:

$$RI = 0.910. \quad (35)$$

Moreover, the method of optimization are practically tested to the minimizing losses. The optimization problem is formulated as a linear programming model with the objective function of the form (16) and (21) respectively, where $L_{(k)}^i(1)$, $L_{(k)}^i(1) \geq 0$, $k = 1, 2, \dots, 5$ are given by (26) and $[L_{(k)}^i(t)]^{(b)}$, $[L_{(k)}^i(t)]^{(b)} \geq 0$, $k = 1, 2, \dots, 5$ are given by (26) with considering (29). Next, using the procedure given in [4] we can find the optimal values $\dot{q}_{(k)}^i$, of the limit transient probabilities $q_{(k)}^i$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ and the optimal values $q_b \dot{q}_{(k)}^i$, of the transient probabilities $q_b q_{(k)}^i$, $b = 1, 2, \dots, 6$, $k = 1, 2, \dots, 5$, $i = 1, 2, \dots, \ell_k$, $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ that minimize the objective functions (16) and (21) respectively. Hence, the optimal value of the losses $\dot{L}_{(k)}(t)$ during the time $t = 1$ hour, associated with the process of the environment degradation $R_{(k)}(t)$ in the sub-areas D_k , $k = 1, 2, 3, 4$ of the Baltic Sea open waters are (in PLN):

$$\dot{L}_{(1)}(1) \cong 1.007, \dot{L}_{(2)}(1) \cong 1.592, \dot{L}_{(3)}(1) \cong 2.859, \dot{L}_{(4)}(1) \cong 2.811, \quad (36)$$

and the optimal value of the total losses $\dot{L}(t)$ during the time $t = 1$ hour, associated with the process of the environment degradation $R(t)$ in the entire area D of the Baltic Sea open waters is (in PLN):

$$\dot{L}(1) \cong 8.269. \quad (37)$$

The optimal value of the losses $\dot{\bar{L}}_{(k)}(t)$ during the time $t = 1$ hour, associated with the process of the environment degradation $R_{(k)}(t)$ of the sub-areas D_k , $k = 1, 2, 3, 4$ (in PLN) of the Baltic Sea open waters, impacted by the climate-weather change are:

$$\dot{\bar{L}}_{(1)}(1) \cong 1.009, \dot{\bar{L}}_{(2)}(1) \cong 1.668, \dot{\bar{L}}_{(3)}(1) \cong 2.984, \dot{\bar{L}}_{(4)}(1) \cong 2.811, \quad (38)$$

and the optimal value of the total losses $\dot{\bar{L}}(t)$ during the time $t = 1$ hour, associated with the process of the environment degradation $R(t)$ of the entire area D of the Baltic Sea open waters, impacted by the climate-weather change (in PLN) is:

$$\dot{\bar{L}}(1) \cong 8.472. \quad (39)$$

Thus, the indicators $R\dot{I}_{(k)}$ of the environment in the sub-area D_k , $k = 1, 2, 3, 4$ resilience to the losses associated with the critical infrastructure accident related to the climate-weather change, after the optimization, amount:

$$R\dot{I}_{(1)} = 0.998, R\dot{I}_{(2)} = 0.954, R\dot{I}_{(3)} = 0.958, R\dot{I}_{(4)} = 1; \quad (40)$$

and the indicator $R\dot{I}$ of the environment in the entire area D resilience to the total losses associated with the critical infrastructure accident related to the climate-weather change, after the optimization, amounts:

$$R\dot{I} = 0.976. \quad (41)$$

4. Conclusions

The comparison of values of losses associated with the shipping critical infrastructure accident without and with considering the climate-weather change impact and values of resilience indicators before and after losses optimization confirm and justify the reasonableness of the critical infrastructure accident losses optimization. It can 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. In practice it includes strategies [8], [9], [13], [16] such as: establish and revision of national laws, regulations, certification and auditing, investigation of accidents and learning from them experience, preparation and revision of emergency action plans and reduction the time of emergency response process.

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 an accident of any other critical infrastructures, industrial installations and systems.

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