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# Modelling maritime critical infrastructure accident consequences with semi-Markov chain method

**Keywords**

shipping, hazardous chemical, initiating event, environmental threat, environmental degradation, cost of losses

**Abstract**

The probabilistic general model of critical infrastructure accident consequences consists of three particular models of semi-Markov processes such as: the process of initiating events generated by a critical infrastructure accident, the process of environmental threats coming from released chemicals that are a result of initiating events and the process of environmental degradation as a result of environmental threats. The general model of critical infrastructure accident consequences and procedure of its application to the maritime transport critical infrastructure understood as a network of ships operating at the sea waters is presented in the research. By using the statistical data coming from sea accidents reports, the general model is applied to the identification and prediction of the environmental degradation associated with ship accidents and chemical releases within the Baltic Sea. Moreover, the proposed model is applied to estimate the environmental losses associated with these accidents and the environmental degradation in the neighborhood area.

## 1. Introduction

The semi-Markov process theory is developed by Lévy [24] and Smith [31]. The semi-Markov process is a stochastic one evolves over time. These processes provide modelling real systems commonly applied in the queening and reliability theory [15]–[16], [18]–[19], [21], [25]–[27]. The semi-Markov processes are also used in the critical infrastructure accident consequences assessment [3]–[11].

The critical infrastructure accident is understood as an event causing changes of the critical infrastructure safety state into the worse one that is dangerous for the critical infrastructure itself, its operating surroundings and has the disastrous influence on the human health and activity [1], [12], [17], [20], [22]-[23], [28], [30]. Each critical infrastructure accident can generate the initiating events causing dangerous situations in the critical infrastructure environment. The process of these initiating events can result in this environment's threats coming from released chemicals during the accident and lead to dangerous degradations of the environment. Thus, the probabilistic general model of critical infrastructure accident consequences includes the superposition of semi-Markov models of three particular processes: initiating events, environmental threats and environmental degradation, particularly described in [6].

This model and the results of its application in maritime transport are presented in the paper. The chapter is organized into 4 parts, this Introduction as Section 1, Sections 2–3 and Conclusions as Section 4. In Section 2, the general model of critical infrastructure accident consequences is introduced and presented, its parameters are defined and its characteristics are determined. Moreover, the function of the environmental losses associated with the process of environmental degradation is defined. In Section 3, the proposed model of critical infrastructure accident consequences is applied to the maritime transport critical infrastructure understood as a ship network operating at the sea waters [2], [10], [12], [29]. The model is examined and its parameters are determined. Additionally, the expected values of the total environmental loss generated by the accident of one of ships of the shipping critical infrastructure network operating at the sea waters, for the fixed time interval, are determined. Finally, the evaluation of results is discussed.

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The possibility of the presented model's wider applications in the field considered in this chapter is suggested in conclusions.

## 2. General model of critical infrastructure accident consequences

### 2.1. Semi-Markov model of initiating events process

To model the process of initiating events [4], [6] generated by a critical infrastructure accident, the time interval $t \in \langle 0, +\infty)$ of the critical infrastructure operation is fixed and $n_1, n_1 \in N$ events initiating a dangerous situation for the critical infrastructure operating environment are distinguish and marked by $E_1, E_2, \dots, E_{n_1}$. Further, the set of vectors

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

where

$$e_i = \begin{cases} 1, \text{ if an initiating event } E_i \text{ occurs,} \\ 0, \text{ if an initiating event } E_i \text{ does not occur,} \end{cases}$$

for $i = 1,2,\dots,n_1$ is introduced.

The vectors (1) are called the initiating events state. The vectors that cannot occur are eliminated and the remaining ones of the set $E$ are numbered from $l = 1$ up to $\omega$, $\omega \in N$, where $\omega$ is the number of different elements of the set

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

where

$$e^l = \left[e_1^l, e_2^l, \dots, e_{n_1}^l\right], l = 1,2,\dots,\omega$$

and

$$e_i^l \in \{0,1\}, i = 1,2,\dots,n_1.$$

Further, the semi-Markov model [15]–[16], [18]–[19], [21], [25]–[27], [31] of the process of initiating events $E(t)$ on the time interval $t \in \langle 0, +\infty)$ with its discrete states from the set (2) is assumed and its random conditional sojourn times at the state $e^l$ while the next transition will be done to the state $e^j$ are marked by $\theta^{lj}$ $l, j = 1,2,\dots,\omega$, $l \neq j$.

The process of initiating events $E(t)$ may be described by the following parameters:

- the number of states $\omega$, $\omega \in N$;
- the initial probabilities:

  $$p^l(0) = P\big(E(0) = e^l\big),\ l = 1,2,\dots,\omega,$$

  staying at the states $e^l$ at the moment $t = 0$;
- the probabilities $p^{lj}$, $l, j = 1,2,\dots,\omega$, $l \neq j$ of transitions between the states $e^l$ and $e^j$;
- the conditional distribution functions

  $$H^{lj}(t) = P\big(\theta^{lj} < t\big), t \in \langle 0, +\infty),$$
  $$l, j = 1,2,\dots,\omega, l \neq j$$

  of the conditional sojourn times $\theta^{lj}$ at the state $e^l$ while its next transition will be done to the state $e^j$.

The statistical identification of unknown parameters of the process of initiating events, i.e. estimating the probabilities of this process staying at particular states at the initial moment, the probabilities of this process transitions between its states and the parameters and forms of distributions fixed for the description of this process conditional sojourn times at their states can be performed according to the way presented in [4], [7].

After the process of initiating events $E(t)$ identification, its main characteristics can be predicted [4]. Namely, the process of initiating events $E(t)$ may be characterized by:

- the unconditional distribution functions

  $$H^l(t) = P\big(\theta^l < t\big), t \in \langle 0, +\infty),$$
  $$l = 1,2,\dots,\omega$$

  of the sojourn times $\theta^l$ at the states $e^l$, $l = 1,2,\dots,\omega$;
- the limit transient probabilities $p^l$ of the probabilities

  $$p^l(t) = P\big(E(t) = e^l\big), t \in \langle 0, +\infty),$$
  $$l = 1,2,\dots,\omega,$$

  staying at the states $e^l$, $l = 1,2,\dots,\omega$;
- the mean values $\hat{M}^l = E\big[\hat{\theta}^l\big] \cong p^l\theta$ of the sojourn total times $\hat{\theta}^l$ in the time interval $\langle 0, \theta\rangle$, $\theta > 0$ at particular states $e^l$, $l = 1,2,\dots,\omega$.

### 2.2. Semi-Markov model of environmental threats process

To model the process of environmental threats [5]–[6] caused by the process of initiating events generated by the critical infrastructure accident, described in Section 1.1, the set of $n_2$, $n_2 \in N$ kinds of threats that may cause the environmental degradation are distinguished and denoted by $H_1, H_2, \dots, H_{n_2}$. There are also distinguished $n_3$,

$n_3 \in N$ environment subareas $D_1, D_2, \ldots, D_{n_3}$ of the critical infrastructure operating within the environment area $D = D_1 \cup D_2 \cup \ldots \cup D_{n_3}$ that may be degraded by the environmental threats $H_i$, $i = 1,2,\ldots,n_2$.

It is assumed that the particular environment threat depends on $n_2$, $n_2 \in N$ factors $f^1, f^2, \ldots, f^{n_2}$ and characterising the environmental threats $H_i$, $i = 1,2,\ldots,n_2$. Simultaneously, it is assumed that the scale of the threat $H_i$, $i = 1,2,\ldots,n_2$ influence on area $D$ depends on the range of its factor value. Namely, the factor $f^i$, $i = 1,2,\ldots,n_2$ may assume $l^i$ ranges $f^{i1}, f^{i2}, \ldots, f^{il^i}$ of its values.

Further, a vector

$$s_{(k)} = [f^1_{(k)}, f^2_{(k)}, \ldots, f^{n_2}_{(k)}], \quad (3)$$

where

$$f^i_{(k)} = \begin{cases} 0, & \text{if a threat } H_i \text{ does not appear in the subarea } D_k, \\ f^{ij}_{(k)}, & \text{if a threat } H_i \text{ appears in the subarea } D_k \text{ and its parameter is in the range } f^{ij}_{(k)} \end{cases}$$

for $i,j = 1,2,\ldots,n_2$, $k = 1,2,\ldots,n_3$ is introduced and called the state of environment threat in the subarea $D_k$.

The vectors (3) that cannot occur are eliminated and the remaining ones are numbered from $i = 1$ up to $\upsilon_k$, $\upsilon_k \in N$, $k = 1,2,\ldots,n_3$ and the set

$$S_{(k)} = \{s^{\upsilon}_{(k)},\ \upsilon = 1,2,\ldots,\upsilon_k\}, k = 1,2,\ldots,n_3 \quad (4)$$

is formed, where $s^i_{(k)} \neq s^j_{(k)}$, for $i \neq j$, $i,j \in \{1,2,\ldots,\upsilon_k\}$ and a number $\upsilon_k$ is called the number of threat states of the subarea $D_k$, $k = 1,2,\ldots,n_3$.

Under the above assumptions, the process of environmental threats of the subarea $D_k$, $k = 1,2,\ldots,n_3$ is introduced as a function $S_{(k)}(t)$, $k = 1,2,\ldots,n_3$ defined on the time interval $t \in \langle 0,+\infty)$ and having values in the threat states set (4).

After that, the process of environmental threats $S_{(k)}(t)$ in the subarea $D_k$, $k = 1,2,\ldots,n_3$ is involved with the process of initiating events $E(t)$. The function $S_{(k/l)}(t)$, $t \in \langle 0,+\infty)$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$ depending on the states of the process of initiating events $E(t)$ and having values in the environment threat states set (4) is called the conditional process of the environmental threats of the subarea $D_k$, $k = 1,2,\ldots,n_3$ while the process of initiating events $E(t)$ is at the state $e^l$, $l = 1,2,\ldots,\omega$.

Further, the semi-Markov model [15]–[16], [18]–[19], [21], [25]–[27], [31] of the conditional process of the environmental threats $S_{(k/l)}(t)$, $t \in \langle 0,+\infty)$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$ with its discrete states from the set (4) is assumed and its random conditional sojourn times at the state $s^i_{(k/l)}$ while the next transition will be done to the state $s^j_{(k/l)}$ are marked by $\eta^{ij}_{(k/l)}$ $i,j = 1,2,\ldots,\upsilon_k$, $i \neq j$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$.

The conditional process of the environmental threats $S_{(k/l)}(t)$ may be described by the following parameters:

- the number of states $\upsilon_k$, $\upsilon_k \in N$,
- the initial probabilities

  $$p^i_{(k/l)}(0) = P(S_{(k/l)}(0) = s^i_{(k/l)}), \\ i = 1,2,\ldots,\upsilon_k, k = 1,2,\ldots,n_3, \\ l = 1,2,\ldots,\omega$$

  staying at the states $s^i_{(k/l)}$ at the moment $t = 0$,
- the probabilities

  $$p^{ij}_{(k/l)}, i,j = 1,2,\ldots,\upsilon_k, i \neq j, \\ k = 1,2,\ldots,n_3, l = 1,2,\ldots,\omega$$

  of transitions between the states $s^i_{(k/l)}$ and $s^j_{(k/l)}$,
- the conditional distribution functions

  $$H^{ij}_{(k/l)}(t) = P\left(\eta^{ij}_{(k/l)} < t\right),\ t \in \langle 0,+\infty), \\ i,j = 1,2,\ldots,\upsilon_k, i \neq j, k = 1,2,\ldots,n_3, \\ l = 1,2,\ldots,\omega$$

  of the conditional sojourn times $\eta^{ij}_{(k/l)}$ at the state $s^i_{(k/l)}$ while its next transition will be done to the state $s^j_{(k/l)}$.

The statistical identification of unknown parameters of the conditional process of environmental threats i.e. estimating the probabilities of this process staying at particular states at the initial moment, the probabilities of this process transitions between its states and the parameters and forms of distributions fixed for the description of this process conditional sojourn times at their states can be performed in the similar way to that presented in [8].

After the conditional process of environmental threats $S_{(k/l)}(t)$ identification, its main characteristics can be predicted. Namely, the conditional process of environmental threats $S_{(k/l)}(t)$ may be characterized by:

- the conditional distribution functions

$$H^i_{(k/l)}(t) = P\big(\eta^i_{(k/l)} < t\big), t \in \langle 0, +\infty),$$
$$i = 1,2,\ldots,\upsilon_k, k = 1,2,\ldots,n_3,$$
$$l = 1,2,\ldots,\omega,$$

  of the sojourn times $\eta^i_{(k/l)}$ at the states $s^i_{(k/l)}$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$,

- the limit transient probabilities $p^i_{(k/l)}$ of the probabilities

$$p^i_{(k/l)}(t) = P(S_{(k/l)}(t) = s^i_{(k/l)}),$$
$$t \in \langle 0, +\infty), i = 1,2,\ldots,\upsilon_k,$$
$$k = 1,2,\ldots,n_3, l = 1,2,\ldots,\omega,$$

  staying at the states $s^i_{(k/l)}$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$,

- the mean values

$$\hat{M}^i_{(k/l)} = E[\hat{\eta}^i_{(k/l)}] \cong p^i_{(k/l)}\eta$$

  of the sojourn total time $\hat{\eta}^i_{(k/l)}$ in the time interval $\langle 0, \eta\rangle$, $\eta > 0$ at particular states $s^i_{(k/l)}$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$.

Further, the unconditional process of environmental threats $S_{(k)}(t)$ may be characterized by:

- the unconditional distribution functions

$$H^i_{(k)}(t) = P\big(\eta^i_{(k)} < t\big), t \in \langle 0, +\infty),$$
$$i = 1,2,\ldots,\upsilon_k, k = 1,2,\ldots,n_3,$$

  of the sojourn times $\eta^i_{(k)}$ at the states $s^i_{(k)}$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$,

- the limit transient probabilities $p^i_{(k)}$ of the probabilities

$$p^i_{(k)}(t) = \textstyle\sum_{l=1}^{\omega} P\big(E(t) = e^l\big)$$
$$\cdot P\big(S_{(k)}(t) = s^i_{(k)} \big| E(t) = e^l\big)$$
$$= \textstyle\sum_{l=1}^{\omega} p^l(t) \cdot p^i_{(k/l)}(t),$$
$$t \in \langle 0, +\infty), i = 1,2,\ldots,\upsilon_k,$$
$$k = 1,2,\ldots,n_3,$$

  staying at the states $s^i_{(k)}$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$ are

$$p^i_{(k)} = \textstyle\sum_{l=1}^{\omega} p^l \cdot p^i_{(k/l)}, \tag{5}$$

where $p^l$ and $p^i_{(k/l)}$ are defined earlier.

### 2.3. Semi-Markov model of environmental degradation process

The particular states of the process of environmental threats $S_{(k)}(t)$, $k = 1,2,\ldots,n_3$ of the subarea $D_k$, $k = 1,2,\ldots,n_3$ introduced in Section 1.2, may lead to dangerous effects degrading the environment of this subarea [6]. There are $m_k$ different dangerous degradation effects for the environment subarea $D_k$, $k = 1,2,\ldots,n_3$ assumed and marked by $R^1_{(k)}, R^2_{(k)}, \ldots, R^{m_k}_{(k)}$. Thus the set

$$R_{(k)} = \left\{R^1_{(k)}, R^2_{(k)}, \ldots, R^{m_k}_{(k)}\right\}, k = 1,2,\ldots,n_3$$

is the set of degradation effects for the environment in the subarea $D_k$. These degradation effects may attain different levels. Namely, the degradation effect $R^m_{(k)}$, $m = 1,2,\ldots,m_k$, $k = 1,2,\ldots,n_3$ may reach $\nu^m_{(k)}$ levels $R^{m1}_{(k)}, R^{m2}_{(k)}, \ldots, R^{m\nu^m_{(k)}}_{(k)}$, $m = 1,2,\ldots,m_k$, $k = 1,2,\ldots,n_3$ that are called the states of this degradation effect.

Under the above assumptions, the process of degradation effects of the subarea $D_k$, $k = 1,2,\ldots,n_3$ is introduced as a vector

$$R_{(k)}(t) = \left[R^1_{(k)}(t), R^2_{(k)}(t), \ldots, R^{m_k}_{(k)}(t)\right]$$

defined on the time interval $t \in \langle 0, +\infty)$ where $R^m_{(k)}(t)$, $m = 1,2,\ldots,m_k$, $k = 1,2,\ldots,n_3$ are the processes of degradation effects for the environment in the subarea $D_k$, $k = 1,2,\ldots,n_3$ and having their values in the degradation effect state sets $R^m_{(k)}$, $m = 1,2,\ldots,m_k$, $k = 1,2,\ldots,n_3$.

Further, a vector

$$r^m_{(k)} = \left[d^1_{(k)}, d^2_{(k)}, \ldots, d^{m_k}_{(k)}\right], k = 1,2,\ldots,n_3, \tag{6}$$

where

$$d^m_{(k)} = \begin{cases} 0, & \text{if a degradation effect } R^m_{(k)} \text{ does not appear in the subarea } D_k, \\ R^{mj}_{(k)}, & \text{if a degradation effect } R^m_{(k)} \text{ appears in the subarea } D_k \text{ and its level is equal } R^{mj}_{(k)}, j = 1,2,\ldots \nu^m_{(k)}, \end{cases}$$

for $m = 1,2,\ldots,m_k$, $k = 1,2,\ldots,n_3$ is called the degradation state in the subarea $D_k$, $k = 1,2,\ldots,n_3$.

The vectors (6) that cannot occur are eliminated and the remaining ones are numbered from $i = 1$ up to $\ell_k$, $\ell_k \in N$, $k = 1,2,\dots,n_3$ and the set

$$R_{(k)} = \{r_{(k)}^{\ell}, \ell = 1,2,\dots,\ell_k\}, k = 1,2,\dots,n_3 \quad (7)$$

is formed, where $r_{(k)}^{i} \neq r_{(k)}^{j}$, for $i \neq j$, $i,j \in \{1,2,\dots,\ell_k\}$ and a number $\ell_k$ is called the number of the environmental degradation states of the subarea $D_k$, $k = 1,2,\dots,n_3$.

Under the above assumptions, the process of environmental degradation in the subarea $D_k$, $k = 1,2,\dots,n_3$ is introduced as a function $R_{(k)}(t)$, $k = 1,2,\dots,n_3$ defined on the time interval $t \in \langle 0,+\infty)$ and having values in the environmental degradation states set (7).

After that, the process of environmental degradation $R_{(k)}(t)$ in the subarea $D_k$, $k = 1,2,\dots,n_3$ is involved with the process of environmental threats $S_{(k)}(t)$. The function $R_{(k/\upsilon)}(t)$, $t \in \langle 0,+\infty)$, $k = 1,2,\dots,n_3$, $\upsilon = 1,2,\dots,\upsilon_k$ depending on the states of the process of environmental threats $S_{(k)}(t)$ and having values in the environmental degradation states set (7) is called the conditional process of the environmental degradation of the subarea $D_k$, $k = 1,2,\dots,n_3$ while the process of environmental threats $S_{(k)}(t)$ is at the state $s_{(k)}^{\upsilon}$, $\upsilon = 1,2,\dots,\upsilon_k$, $k = 1,2,\dots,n_3$.

Further, the semi-Markov model [15]–[16], [18]–[19], [21], [25]–[27], [31] of the conditional process of environmental degradation $R_{(k/\upsilon)}(t)$, $t \in \langle 0,+\infty)$, $k = 1,2,\dots,n_3$, $\upsilon = 1,2,\dots,\upsilon_k$ with its discrete states from the set (7) is assumed and its random conditional sojourn times at the state $r_{(k/\upsilon)}^{i}$ while the next transition will be done to the state $r_{(k/\upsilon)}^{j}$ are marked by $\zeta_{(k/\upsilon)}^{ij}$, $i,j = 1,2,\dots,\ell_k$, $i \neq j$, $k = 1,2,\dots,n_3$, $\upsilon = 1,2,\dots,\upsilon_k$.

The conditional process of the environmental degradation $R_{(k/\upsilon)}(t)$ may be described by the following parameters:

- the number of states $\ell_k$, $\ell_k \in N$,
- the initial probabilities

  $$q_{(k/\upsilon)}^{i}(0) = P(R_{(k/\upsilon)}(0) = r_{(k/\upsilon)}^{i}),$$
  $$i = 1,2,\dots,\ell_k, k = 1,2,\dots,n_3,$$
  $$\upsilon = 1,2,\dots,\upsilon_k$$

  staying at the states $r_{(k/\upsilon)}^{i}$ at the moment $t = 0$,
- the probabilities

  $$q_{(k/\upsilon)}^{ij}, i,j = 1,2,\dots,\ell_k, i \neq j,$$
  $$k = 1,2,\dots,n_3, \upsilon = 1,2,\dots,\upsilon_k$$

  of transitions between the states $r_{(k/\upsilon)}^{i}$ and $r_{(k/\upsilon)}^{j}$,
- the conditional distribution functions

  $$G_{(k/\upsilon)}^{ij}(t) = P\left(\zeta_{(k/\upsilon)}^{ij} < t\right), t \in \langle 0,+\infty),$$
  $$i,j = 1,2,\dots,\ell_k, i \neq j, k = 1,2,\dots,n_3,$$
  $$\upsilon = 1,2,\dots,\upsilon_k$$

  of the conditional sojourn times $\zeta_{(k/\upsilon)}^{ij}$ at the state $r_{(k/\upsilon)}^{i}$ while its next transition will be done to the state $r_{(k/\upsilon)}^{j}$.

The statistical identification of unknown parameters of the process of environmental degradation, i.e. estimating the probabilities of this process staying at particular states at the initial moment, the probabilities of this process transitions between its states and the parameters and forms of distributions fixed for the description of this process conditional sojourn times at their states can be performed in the similar way to that presented in [9].

After the conditional process of environmental degradation $R_{(k/\upsilon)}(t)$ identification, its main characteristics can be predicted. Namely, the conditional process of environmental degradation $R_{(k/\upsilon)}(t)$ may be characterized by:

- the conditional distribution functions

  $$G_{(k/\upsilon)}^{i}(t) = P(\zeta_{(k/\upsilon)}^{i} < t), t \in \langle 0,+\infty),$$
  $$i = 1,2,\dots,\ell_k, k = 1,2,\dots,n_3,$$
  $$\upsilon = 1,2,\dots,\upsilon_k$$

  of the sojourn times $\zeta_{(k/\upsilon)}^{i}$ at the states $r_{(k/\upsilon)}^{i}$, for $i = 1,2,\dots,\ell_k$, $k = 1,2,\dots,n_3$, $\upsilon = 1,2,\dots,\upsilon_k$,
- the limit transient probabilities $q_{(k/\upsilon)}^{i}$ of the probabilities

  $$q_{(k/\upsilon)}^{i}(t) = P(R_{(k/\upsilon)}(t) = r_{(k/\upsilon)}^{i}),$$
  $$t \in \langle 0,+\infty), \quad i = 1,2,\dots,\ell_k,$$
  $$k = 1,2,\dots,n_3, \upsilon = 1,2,\dots,\upsilon_k$$

  staying at the states $r_{(k/\upsilon)}^{i}$, $i = 1,2,\dots,\ell_k$, $k = 1,2,\dots,n_3$, $\upsilon = 1,2,\dots,\upsilon_k$,
- the mean values

  $$\hat{M}_{(k/\upsilon)}^{i} = E[\hat{\zeta}_{(k/\upsilon)}^{i}] \cong q_{(k/\upsilon)}^{i}\zeta$$

  of the sojourn total time $\hat{\zeta}_{(k/l)}^{i}$ in the time interval $\langle 0,\zeta \rangle$, $\zeta > 0$ at particular states $r^i_{(k/\upsilon)}$, $i = 1,2,\dots,\ell_k$, $k = 1,2,\dots,n_3$, $\upsilon = 1,2,\dots,\upsilon_k$.

Further, the unconditional process of environmental degradation $R_{(k)}(t)$ for the sufficiently large *t*, may be characterized by:

- the unconditional distribution functions

$$G^i_{(k)}(t) = P(\zeta^i_{(k)} < t),\ t \in \langle 0,+\infty),$$
$$i = 1,2,\dots,\ell_k,\ k = 1,2,\dots,n_3$$

  of the sojourn times $\zeta^i_{(k)}$ at the states $r^i_{(k)}$, $i = 1,2,\dots,\ell_k$, $k = 1,2,\dots,n_3$,

- the limit transient probabilities $q^i_{(k)}$ of the probabilities

$$q^i_{(k)}(t) = \sum_{\upsilon=1}^{\upsilon_k} P(S(t) = s^\upsilon_{(k)})$$
$$\cdot P(R_{(k)}(t) = r^i_{(k)} | S(t) = s^\upsilon_{(k)})$$
$$= \sum_{\upsilon=1}^{\upsilon_k} p^\upsilon_{(k)}(t) \cdot q^i_{(k/\upsilon)}(t),$$
$$t \in \langle 0,+\infty),\ i = 1,2,\dots,\ell_k,$$
$$k = 1,2,\dots,n_3,$$

  staying at the states $r^i_{(k)}$, $i = 1,2,\dots,\ell_k$, $k = 1,2,\dots,n_3$ are

$$q^i_{(k)} = \sum_{\upsilon=1}^{\upsilon_k} p^\upsilon_{(k)} \cdot q^i_{(k/\upsilon)}$$
$$= \sum_{\upsilon=1}^{\upsilon_k} \left[\sum_{l=1}^{\omega} p^l \cdot p^\upsilon_{(k/l)}\right] q^i_{(k/\upsilon)}, \qquad (8)$$

  for $= 1,2,\dots,\ell_k$, $k = 1,2,\dots,n_3$, where $p^l$, $p^i_{(k/l)}$ and $q^i_{(k/\upsilon)}$ are defined earlier.

## 2.4. Losses of critical infrastructure accident

The cost analysis of losses associated with the critical infrastructure accident consequences in the accident area and environmental degradation states are also included in the designed general model. These losses can be expressed with the number of victims and fatalities or the cost of the negative consequences in the environment [6]. The second ones are only considered in the paper. Under this assumption, the set of $\xi, \xi \in N$ negative consequences of critical infrastructure accident are distinguished and denoted by $K^1, K^2, \dots, K^\xi$. Next, the cost function of the single consequence lasting $t$ is expressed by

$$\left[K^i_{(k)}(t)\right]^{(j)}, \qquad (9)$$

where $i = 1,2,\dots,\ell_k$, $k = 1,2,\dots,n_3$, $j = 1,2,\dots,\xi$.

Thus, a single loss $L^i_{(k)}(t)$ associated with the environmental degradation state $r^i_{(k)}$ of the process $R_{(k)}(t)$ in the subarea $D_k$ is expressed by the total cost of all consequences (9) lasting *t* in the subarea $D_k$

$$L^i_{(k)}(t) = \sum_{j=1}^{\xi} \left[K^i_{(k)}(t)\right]^{(j)} \qquad (10)$$

where $t \in \langle 0,+\infty)$, $i = 1,2,\dots,\ell_k$, $k = 1,2,\dots,n_3$.

The expected value of the losses $L_{(k)}(t)$ associated with the process of the environmental degradation $R_{(k)}(t)$ in the subarea $D_k$ is defined by

$$L_{(k)}(t) = \sum_{i=1}^{\ell_k} q^i_{(k)} \cdot L^i_{(k)}(t) \qquad (11)$$

where $t \in \langle 0,+\infty)$, $i = 1,2,\dots,\ell_k$, $k = 1,2,\dots,n_3$ and $q^i_{(k)}$ and $L^i_{(k)}(t)$ are given by (8) and (10) respectively. Finally, a sum of losses given by (11) expresses total losses $L(t)$ in all subareas $D_k$ of the considered critical infrastructure operating at the environment area is defined by

$$L(t) = \sum_{k=1}^{n_3} L_{(k)}(t),\ t \in < 0,+\infty). \qquad (12)$$

## 3. Application of general model of critical infrastructure accident consequences to maritime transport critical infrastructure

The probabilistic general model of critical infrastructure accident consequences including three processes: the process of initiating events, the process of environmental threats and the process of environmental degradation is applied to the maritime transport critical infrastructure understood as a ship network operating within the sea waters [2], [10], [12], [29]. Using the statistical data coming from the Centre of documentation, research and experimentation on accidental water pollution [13] and the Global Integrated Shipping Information System [14], containing the free-accessible reports of chemical accidents at sea happened at the Baltic Sea in 2004–2014, the environmental degradation as consequences of sea accidents and chemical releases are identified and predicted. The example of the general model of critical infrastructure accident consequences application regards to the Baltic Sea open waters that may be degraded by the environmental threats coming from chemical releases is presented below. The background parameters of the process of initiating events, the process of environmental threats and the process of environmental degradation are similar to distinguished by maritime authorities such as the International Maritime Organization. These parameters are described in *Tables 1–3*.

*Table 1*. Modelling the maritime transport critical infrastructure accident consequences – modelling the process of initiating events $E(t)$ – background parameters

| Procedure | Result of application |
|---|---|
| i) to fix initiating events $E_i$, $i = 1,2,\dots,7$ | $E_1$ – 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 a board, $E_5$– shipping without control (drifting of ship) or missing of a ship, $E_6$ – capsizing or listing of a ship, $E_7$ – movement of cargo in the a ship |
| ii) to fix or define general parameters of the process $E(t)$:<br>– the number of states $\omega$<br>– the states $e^1, e^2, \dots, e^\omega$, according to (1)–(2) | $\omega = 16$<br>$e^1$ = [0,0,0,0,0,0,0], $e^2$ = [1,0,0,0,0,0,0], $e^3$ = [0,1,0,0,0,0,0], $e^4$ = [0,0,1,0,0,0,0], $e^5$ = [0,0,0,1,0,0,0], $e^6$ = [0,0,0,0,1,0,0], $e^7$ = [0,0,0,0,0,1,0], $e^8$ = [0,0,0,0,0,0,1], $e^9$ = [0,1,0,1,0,0,0], $e^{10}$ = [0,0,0,1,1,0,0], $e^{11}$ = [0,0,0,0,1,1,0], $e^{12}$ = [0,0,0,1,0,0,1], $e^{13}$ = [0,0,0,0,0,1,1], $e^{14}$ = [0,0,0,1,1,1,0], $e^{15}$ = [0,0,0,0,1,1,1], $e^{16}$ = [0,0,0,1,0,1,0] |

*Table 2*. Modelling the maritime transport critical infrastructure accident consequences – modelling the process of environmental threats $S_{(k/l)}(t)$ – background parameters

| Procedure | Result of application |
|---|---|
| i) to fix subareas $D_k$, $k = 1,2,\dots,5$ that may be degraded by the environmental threats (if necessary) | $D_1$ – air, $D_2$ – water surface, $D_3$ – water column, $D_4$ – sea floor, $D_5$– coast (not considered as the example application concerns the open sea waters) |
| ii) to fix environmental threats $H_i$, $i = 1,2,\dots,6$ | $H_1$ – explosion of the chemical substance in the ship accident area, $H_2$ – fire of the chemical substance in the ship accident area, $H_3$ – toxic substance presence in the ship accident area, $H_4$ – corrosive substance presence in the ship accident area, $H_5$ – bioaccumulative substance presence in the ship accident area, $H_6$ – other dangerous chemical substances presence in the ship accident area |
| iii) to fix the parameters $f^i$ and their range $l^i$ to characterize the particular environmental threats $H_i$, $i = 1,2,\dots,6$ | $f^1$ – explosiveness of the chemical substance causing the explosion may reach $l^1 = 6$ ranges, $f^2$ – flashpoint of the chemical substance causing the fire may reach $l^2 = 4$ ranges, $f^3$ – toxicity of the chemical substance may reach $l^3 = 6$ ranges, $f^4$ – time of causing the skin necrosis by the corrosive substance may reach $l^4 = 3$ ranges, $f^5$ – ability of the chemical substance to bioaccumulation in living organisms may reach $l^5 = 5$ ranges, $f^6$ – ability of the chemical substance to cause other threats may reach $l^6 = 1$ range |
| iv) to fix or define general parameters of the process $S_{(k/l)}(t)$<br>– the number of states $\upsilon_k$ of the subarea $D_k$, $k = 1,2,\dots,4$<br>– the states $s^{\upsilon}_{(k)}$, $\upsilon = 1,2,\dots,\upsilon_k$ according to (3)–(4) | $\upsilon_1 = 35, \upsilon_2 = 33, \upsilon_3 = 29, \upsilon_4 = 29$<br>(there are presented only states using for the identification that results are given in *Table 5*):<br>$s^1_{(1)}$ = [0,0,0,0,0,0], $s^6_{(1)}$ = [0,0,1,0,0,0], $s^{27}_{(1)}$ = [0,0,2,0,3,1], $s^{30}_{(1)}$ = [0,0,4,3,0,0],<br>$s^1_{(2)}$ = [0,0,0,0,0,0], $s^{17}_{(2)}$ = [0,0,2,3,0,0], $s^{33}_{(2)}$ = [0,0,2,0,3,1],<br>$s^1_{(3)}$ = [0,0,0,0,0,0], $s^{14}_{(3)}$ = [0,0,2,0,0,0], $s^{24}_{(3)}$ = [0,0,2,0,3,1],<br>$s^1_{(4)}$ = [0,0,0,0,0,0], $s^{14}_{(4)}$ = [0,0,2,3,0,0] |

*Table 3*. Modelling the maritime transport critical infrastructure accident consequences – modelling the process of environmental degradation $R_{(k/\upsilon)}(t)$ – background parameters

| Procedure | Result of application |
|---|---|
| i) to fix dangerous degradation effects $R^m$, $m = 1,2,\ldots,5$ | $R^1$ – the increase of temperature in the accident area, $R^2$– the decrease of oxygen concentration in the accident area, $R^3$– the disturbance of pH regime in the accident area, $R^4$– the aesthetic nuisance (caused by smells, fume, discoloration etc.) in the accident area, $R^5$– the pollution in the accident area |
| ii) to fix the range of degradation effect $\upsilon^m$, $m = 1,2,\ldots,5$ | $\upsilon^m = 3$, $m = 1,2,\ldots,5$ |
| iii) to fix or define general parameters of the process $R_{(k/\upsilon)}(t)$: | |
| – the number of the environmental degradation states $\ell_k$ of the subarea $D_k$, $k = 1,2,\ldots,4$ | $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$ |
| – the states $r_{(k)}^{\ell}$, $\ell = 1,2,\ldots,\ell_k$, according to (6)–(7) | (there are presented only states using for the identification that results are given in *Table 6*):<br>$r_{(1)}^{1}$ = [0,0,0,0,0], $r_{(1)}^{2}$ = [0,0,0,0,1], $r_{(1)}^{6}$ = [0,0,0,1,1],<br>$r_{(1)}^{11}$ = [0,0,1,0,0],<br>$r_{(2)}^{1}$ = [0,0,0,0,0], $r_{(2)}^{6}$ = [0,0,0,1,1], $r_{(2)}^{12}$ = [0,0,1,0,1],<br>$r_{(2)}^{16}$ = [0,0,2,0,2], $r_{(2)}^{21}$ = [0,0,3,0,3], $r_{(2)}^{25}$ = [1,0,3,0,3],<br>$r_{(2)}^{27}$ = [2,0,3,0,3],<br>$r_{(3)}^{1}$ = [0,0,0,0,0], $r_{(3)}^{6}$ = [0,0,0,1,1], $r_{(3)}^{12}$ = [0,0,1,0,1],<br>$r_{(3)}^{16}$ = [0,0,2,0,2], $r_{(3)}^{21}$ = [0,0,3,0,3], $r_{(3)}^{25}$ = [1,0,3,0,3],<br>$r_{(3)}^{27}$ = [2,0,3,0,3],<br>$r_{(4)}^{1}$ = [0,0,0,0,0], $r_{(4)}^{12}$ = [0,0,1,0,1], $r_{(4)}^{16}$ = [0,0,2,0,2],<br>$r_{(4)}^{21}$ = [0,0,3,0,3], $r_{(4)}^{28}$ = [1,0,3,0,3], $r_{(4)}^{30}$ = [2,0,3,0,3] |

Namely, the kinds of initiating events, environmental threats and dangerous degradation effects as well as the states of particular processes are fixed. Next, to identify the unknown parameters of the process of initiating events $E(t)$, the process of environmental threats $S_{(k/l)}(t)$ and the process of environmental degradation $R_{(k/\upsilon)}(t)$, the suitable statistic data coming from their real realizations should be collected. The statistical identification of the processes $E(t)$, $S_{(k/l)}(t)$ and $R_{(k/\upsilon)}(t)$ is particularly described in [7]–[9]. The results of the identification of the process of initiating events, the process of environmental threats and the process of environmental degradation are presented in *Tables 4–6*. Now, the general model is adapted to the prediction of critical infrastructure accident consequences at the Baltic Sea open waters through the determining the characteristics of the process of initiating events $E(t)$, the process of environmental threats $S_{(k/l)}(t)$ and the process of environmental degradation $R_{(k/\upsilon)}(t)$ such as: unconditional mean sojourn times, limit values of transient probabilities staying at their states, and approximate mean values of sojourn total times at particular states for the fixed time. The results of the prediction of the process of initiating events, the process of environmental threats and the process of environmental degradation are presented in *Tables 7–9*. Farther, the unconditional limit transient probabilities $q_{(k)}^{i}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$, and mean values of sojourn total times $\hat{M}_{(k)}^{i} = E\left[\hat{\zeta}_{(k)}^{i}\right]$ for the fixed sufficiently large time of the joined (the superposition) process of initiating events $E(t)$, the process of environmental threats $S_{(k/l)}(t)$ and the process of environmental degradation $R_{(k/\upsilon)}(t)$ may be found. These results are presented in *Table 10*. Next, these results are used to determine the environment losses associated with the chemical releases generated through accidents of ships operating within the Baltic Sea open waters. The cost analysis of these environment losses are presented in *Table 11*.

*Table 4*. Identification of the maritime transport critical infrastructure accident consequences – identification of the process of initiating events $E(t)$

| Procedure | Result of application |
|---|---|
| i) to fix the duration time of the experiment Θ | Θ = 14 years (2004–2014) |
| ii) to collect statistical data necessary to evaluate the unknown basic parameters of the process $E(t)$:<br>– the vector of the initial probabilities $p^l(0)$, $l = 1,2,\dots,16$ at the particular states $e^l$ at the moment $t = 0$<br>– the matrix $[p^{lj}]_{16\mathrm{x}16}$, $l,j = 1,2,\dots,16$, $l \neq j$ of the probabilities of transitions from the state $e^l$ into the state $e^j$ during the experimental time<br>– the matrix of mean values [min] $M^{lj} = E[\theta^{lj}]$, $l,j = 1,2,\dots,16$, $l \neq j$ of the conditional sojourn times $\theta^{lj}$ at the particular states | $[p^l(0)]_{1\mathrm{x}16}$ = [1,0,…,0]<br>(probabilities of transitions that are not equal to 0 are as follows):<br>$p^{12}$ = 0.1731, $p^{13}$ = 0.3558, $p^{14}$ = 0.0481, $p^{15}$ = 0.0961, $p^{16}$ = 0.2308, $p^{17}$ = 0.0865, $p^{18}$ = 0.0096, $p^{21}$ = 0.7500, $p^{23}$ = 0.1000, $p^{26}$ = 0.0500, $p^{27}$ = 0.1000, $p^{31}$ = 1, $p^{41}$ = 0.8333, $p^{47}$ = 0.1667, $p^{51}$ = 0.9000, $p^{5\,10}$ = 0.1000, $p^{61}$ = 0.0400, $p^{62}$ = 0.0800, $p^{63}$ = 0.8400, $p^{64}$ = 0.0400, $p^{71}$ = 0.5000, $p^{73}$ = 0.4167, $p^{7\,13}$ = 0.0833, $p^{81}$ = 1, $p^{10\,1}$ = 1, $p^{13\,1}$ = 1.<br>$M^{12}$ = 10249200, $M^{13}$ =8928571.43, $M^{14}$ = 12614400, $M^{15}$ = 13402800, $M^{16}$ = 8694300, $M^{17}$ = 5869200, $M^{18}$ = 1576800, $M^{21}$ = 1.00, $M^{23}$ = 22.50, $M^{26}$ = 1, $M^{27}$ = 5.50, $M^{31}$ = 1933.68, $M^{41}$ = 1, $M^{47}$ = 1, $M^{51}$ = 163.33, $M^{5\,10}$ = 10, $M^{61}$ = 120, $M^{62}$ = 80, $M^{63}$ = 324.05, $M^{64}$ = 15, $M^{71}$ = 225.83, $M^{73}$ = 21.60, $M^{7\,13}$ = 1, $M^{81}$ = 5, $M^{10\,1}$ = 10, $M^{13\,1}$ = 10 |

*Table 5*. Identification of the maritime transport critical infrastructure accident consequences – identification of the process of environmental threats $S_{(k/l)}(t)$

| Procedure | Result of application |
|---|---|
| i) to fix the duration time of the experiment Θ | Θ = 14 years (2004–2014) |
| ii) to collect statistical data necessary to evaluate the unknown basic parameters of the process $S_{(k/l)}(t)$:<br>– the vectors of the initial probabilities $p^i_{(k/l)}(0)$, $i = 1,2,\dots,\upsilon_k$, $k = 1,2,\dots,4$, $\upsilon_1 = 35, \upsilon_2 = 33,\ \upsilon_3 = 29,$ $\upsilon_4 = 29$, $l = 1,2,\dots,16$ at the particular states $s^i_{(k/l)}$ at the moment $t = 0$<br>– the matrices $[p^{ij}_{(k/l)}]_{\upsilon_k\mathrm{x}\upsilon_k}$, $i,j = 1,2,\dots,\upsilon_k$, $i \neq j$ $k = 1,2,\dots,4,\ \upsilon_1 = 35,$ $\upsilon_2 = 33,\ \upsilon_3 = 29,\ \upsilon_4 = 29,$ $l = 1,2,\dots,16$ of the probabilities of transitions from the state $s^i_{(k/l)}$ into the state $s^j_{(k/l)}$ during the experimental time | $\left[p^i_{(k/l)}(0)\right]_{1\mathrm{x}\upsilon_k}$ = [1,0,…0]<br>(probabilities of transitions that are not equal to 0 are as follows):<br>$p^{1\,27}_{(1/2)} = 1$, $p^{27\,1}_{(1/2)} = 1$, $p^{1\,27}_{(1/3)} = 0.5$, $p^{1\,30}_{(1/3)} = 0.5$, $p^{27\,1}_{(1/3)} = 1$, $p^{30\,1}_{(1/3)} = 1$, $p^{1\,6}_{(1/8)} = 1$, $p^{6\,1}_{(1/8)} = 1$, $p^{1\,33}_{(2/2)} = 1$, $p^{33\,1}_{(2/2)} = 1$, $p^{1\,17}_{(2/3)} = 0.5$, $p^{1\,33}_{(2/3)} = 0.5$, $p^{17\,1}_{(2/3)} = 1$, $p^{33\,1}_{(2/3)} = 1$, $p^{1\,24}_{(3/2)} = 1$, $p^{24\,1}_{(3/2)} = 1$, $p^{1\,14}_{(3/3)} = 0.5$, $p^{1\,24}_{(3/3)} = 0.5$, $p^{14\,1}_{(3/3)} = 1$, $p^{24\,1}_{(3/3)} = 1$, $p^{1\,14}_{(4/3)} = 1$, $p^{14\,1}_{(4/3)} = 1$ |

| | |
|---|---|
| – the matrices of mean values [min] $M_{(k/l)}^{ij} = E[\eta_{(k/l)}^{ij}]$, $i,j = 1,2,\ldots,\upsilon_k, i \neq j$ $k = 1,2,\ldots,4,\ \upsilon_1 = 35,$ $\upsilon_2 = 33,\ \upsilon_3 = 29,\ \upsilon_4 = 29,$ $l = 1,2,\ldots,16$ of the process $S_{(k/l)}$ conditional sojourn times $\eta_{(k/l)}^{ij}$ at the particular states | $M_{(1/2)}^{1\,27} = 1$, $M_{(1/2)}^{27\,1} = 300$, $M_{(1/3)}^{1\,27} = 1$, $M_{(1/3)}^{1\,30} = 1$, $M_{(1/3)}^{27\,1} = 180$, $M_{(1/3)}^{30\,1} = 240$, $M_{(1/8)}^{1\,6} = 1$, $M_{(1/8)}^{6\,1} = 240$, $M_{(2/2)}^{1\,33} = 1$, $M_{(2/2)}^{33\,1} = 1440$, $M_{(2/3)}^{1\,17} = 1$, $M_{(2/3)}^{1\,33} = 1$, $M_{(2/3)}^{17\,1} = 10080$, $M_{(2/3)}^{33\,1} = 1440$, $M_{(3/2)}^{1\,24} = 1$, $M_{(3/2)}^{24\,1} = 1440$, $M_{(3/3)}^{1\,14} = 1$, $M_{(3/3)}^{1\,24} = 1$, $M_{(3/3)}^{14\,1} = 10080$, $M_{(3/3)}^{24\,1} = 1440$, $M_{(4/3)}^{1\,14} = 1$, $M_{(4/3)}^{14\,1} = 10080$ |

*Table 6.* Identification of the maritime transport critical infrastructure accident consequences – identification of the process of environmental degradation $R_{(k/\upsilon)}(t)$

| Procedure | Result of application |
|---|---|
| i) to fix the duration time of the experiment $\Theta$ | $\Theta$ = 14 years (2004–2014) |
| ii) to collect statistical data necessary to evaluate the unknown basic parameters of the process $R_{(k/\upsilon)}(t)$: <br>– the vectors of the initial probabilities $q_{(k/\upsilon)}^{i}(0)$, $i,j = 1,2,\ldots,\ell_k, i \neq j,$ $k = 1,2,\ldots,4,\ \ell_1 = 35,$ $\ell_2 = 33,\ \ell_3 = 29,\ \ell_4 = 29,$ $\upsilon_1 = 35, \upsilon_2 = 33,\ \upsilon_3 = 29,$ $\upsilon_4 = 29$ at the particular states $r_{(k/\upsilon)}^{i}$ at the moment $t = 0$ | $\left[q_{(k/\upsilon)}^{i}(0)\right]_{1\text{x}\ell_k}$ = [1,0,…0], for $k = 1,\ \upsilon = 1,6,27,30,\ \ell_1 = 30,$ and $k = 2,\ \upsilon = 1,17,33,\ \ell_2 = 28,$ and $k = 3,\ \upsilon = 1,14,24,\ \ell_3 = 28,$ and $k = 4,\ \upsilon = 1,14,\ \ell_4 = 31,$ <br>and <br>$\left[q_{(k/\upsilon)}^{i}(0)\right]_{1\text{x}\ell_k}$ = [0,0,…0] for remaining cases |
| – the matrices $[q_{(k/\upsilon)}^{ij}]_{\ell_k\text{x}\ell_k}$, $i,j = 1,2,\ldots,\ell_k, i \neq j,$ $k = 1,2,\ldots,4,\ \ell_1 = 35,$ $\ell_2 = 33,\ \ell_3 = 29,\ \ell_4 = 29,$ $\upsilon_1 = 35, \upsilon_2 = 33,\ \upsilon_3 = 29,$ $\upsilon_4 = 29$ of the probabilities of transitions from the state $r_{(k/\upsilon)}^{i}$ into the state $r_{(k/\upsilon)}^{j}$ during the experimental time | (probabilities of transitions that are not equal to 0 are as follows): $q_{(1/6)}^{1\,2} = 1$, $q_{(1/6)}^{2\,1} = 1$, $q_{(1/27)}^{1\,6} = 1$, $q_{(1/27)}^{6\,1} = 1$, $q_{(1/30)}^{1\,11} = 1$, $q_{(1/30)}^{11\,1} = 1$, $q_{(2/17)}^{1\,27} = 1$, $q_{(2/17)}^{12\,1} = 1$, $q_{(2/17)}^{16\,12} = 1$, $q_{(2/17)}^{21\,16} = 1$, $q_{(2/17)}^{25\,21} = 1$, $q_{(2/17)}^{27\,25} = 1$, $q_{(2/33)}^{1\,6} = 1$, $q_{(2/33)}^{6\,1} = 1$, $q_{(3/14)}^{1\,27} = 1$, $q_{(3/14)}^{12\,1} = 1$, $q_{(3/14)}^{16\,12} = 1$, $q_{(3/14)}^{21\,16} = 1$, $q_{(3/14)}^{25\,21} = 1$, $q_{(3/14)}^{27\,25} = 1$, $q_{(3/24)}^{1\,6} = 1$, $q_{(3/24)}^{6\,1} = 1$, $q_{(4/14)}^{1\,30} = 1$, $q_{(4/14)}^{12\,1} = 1$, $q_{(4/14)}^{16\,12} = 1$, $q_{(4/14)}^{21\,16} = 1$, $q_{(4/14)}^{28\,21} = 1$, $q_{(4/14)}^{30\,28} = 1$ |
| – the matrices of mean values [min] $M_{(k/\upsilon)}^{ij} = E[\zeta_{(k/\upsilon)}^{ij}]$, $i,j = 1,2,\ldots,\ell_k, i \neq j,$ $k = 1,2,\ldots,4,\ \ell_1 = 35,$ $\ell_2 = 33,\ \ell_3 = 29,\ \ell_4 = 29,$ $\upsilon_1 = 35, \upsilon_2 = 33,\ \upsilon_3 = 29,$ $\upsilon_4 = 29$ of the conditional sojourn times $\zeta_{(k/\upsilon)}^{ij}$ at the particular states | $M_{(1/6)}^{1\,2} = 1$, $M_{(1/6)}^{2\,1} = 240$, $M_{(1/27)}^{1\,6} = 1$, $M_{(1/27)}^{6\,1} = 240$, $M_{(1/30)}^{1\,11} = 1$, $M_{(1/30)}^{11\,1} = 240$, $M_{(2/17)}^{1\,27} = 1$, $M_{(2/17)}^{12\,1} = 2880$, $M_{(2/17)}^{16\,12} = 3780$, $M_{(2/17)}^{21\,16} = 2880$, $M_{(2/17)}^{25\,21} = 300$, $M_{(2/17)}^{27\,25} = 240$, $M_{(2/33)}^{1\,6} = 1$, $M_{(2/33)}^{6\,1} = 1440$, $M_{(3/14)}^{1\,27} = 1$, $M_{(3/14)}^{12\,1} = 2880$, $M_{(3/14)}^{16\,12} = 3780$, $M_{(3/14)}^{21\,16} = 2880$, $M_{(3/14)}^{25\,21} = 300$, $M_{(3/14)}^{27\,25} = 240$, $M_{(3/24)}^{1\,6} = 1$, $M_{(3/24)}^{6\,1} = 1440$, $M_{(4/14)}^{1\,30} = 1$, $M_{(4/14)}^{12\,1} = 2880$, $M_{(4/14)}^{16\,12} = 3780$, $M_{(4/14)}^{21\,16} = 2880$, $M_{(4/14)}^{28\,21} = 300$, $M_{(4/14)}^{30\,28} = 240$ |

*Table 7.* Prediction of the maritime transport critical infrastructure accident consequences – prediction of the process of initiating events $E(t)$

| Procedure | Result of application |
|---|---|
| i) to estimate mean values [min] of unconditional sojourn times $E[\theta^l]$, $l = 1,2,\dots,16$ at particular states, according to $M^l = E[\theta^l] = \sum_{j=1}^{16} p^{lj} M^{lj}$ | $M^1 = 9376491.76$, $M^2 = 3.60$, $M^3 = 1933.69$, $M^4 = 1.00$, $M^5 = 148.00$, $M^6 = 284.00$, $M^7 = 122.00$, $M^8 = 5.00$, $M^{10} = 10.00$, $M^{13} = 10.00$ |
| ii) to solve the system of equations $\begin{cases} [\pi^l] = [\pi^l][p^{lj}] \\ \sum_{j=1}^{16} \pi^j = 1 \end{cases}$ $l = 1,2,\dots,16$ | $\pi^1 = 0.42449$, $\pi^2 = 0.08164$, $\pi^3 = 0.26533$, $\pi^4 = 0.02450$, $\pi^5 = 0.04079$, $\pi^6 = 0.10205$, $\pi^7 = 0.04897$, $\pi^8 = 0.00407$, $\pi^{10} = 0.00408$, $\pi^{13} = 0.00408$ |
| iii) to estimate approximate limit values of transient probabilities at the particular states, according to $p^l = \lim_{t\to+\infty} p^l(t) = \frac{\pi^l M^l}{\sum_{j=1}^{16} \pi^j M^j}$ $l = 1,2,\dots,16$ | $p^1 = 0.999860710821154$, $p^2 = 0.000000073830730$, $p^3 = 0.000128885740640$, $p^4 = 0.000000006154570$, $p^5 = 0.000001516516305$, $p^6 = 0.000007280530278$, $p^7 = 0.000001500795773$, $p^8 = 0.000000005112062$, $p^{10} = 0.000000010249244$, $p^{13} = 0.000000010249244$ |
| iv) to estimate the approximate mean values [min] of the sojourn total times $\hat{\theta}^l$ in the time interval e.g. $\theta$=1 month = 43200 minutes at the particular states $e^l$, according to $\hat{M}^l = E[\hat{\theta}^l] \cong p^l \theta$ $l = 1,2,\dots,16$ | $\hat{M}^1 = 43193.98271$, $\hat{M}^2 = 0.00319$, $\hat{M}^3 = 5.56786$, $\hat{M}^4 = 0.00027$, $\hat{M}^5 = 0.06551$, $\hat{M}^6 = 0.31452$, $\hat{M}^7 = 0.06483$, $\hat{M}^8 = 0.00022$, $\hat{M}^{10} = 0.00044$, $\hat{M}^{13} = 0.00044$ |

*Table 8.* Prediction of the maritime transport critical infrastructure accident consequences – prediction of the process of environmental threats $S_{(k/l)}(t)$

| Procedure | Result of application |
|---|---|
| i) to estimate mean values [min] of unconditional sojourn times $E[\eta^i_{(k/l)}]$, $i = 1,2,\dots,\upsilon_k$, $k = 1,2,\dots,4$, $\upsilon_1 = 35$, $\upsilon_2 = 33$, $\upsilon_3 = 29$, $\upsilon_4 = 29$, $l = 1,2,\dots,16$ at particular states, according to $M^i_{(k/l)} = E[\eta^i_{(k/l)}] = \sum_{j=1}^{\upsilon_k} p^{ij}_{(k/l)} M^{ij}_{(k/l)}$ | $M^1_{(1/2)} = 1$, $M^{27}_{(1/2)} = 300$, $M^1_{(1/3)} = 1$, $M^{27}_{(1/3)} = 180$, $M^{30}_{(1/3)} = 240$, $M^1_{(1/8)} = 1$, $M^6_{(1/8)} = 240$, $M^1_{(2/2)} = 1$, $M^{33}_{(2/2)} = 1440$, $M^1_{(2/3)} = 1$, $M^{17}_{(2/3)} = 10080$, $M^{33}_{(2/3)} = 1440$, $M^1_{(3/2)} = 1$, $M^{24}_{(3/2)} = 1440$, $M^1_{(3/3)} = 1$, $M^{14}_{(3/3)} = 10080$, $M^{24}_{(3/3)} = 1440$, $M^1_{(4/3)} = 1$, $M^{14}_{(4/3)} = 10080$ |
| ii) to solve the system of equations $\begin{cases} [\pi^i_{(k/l)}] = [\pi^i_{(k/l)}][p^{ij}_{(k/l)}] \\ \sum_{j=1}^{\upsilon_k} \pi^j_{(k/l)} = 1 \end{cases}$ $i = 1,2,\dots,\upsilon_k$, $k = 1,2,\dots,4$, $\upsilon_1 = 35$, $\upsilon_2 = 33$, $\upsilon_3 = 29$, $\upsilon_4 = 29$, $l = 1,2,\dots,16$ | $\pi^1_{(1/2)} = 0.5$, $\pi^{27}_{(1/2)} = 0.5$, $\pi^1_{(1/3)} = 0.5$, $\pi^{27}_{(1/3)} = 0.25$, $\pi^{30}_{(1/3)} = 0.25$, $\pi^1_{(1/8)} = 0.5$, $\pi^6_{(1/8)} = 0.5$, $\pi^1_{(2/2)} = 0.5$, $\pi^{33}_{(2/2)} = 0.5$, $\pi^1_{(2/3)} = 0.5$, $\pi^{17}_{(2/3)} = 0.25$, $\pi^{33}_{(2/3)} = 0.25$, $\pi^1_{(3/2)} = 0.5$, $\pi^{24}_{(3/2)} = 0.5$, $\pi^1_{(3/3)} = 0.5$, $\pi^{14}_{(3/3)} = 0.25$, $\pi^{24}_{(3/3)} = 0.25$, $\pi^1_{(4/3)} = 0.5$, $\pi^{14}_{(4/3)} = 0.5$ |

| | | |
|---|---|---|
| iii) | to estimate approximate limit values of transient probabilities at the particular states, according to<br><br>$p^i_{(k/l)} = \lim_{t\to+\infty} p^i_{(k/l)}(t) = \frac{\pi^i_{(k/l)} M^i_{(k/l)}}{\sum_{j=1}^{\upsilon_k} \pi^j_{(k/l)} M^j_{(k/l)}}$<br><br>$i = 1,2,\dots,\upsilon_k$, $k = 1,2,\dots,4$, $\upsilon_1 = 35$, $\upsilon_2 = 33$, $\upsilon_3 = 29$, $\upsilon_4 = 29$, $l = 1,2,\dots,16$ | $p^1_{(1/2)} = 0.003322259136213$, $p^{27}_{(1/2)} = 0.996677740863787$, $p^1_{(1/3)} = 0.004739336492891$, $p^{27}_{(1/3)} = 0.426540284360190$, $p^{30}_{(1/3)} = 0.568720379146919$, $p^1_{(1/8)} = 0.004149377593361$, $p^6_{(1/8)} = 0.995850622406639$,<br>$p^1_{(2/2)} = 0.000693962526024$, $p^{33}_{(2/2)} = 0.999306037473976$, $p^1_{(2/3)} = 0.000173580975525$, $p^{17}_{(2/3)} = 0.874848116646416$, $p^{33}_{(2/3)} = 0.124978302378059$,<br>$p^1_{(3/2)} = 0.000693962526024$, $p^{24}_{(3/2)} = 0.999306037473976$, $p^1_{(3/3)} = 0.000173580975525$, $p^{14}_{(3/3)} = 0.874848116646416$, $p^{24}_{(3/3)} = 0.124978302378059$,<br>$p^1_{(4/3)} = 0.000099196508283$, $p^{14}_{(4/3)} = 0.999900803491717$ |
| iv) | to estimate the approximate mean values [min] of the sojourn total times $\hat{\eta}^i_{(k/l)}$ in the time interval e.g. $\eta$=1 month = 43200 minutes at the particular states $s^i_{(k/l)}$, according to<br><br>$\hat{M}^i_{(k/l)} = E[\hat{\eta}^i_{(k/l)}] = p^i_{(k/l)}\eta$,<br><br>$i = 1,2,\dots,\upsilon_k$, $k = 1,2,\dots,4$, $\upsilon_1 = 35$, $\upsilon_2 = 33$, $\upsilon_3 = 29$, $\upsilon_4 = 29$, $l = 1,2,\dots,16$ | $\hat{M}^1_{(1/2)} = 143.52$, $\hat{M}^{27}_{(1/2)} = 43056.48$, $\hat{M}^1_{(1/3)} = 204.74$, $\hat{M}^{27}_{(1/3)} = 18426.54$, $\hat{M}^{30}_{(1/3)} = 24568.72$, $\hat{M}^1_{(1/8)} = 179.25$, $\hat{M}^6_{(1/8)} = 43020.75$,<br>$\hat{M}^1_{(2/2)} = 29.98$, $\hat{M}^{33}_{(2/2)} = 43170.02$, $\hat{M}^1_{(2/3)} = 7.50$, $\hat{M}^{17}_{(2/3)} = 37793.44$, $\hat{M}^{33}_{(2/3)} = 5399.06$,<br>$\hat{M}^1_{(3/2)} = 29.98$, $\hat{M}^{24}_{(3/2)} = 43170.02$, $\hat{M}^1_{(3/3)} = 7.50$, $\hat{M}^{14}_{(3/3)} = 37793.44$, $\hat{M}^{24}_{(3/3)} = 5399.06$,<br>$\hat{M}^1_{(4/3)} = 4.29$, $\hat{M}^{14}_{(4/3)} = 43195.71$ |

*Table 9.* Prediction of the maritime transport critical infrastructure accident consequences – prediction of the process environmental degradation $R_{(k/\upsilon)}(t)$

| Procedure | | Result of application |
|---|---|---|
| i) | to estimate mean values [min] of unconditional sojourn times $E[\zeta^i_{(k/\upsilon)}]$, $i = 1,2,\dots,\ell_k$, $k = 1,2,\dots,4$, $\ell_1 = 35$, $\ell_2 = 33$, $\ell_3 = 29$, $\ell_4 = 29$, $\upsilon_1 = 35$, $\upsilon_2 = 33$, $\upsilon_3 = 29$, $\upsilon_4 = 29$ at particular states, according to<br><br>$M^i_{(k/\upsilon)} = E[\zeta^i_{(k/\upsilon)}] = \sum_{j=1}^{\ell_k} q^{ij}_{(k/\upsilon)} M^{ij}_{(k/\upsilon)}$ | $M^1_{(1/6)} = 1$, $M^2_{(1/6)} = 240$, $M^1_{(1/27)} = 1$, $M^6_{(1/27)} = 240$, $M^1_{(1/30)} = 1$, $M^{11}_{(1/30)} = 240$,<br>$M^1_{(2/17)} = 1$, $M^{12}_{(2/17)} = 2880$, $M^{16}_{(2/17)} = 3780$, $M^{21}_{(2/17)} = 2880$, $M^{25}_{(2/17)} = 300$, $M^{27}_{(2/17)} = 240$, $M^1_{(2/33)} = 1$, $M^6_{(2/33)} = 1440$,<br>$M^1_{(3/14)} = 1$, $M^{12}_{(3/14)} = 2880$, $M^{16}_{(3/14)} = 3780$, $M^{21}_{(3/14)} = 2880$, $M^{25}_{(3/14)} = 300$, $M^{27}_{(3/14)} = 240$, $M^1_{(3/24)} = 1$, $M^6_{(3/24)} = 1440$,<br>$M^1_{(4/14)} = 1$, $M^{12}_{(4/14)} = 2880$, $M^{16}_{(4/14)} = 3780$, $M^{21}_{(4/14)} = 2880$, $M^{28}_{(4/14)} = 300$, $M^{30}_{(4/14)} = 240$ |
| ii) | to solve the system of equations<br><br>$\begin{cases}[\pi^i_{(k/\upsilon)}] = [\pi^i_{(k/\upsilon)}][q^{ij}_{(k/\upsilon)}] \\ \sum_{j=1}^{\ell_k} \pi^j_{(k/\upsilon)} = 1\end{cases}$<br><br>$i = 1,2,\dots,\ell_k$, $k = 1,2,\dots,4$, $\ell_1 = 35$, $\ell_2 = 33$, $\ell_3 = 29$, $\ell_4 = 29$, $\upsilon_1 = 35$, $\upsilon_2 = 33$, $\upsilon_3 = 29$, $\upsilon_4 = 29$ | $\pi^1_{(1/6)} = 0.5$, $\pi^2_{(1/6)} = 0.5$, $\pi^1_{(1/27)} = 0.5$, $\pi^6_{(1/27)} = 0.5$, $\pi^1_{(1/30)} = 0.5$, $\pi^{11}_{(1/30)} = 0.5$,<br>$\pi^1_{(2/17)} = 0.1667$, $\pi^{12}_{(2/17)} = 0.1667$, $\pi^{16}_{(2/17)} = 0.1667$, $\pi^{21}_{(2/17)} = 0.1667$, $\pi^{25}_{(2/17)} = 0.1666$, $\pi^{27}_{(2/17)} = 0.1666$, $\pi^1_{(2/33)} = 0.5$, $\pi^6_{(2/33)} = 0.5$,<br>$\pi^1_{(3/14)} = 0.1667$, $\pi^{12}_{(3/14)} = 0.1667$, $\pi^{16}_{(3/14)} = 0.1667$, $\pi^{21}_{(3/14)} = 0.1667$, $\pi^{25}_{(3/14)} = 0.1666$, $\pi^{27}_{(3/14)} = 0.1666$, $\pi^1_{(3/24)} = 0.5$, $\pi^6_{(3/24)} = 0.5$,<br>$\pi^1_{(4/14)} = 0.1667$, $\pi^{12}_{(4/14)} = 0.1667$, $\pi^{16}_{(4/14)} = 0.1667$, $\pi^{21}_{(4/14)} = 0.1667$, $\pi^{28}_{(4/14)} = 0.1666$, $\pi^{30}_{(4/14)} = 0.1666$ |

| | |
|---|---|
| iii) to estimate approximate limit values of transient probabilities at the particular states, according to $q^i_{(k/\upsilon)} = \lim_{t\to+\infty} q^i_{(k/\upsilon)}(t) = \frac{\pi^i_{(k/\upsilon)} M^i_{(k/\upsilon)}}{\sum_{j=1}^{\ell_k} \pi^j_{(k/\upsilon)} M^j_{(k/\upsilon)}}$ $i = 1,2,\dots,\ell_k$, $k = 1,2,\dots,4$, $\ell_1 = 35$, $\ell_2 = 33$, $\ell_3 = 29$, $\ell_4 = 29$, $\upsilon_1 = 35$, $\upsilon_2 = 33$, $\upsilon_3 = 29$, $\upsilon_4 = 29$ | $q^1_{(1/6)} = 0.004149377593361$, $q^2_{(1/6)} = 0.995850622406639$, $q^1_{(1/27)} = 0.004149377593361$, $q^6_{(1/27)} = 0.995850622406639$, $q^1_{(1/30)} = 0.004149377593361$, $q^{11}_{(1/30)} = 0.995850622406639$, $q^1_{(2/17)} = 0.000099199695891$, $q^{12}_{(2/17)} = 0.285695124165349$, $q^{16}_{(2/17)} = 0.374974850467021$, $q^{21}_{(2/17)} = 0.285695124165349$, $q^{25}_{(2/17)} = 0.029742056392439$, $q^{27}_{(2/17)} = 0.023793645113951$, $q^1_{(2/33)} = 0.000693962526024$, $q^6_{(2/33)} = 0.999306037473976$, $q^1_{(3/14)} = 0.000099199695891$, $q^{12}_{(3/14)} = 0.285695124165349$, $q^{16}_{(3/14)} = 0.374974850467021$, $q^{21}_{(3/14)} = 0.285695124165349$, $q^{25}_{(3/14)} = 0.029742056392439$, $q^{27}_{(3/14)} = 0.023793645113951$, $q^1_{(3/24)} = 0.000693962526024$, $q^6_{(3/24)} = 0.999306037473976$, $q^1_{(4/14)} = 0.000099199695891$, $q^{12}_{(4/14)} = 0.285695124165349$, $q^{16}_{(4/14)} = 0.374974850467021$, $q^{21}_{(4/14)} = 0.285695124165349$, $q^{28}_{(4/14)} = 0.029742056392439$, $q^{30}_{(4/14)} = 0.023793645113951$ |
| iv) to estimate the approximate mean values [min] of the sojourn total times $\hat{\zeta}^i_{(k/\upsilon)}$ in the time interval e.g. $\zeta$=1 month = 43200 minutes at the particular states $r^i_{(k/\upsilon)}$, according to $\hat{M}^i_{(k/\upsilon)} = E[\hat{\zeta}^i_{(k/\upsilon)}] = q^i_{(k/\upsilon)}\zeta$, $i = 1,2,\dots,\ell_k$, $k = 1,2,\dots,4$, $\ell_1 = 35$, $\ell_2 = 33$, $\ell_3 = 29$, $\ell_4 = 29$, $\upsilon_1 = 35$, $\upsilon_2 = 33$, $\upsilon_3 = 29$, $\upsilon_4 = 29$ | $\hat{M}^1_{(1/6)} = 179.25$, $\hat{M}^2_{(1/6)} = 43020.75$, $\hat{M}^1_{(1/27)} = 179.25$, $\hat{M}^6_{(1/27)} = 43020.75$, $\hat{M}^1_{(1/30)} = 179.25$, $\hat{M}^{11}_{(1/30)} = 43020.75$, $\hat{M}^1_{(2/17)} = 4.29$, $\hat{M}^{12}_{(2/17)} = 12342.03$, $\hat{M}^{16}_{(2/17)} = 16198.91$, $\hat{M}^{21}_{(2/17)} = 12342.03$, $\hat{M}^{25}_{(2/17)} = 1284.86$, $\hat{M}^{27}_{(2/17)} = 1027.89$, $\hat{M}^1_{(2/33)} = 29.98$, $\hat{M}^6_{(2/33)} = 43170.02$, $\hat{M}^1_{(3/14)} = 4.29$, $\hat{M}^{12}_{(3/14)} = 12342.03$, $\hat{M}^{16}_{(3/14)} = 16198.91$, $\hat{M}^{21}_{(3/14)} = 12342.03$, $\hat{M}^{25}_{(3/14)} = 1284.86$, $\hat{M}^{27}_{(3/14)} = 1027.89$, $\hat{M}^1_{(3/24)} = 29.98$, $\hat{M}^6_{(3/24)} = 43170.02$, $\hat{M}^1_{(4/14)} = 4.29$, $\hat{M}^{12}_{(4/14)} = 12342.03$, $\hat{M}^{16}_{(4/14)} = 16198.91$, $\hat{M}^{21}_{(4/14)} = 12342.03$, $\hat{M}^{28}_{(4/14)} = 1284.86$, $\hat{M}^{30}_{(4/14)} = 1027.89$ |

*Table 10*. Superposition of initiating events, environmental threats and environmental degradation processes

| Procedure | Result of application |
|---|---|
| i) to estimate approximate limit transient probabilities $q^i_{(k)}$, $i = 1,2,\dots,\ell_k$, $k = 1,2,\dots,4$, $\ell_1 = 35$, $\ell_2 = 33$, $\ell_3 = 29$, $\ell_4 = 29$ at the particular states of the unconditional process $R_{(k)}(t)$, according to (8) | $q^1_{(1)} = 0.999872179003445$, $q^2_{(1)} = 0.000000005069726$, $q^6_{(1)} = 0.000054820128704$, $q^{11}_{(1)} = 0.000072995798125$, $q^1_{(2)} = 0.999871085266778$, $q^6_{(2)} = 0.000016170471066$, $q^{12}_{(2)} = 0.000032213681563$, $q^{16}_{(2)} = 0.000042280457051$, $q^{21}_{(2)} = 0.000032213681563$, $q^{25}_{(2)} = 0.000003353578877$, $q^{27}_{(2)} = 0.000002682863102$, $q^1_{(3)} = 0.999871085266778$, $q^6_{(3)} = 0.000016170471066$, $q^{12}_{(3)} = 0.000032213681563$, $q^{16}_{(3)} = 0.000042280457051$, $q^{21}_{(3)} = 0.000032213681563$, $q^{25}_{(3)} = 0.000003353578877$, $q^{27}_{(3)} = 0.000002682863102$, $q^1_{(4)} = 0.999871139828532$, $q^{12}_{(4)} = 0.000036818375059$, $q^{16}_{(4)} = 0.000048324117265$, $q^{21}_{(4)} = 0.000036818375059$, $q^{28}_{(4)} = 0.000003832946714$, $q^{30}_{(4)} = 0.000003066357371$ |

| | |
|---|---|
| ii) to estimate the approximate mean values [min] of the sojourn total times $\hat{\zeta}^i_{(k)}$ of the unconditional process $R_{(k)}(t)$ in the time interval e.g. $\theta = 1$ month = 43200 minutes at particular states $r^i_{(k)}$, according to<br><br>$\hat{M}^i_{(k)} = E[\hat{\zeta}^i_{(k)}] = q^i_{(k)}\theta,$<br><br>$i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,4$, $\ell_1 = 35$, $\ell_2 = 33$, $\ell_3 = 29$, $\ell_4 = 29$ where $q^i_{(k)}$ are given by (8) | $\hat{M}^1_{(1)} = 43194.47813$, $\hat{M}^2_{(1)} = 0.00022$, $\hat{M}^6_{(1)} = 2.36823$, $\hat{M}^{11}_{(1)} = 3.15342$,<br>$\hat{M}^1_{(2)} = 43194.43088$, $\hat{M}^6_{(2)} = 0.69856$, $\hat{M}^{12}_{(2)} = 1.39163$, $\hat{M}^{16}_{(2)} = 1.82652$, $\hat{M}^{21}_{(2)} = 1.39163$, $\hat{M}^{25}_{(2)} = 0.14487$, $\hat{M}^{27}_{(2)} = 0.11590$,<br>$\hat{M}^1_{(3)} = 43194.43088$, $\hat{M}^6_{(3)} = 0.69856$, $\hat{M}^{12}_{(3)} = 1.39163$, $\hat{M}^{16}_{(3)} = 1.82652$, $\hat{M}^{21}_{(3)} = 1.39163$, $\hat{M}^{25}_{(3)} = 0.14487$, $\hat{M}^{27}_{(3)} = 0.11590$,<br>$\hat{M}^1_{(4)} = 43194.43324$, $\hat{M}^{12}_{(4)} = 1.59055$, $\hat{M}^{16}_{(4)} = 2.08760$, $\hat{M}^{21}_{(4)} = 1.59055$, $\hat{M}^{28}_{(4)} = 0.16558$, $\hat{M}^{30}_{(4)} = 0.13247$ |

*Table 11*. Prediction of environment losses of accidents

| Procedure | Result of application |
|---|---|
| i) to fix losses $L^i_{(k)}(t)$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,4$, $\ell_1 = 35$, $\ell_2 = 33$, $\ell_3 = 29$, $\ell_4 = 29$ [PLN] associated with the environmental degradation state $r^i_{(k)}$, during the time $t = 1$ hour, according to (10) and the information coming from experts | $L^1_{(1)}(1) = 0$, $L^2_{(1)}(1) = 5000$, $L^6_{(1)}(1) = 5000$, $L^{11}_{(1)}(1) = 7000$,<br>$L^1_{(2)}(1) = 0$, $L^6_{(2)}(1) = 10000$, $L^{12}_{(2)}(1) = 15000$, $L^{16}_{(2)}(1) = 20000$, $L^{21}_{(2)}(1) = 25000$, $L^{25}_{(2)}(1) = 27000$, $L^{27}_{(2)}(1) = 30000$,<br>$L^1_{(3)}(1) = 0$, $L^6_{(3)}(1) = 15000$, $L^{12}_{(3)}(1) = 20000$, $L^{16}_{(3)}(1) = 25000$, $L^{21}_{(3)}(1) = 30000$, $L^{25}_{(3)}(1) = 30000$, $L^{27}_{(3)}(1) = 30000$,<br>$L^1_{(4)}(1) = 0$, $L^{12}_{(4)}(1) = 15000$, $L^{16}_{(4)}(1) = 25000$, $L^{21}_{(4)}(1) = 30000$, $L^{28}_{(4)}(1) = 30000$, $L^{30}_{(4)}(1) = 30000$ |
| ii) to estimate approximate expected value of the losses $L_{(k)}(t)$, $k = 1,2,\ldots,4$ [PLN] associated with the process $R_{(k)}(t)$ of the subarea $D_k$, during the time $t = 1$ hour, according to (11) | $L_{(1)}(1) = 0.785$,<br>$L_{(2)}(1) = 2.467$,<br>$L_{(3)}(1) = 3.091$,<br>$L_{(4)}(1) = 3.072$ |
| iii) to estimate the total expected value of the losses $L(t)$ [PLN] associated with the process $R(t)$ in all subareas, during the time $t = 1$ hour, according to (12) | $L(1) = 9.415$ |

The values of losses, presented in *Table 11*, associated with the process of the environmental degradation are due to closure of fishery areas, ports and harbours or shipping suspension within the accident neighbourhood area. On the other hand the above analysed accidents usually do not cause environmental degradation (values of $q^1_{(1)}$, $q^1_{(2)}$, $q^1_{(3)}$ and $q^1_{(4)}$ close to 1). It is also a reason of low costs of accident losses obtained and presented in *Table 11*.

These losses' values are referred to the time $t = 1$ hour. It is assumed that these values are the same at every hour of the particular environmental degradation state duration. Hence, the every next hour of environmental degradation state duration generates the losses which the total value is a multiple of the state time period and the value of losses given in *Table 11*.

The time functions of environmental losses $L_{(k)}(t)$ and $L(t)$ associated with the process of the environmental degradation in the particular subareas $D_k$, $k = 1,2,\ldots,4$ as well as the entire area $D$ of the Baltic Sea open waters respectively are presented in *Figure 1*.

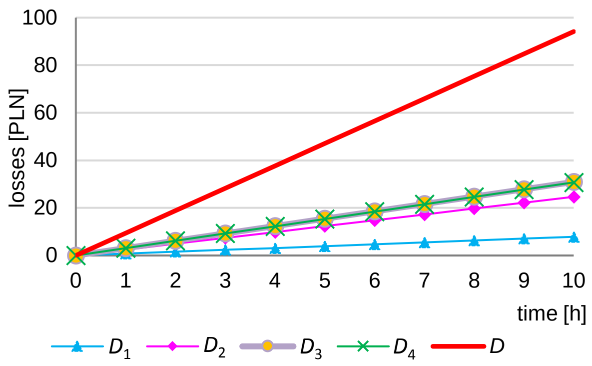


*Figure 1*. The graph of the function of environmental losses associated with the process of the environmental degradation in the particular subareas ($D_1$ – air, $D_2$ – water surface, $D_3$ – water column, $D_4$ – sea floor) as well as the entire area $D$ of the Baltic Sea open waters

## 4. Conclusion

The integrated general model of critical infrastructure accident consequences including and joining the process of initiating events, the process of environmental threats and the process of environmental degradation models is presented and applied to the maritime transport critical infrastructure operating at the Baltic Sea area. The procedure of practical application is illustrated in the modeling, identification and prediction of particular processes caused by the critical infrastructure accident, such as the exceeding a critical safety level by the ship operating at the Baltic Sea open waters. Therefore the obtained results can be practically used by maritime practitioners involved in making decisions related to the safety of maritme transport and prevention of maritime accidents.

Presented in the paper tools and results are also used for forecasting environmental losses associated with the chemical release and environmental degradation generated by the dynamic ship critical infrastructure network. The knowledge of transient probabilities at the particular environmental degradation states of the process of the environmental degradation may be the basis to minimize them and consequently to minimize the expected value of total environmental losses. This way it can be the basis of some suggestions for changes in regulations, technical requirement and organisational factors of maritime transport.

The wider application of the general model is the accident consequences cost optimization through the accident losses minimizing and consequently their mitigation [3]. Moreover, the model can be applied to investigate the climate-weather influence on the losses and to the cost analysis of these losses [11]. Thus, the results are supposed to be interesting for emergency services and rescuers as well as other government, administrative and technical services bearing costs to reduce and remove the critical infrastructure accident consequences.

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