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Modelling critical infrastructure accident consequences – an overall approach

Keywords

critical infrastructure, sea accident, accident consequences, initiating events, environment threats, environment degradation

Abstract

In the paper the probabilistic general model of critical infrastructure accident consequences (GMCIAC) including the process of initiating events, the process of environment threats and the process of environment degradation models is proposed. Next, the methods of its parameters statistical identification are presented. Futher, the marine traffic across the world and sea accidents were observed. Their initiating events and environment threats coming from released chemical substances as well as environment degradations in the neighbourhood region of sea accident were analysed. Then, the process of initiating events, the process of environment threats and the process of environment degradation were analysed and their states are distinguised.

1. Introduction

Some kinds of critical infrastructure accidents concerned with its safety level decrease may occur during its operation [2], [16], [19], [22]-[33], [38]. Those accidents may bring some dangerous consequences for the environment and have disastrous influence on the human health and activity [19], [22]. Each critical infrastructure accident can generate by the initiating event causing dangerous situations in the critical infrastructures operation surroundings. The process of those initiating events can result in the environment threats and lead to the environment dangerous degradations (*Figure 1*) [1], [3]-[4].

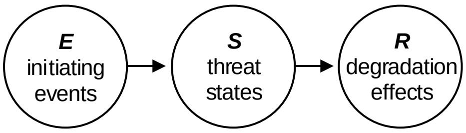

Figure 1. Interrelations of the critical infrastructure accident consequences general model

Thus, the need of designing of the probabilistic joint general model of critical infrastructure accident consequences including the 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 is obvious.

To construct this general model of critical infrastructure accident consequences and to apply it practically, the basic notions concerned with those three particular processes it is composed of should be defined and the methods and procedures of estimating those processes unknown parameters should be developed. Under those all assumptions from the constructed model after its unknown parameters identification, the main characteristics of the process of environment degradation can be predicted. Finally, the proposed model can be applied to modelling, identification and prediction of the critical infrastructure accident consequences generated by real critical infrastructures.

The proposed approach and the methods will be applied in the Project Case Study 2, Scenario 2 [12] to modelling, identification and prediction of the critical infrastructure accident consequences generated by the critical infrastructure defined as a ship operating in the Baltic Sea area, the member of Baltic Shipping Critical Infrastructure Network (BSCIN) defined in [8].

2. Process of initiating events

We call the consequence of the critical infrastructure accident caused by the loss of its required safety critical level the initiating event that is an event initiating dangerous threats for the critical infrastructure operating environment. Next, we can define the process of all initiating events caused by the critical infrastructure accident placed in the critical infrastructure operating environment, interacting with that environment and changing in time its states.

2.1. Process of initiating events modelling

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 $E_1, E_2, ..., E_{n_1}$. Further, we introduce the set of vectors

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

where

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

for $i = 1,2,...,n_1$.

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

$$E = \{e^1, e^2, ..., e^\omega\},$$

where

$$e^l = [e_1^l, e_2^l, ..., e_\omega^l], \quad l = 1,2,...,\omega, \tag{1}$$

and

$$e_i^l \in \{0,1\}, \quad \omega = 1,2,...,n_1.$$

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

$$E = \{e^1, e^2, ..., e^\omega\}.$$

After that, we assume a semi-Markov model [6], [21], [24]-[25], [36]-[37] of the process of initiating events $E(t)$ and denote by θ^{lj} its random conditional sojourn time in the state e^l while its next transition will be done to the state e^j, $l, j = 1,2,...,\omega$, $l \neq j$. This way, the process can be described by:

– the vector $[p^l(0)]_{1x\omega}$ of the probabilities

$$p^l(0) = P(E(0) = e^l), \quad l = 1,2,...,\omega, \tag{2}$$

of its initial states at the moment $t = 0$;

– the matrix $[p^{lj}]_{\omega x\omega}$ of probabilities

$$p^{lj}, \; l, j = 1,2,...,\omega, \tag{3}$$

of transitions between the states e^l and e^j, $l, j = 1,2,...,\omega,$ where by formal agreement $p^{ll} = 0$, $\forall l = 1,2,...,\omega;$

– the matrix $[H^{lj}(t)]_{\omega x\omega}$ of conditional distribution functions

$$H^{lj}(t) = P(\theta^{lj} < t), \tag{4}$$
$$t \in <0,\infty), \quad l, j = 1,2,...,\omega, \quad l \neq j,$$

of sojourn times θ^{lj} of the process $E(t)$ at the state e^l while its next transition will be done to the state e^j, $l, j = 1,2,...,\omega,$ where by formal agreement $H^{ll}(t) = 0, \; l = 1,2,...,\omega.$

2.3. States of initiating events process

The marine traffic across the world and the ship accidents were observed and analysed. Based on that analysis, seven initiating events that generate dangerous situations for the sea environment were distinguished. These initiating events are marked by E_i, $i = 1,2,...,7,$ and defined 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 (drifting of ship) or missing of ship,
E_6 – capsizing or listing of ship,
E_7 – movement of cargo in the ship.

Considering (1) we distinguish the following states of the process of initiating events $E(t)$.

The state

$$e^1=[0,0,0,0,0,0,0]$$

means that no initiating event dangerous for the environment takes place.
The other states of the process of initiating events $E(t)$ are as follows:

$e^2=[1,0,0,0,0,0,0]$, $e^3=[0,1,0,0,0,0,0]$,
$e^4=[0,0,1,0,0,0,0]$, $e^5=[0,0,0,1,0,0,0]$,
$e^6=[0,0,0,0,1,0,0]$, $e^7=[0,0,0,0,0,1,0]$,
$e^8=[0,0,0,0,0,0,1]$, $e^9=[0,1,0,0,0,1,0]$,
$e^{10}=[0,0,0,1,1,0,0]$, $e^{11}=[0,0,0,0,1,1,0]$,
$e^{12}=[0,0,0,1,0,0,1]$.

Then, according to (2)-(4), the process of initiating events $E(t)$ is described by the vector of probabilities $[p(0)]_{1x12}$ of its initial states at the moment $t=0$ the matrix of probabilities of transitions between the states $[p^{lj}]_{12x12}$ and the matrix of conditional distribution functions $[H^{lj}(t)]_{12x12}$ of sojourn times of the process of initiating events at the particular states or equivalently by corresponding to this matrix the matrix of conditional density functions $[h^{lj}(t)]_{12x12}$.

3. Process of environment threats

3.1. Process of environment threats modelling

To construct the general model of the environment threats caused by the process of the initiating events generated by 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 sea environment degradation and denote them by $H_1, H_2, \ldots, H_{n_2}$.
We also distinguish n_3, $n_3 \in N$ environment sub-regions $D_1, D_2, \ldots, D_{n_3}$ of the considered critical infrastructure operating environment region $D = D_1 \cup D_2 \cup \ldots \cup D_{n_3}$, that may be degraded by the environment threats H_i, $i=1,2,\ldots,n_2$.
We assume that the operating environment region D can be affected by some of threats H_i, $i=1,2,\ldots,n_2$, and that a particular environment threat H_i, $i=1,2,\ldots,n_2$, can be characterised by the parameter f_i, $i=1,2,\ldots,n_2$. Moreover, we assume that the scale of the threat H_i, $i=1,2,\ldots,n_2$, influence on region D depends on the range of its parameter value and for particular parameter f_i, $i=1,2,\ldots,n_2$, we distinguish l_i ranges $f_{i1}, f_{i2}, \ldots, f_{il_i}$ of its values.
After that, we introduce the set of vectors

$$S = \{s : s = [f_1, f_2, \ldots, f_{n_2}]\} \qquad (5)$$

where

$$f_i = \begin{cases} 0, & \text{if a threat } H_i \text{ does not appear at} \\ & \text{the region } D, \\ f_{ij}, & \text{if a threat } H_i \text{ appears at the} \\ & \text{region } D \text{ and its parameter is in} \\ & \text{the range } f_{ij},\ j=1,2,\ldots,l_i, \end{cases}$$

for $i=1,2,\ldots,n_2$.
We call vectors (5) the environment threat state of the region D.
Simultaneously, we proceed for the particular sub-regions D_k, $k=1,2,\ldots,n_3$.
The vector

$$s^{(k)} = [f_1^{(k)}, f_2^{(k)}, \ldots, f_{n_2}^{(k)}],\ k=1,2,\ldots,n_3, \qquad (6)$$

where

$$f_i^{(k)} = \begin{cases} 0, & \text{if a threat } H_i \text{ does not appear} \\ & \text{at the sub-region } D_k, \\ f_{ij}^{(k)}, & \text{if a threat } H_i \text{ appears at the} \\ & \text{sub-region } D_k \text{ and its parameter} \\ & \text{is in the range } f_{ij}^{(k)},\ j=1,2,\ldots,l_i, \end{cases} \qquad (7)$$

for $i=1,2,\ldots,n_2$, $k=1,2,\ldots,n_3$, is called the environment threat state of the sub-region D_k.
From the above definition, the maximum number of the environment threat states for the sub-region D_k, $k=1,2,\ldots,n_3$, is equalled to

$$\upsilon_k = (l_1^{(k)}+1), (l_2^{(k)}+1), \ldots, (l_{n_2}^{(k)}+1),\ k=1,2,\ldots,n_3.$$

Further, we number the environment threat states defined by (6) and (7) and mark them by

$$s_\upsilon^{(k)} \text{ for } \upsilon = 1,2,\ldots,\upsilon_k,\ k=1,2,\ldots,n_3,$$

and form the set

$$S^{(k)} = \{s_{\upsilon}^{(k)}, \upsilon = 1,2,...,\upsilon_k\}, \; k = 1,2,..., n_3,$$

where

$$s_i^{(k)} \neq s_j^{(k)} \text{ for } i \neq j, \; i, j \in \{1,2,...,\upsilon_k\}.$$

The set $S^{(k)}$, $k = 1,2,..., n_3$, is called the set of the environment threat states of the sub-region D_k, $k = 1,2,..., n_3$, while a number υ_k is called the number of the environment threat states of this sub-region.

A function

$$S^{(k)}(t), \; k = 1,2,..., n_3,$$

defined on the time interval $t \in < 0, \infty)$, and having values in the environment threat states set

$$S^{(k)}, \; k = 1,2,..., n_3,$$

is called the sub-process of the environment threats of the sub-region D_k, $k = 1,2,..., n_3$.

Next, to involve the sub-process of environment threats of the sub-region with the process of initiating events, we introduced the function

$$S_l^{(k)}(t), \; k = 1,2,..., n_3, \; l = 1,2,...,\omega,$$

defined on the time interval $t \in < 0, \infty)$, depending on the states of the process of initiating events $E(t)$ and taking its values in the set of the environment threat states set $S^{(k)}$, $k = 1,2,..., n_3$. This function is called the conditional sub-process of the environment threats in the sub-region D_k, $k = 1,2,..., n_3$, while the process of initiating events $E(t)$ is in the state e^l, $l = 1,2,...,\omega$.

We assume a semi-Markov model of the sub-process $S_l^{(k)}(t)$, $k = 1,2,..., n_3$, $l = 1,2,...,\omega$, and denote by η_{kl}^{ij} its random conditional sojourn times in the state $S_i^{(k)}$ while its next transition will be done to the state $S_j^{(k)}$, $i, j = 1,2,...,\upsilon_k$, $i \neq j$, $k = 1,2,..., n_3$, $l = 1,2,...,\omega$.

This sub-process is defined by:

– the vector $[p_{kl}^i(0)]_{1x\upsilon_k}$ of probabilities

$$p_{kl}^i(0) = P(S_l^{(k)}(0) = S_i^{(k)}), \; i = 1,2,...,\upsilon_k,$$

of its initial states at the moment $t = 0$;

– the matrix $[p_{kl}^{ij}]_{\upsilon_k x \upsilon_k}$ of probabilities

$$p_{kl}^{ij}, \; i, j = 1,2,...,\upsilon_k,$$

of transitions between the states $S_i^{(k)}$ and $S_j^{(k)}$, $i, j = 1,2,...,\upsilon_k$, where $p_{kl}^{ii} = 0$ for $i = 1,2,...,\upsilon_k$;

– the matrix $[H_{kl}^{ij}(t)]_{\upsilon_k x \upsilon_k}$ of conditional distribution functions

$$H_{kl}^{ij}(t) = P(\eta_{kl}^{ij} < t), \; t \in < 0, \infty), \; i, j = 1,2,...,\upsilon_k,$$

of sojourn times η_{kl}^{ij} of the process $S_l^{(k)}(t)$ in the state $S_i^{(k)}$ while is next transition will be done to the state $S_j^{(k)}$, $i, j = 1,2,...,\upsilon_k$, $i \neq j$, where $H_{kl}^{ii}(t) = 0$ for $i = 1,2,...,\upsilon_k$.

3.2. Threats coming from chemicals released into marine environment

Chemical substances transported by ships throw the sea may unexpected release into the marine environment as a result of initiating events caused by sea accidents characterized by the process of initiating event states defined in Section 2. Some of them are dangerous for the ships operating environment. These substances releases and their consequences for the environment were analysed and there were distinguished $n_2 = 6$ possible environment threats that they may cause in the neighbourhood region of the ship accident area. These threats are marked by H_i, $i = 1,2,...,6$, and they 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,

H_6 – other dangerous chemical substances presence in the accident area.

Each of the environment threat is characterised by one parameter. We mark the parameter of threats H_i, $i = 1,2,...,6$, by f_i, $i = 1,2,...,6$, and they are 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,
f_6 – ability to cause other threats.

The range of each parameter we distinguished based on some common classifications of dangerous chemicals (the International Maritime Dangerous Goods Code – IMDG Code [20] and classification of the United Nation Joint Group of Experts on the Scientific Aspects of Marine Pollution – GESAMP [14]-[15]) [4].

Then, we distinguished l_i ranges $f_{i1}, f_{i2}, ..., f_{il_i}$ for each particular parameter f_i, $i = 1,2,...,n_2$, as follows.

The f_1 parameter (explosiveness range of the substance causing the explosion) may reach $l_1 = 6$ ranges:

$f_{11} = 1$ – the released chemical substance causes the explosion and belongs to class 1.6 of IMDG Code,

$f_{12} = 2$ – the released chemical substance causes the explosion and belongs to class 1.5 of IMDG Code,

$f_{13} = 3$ – the released chemical substance causes the explosion and belongs to class 1.4 of IMDG Code,

$f_{14} = 4$ – the released chemical substance causes the explosion and belongs to class 1.3 of IMDG Code,

$f_{15} = 5$ – the released chemical substance causes the explosion and belongs to class 1.2 of IMDG Code,

$f_{16} = 6$ – the released chemical substance causes the explosion and belongs to class 1.1 of IMDG Code.

The f_2 parameter (flashpoint of the substance causing the fire) may reach $l_2 = 4$ ranges:

$f_{21} = 1$ – the released chemical substance causes the fire and its flashpoint [°C] belongs to the interval $(61, \infty)$,

$f_{22} = 2$ – the released chemical substance causes the fire and its flashpoint [°C] belongs to the interval

$f_{23} = 3$ – the released chemical substance causes the fire and its flashpoint [°C] belongs to the interval $(-18, 23 >$,

$f_{24} = 4$ – the released chemical substance causes the fire and its flashpoint [°C] belongs to the interval $(-\infty, -18 >$.

The f_3 parameter (toxicity of the chemical substance) may reach the $l_3 = 6$ ranges:

$f_{31} = 1$ – the released chemical substance causes the water contamination and its LC_{50} (lethal concentration) [mg/dm^3] belongs to the interval $(100, \infty)$, or if the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval $(10, \infty)$,

$f_{32} = 2$ – the released chemical substance causes the water contamination and its LC_{50} [mg/dm^3] belongs to the interval $(10, 100 >$, or if the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval $(2, 10 >$,

$f_{33} = 3$ – the released chemical substance causes the water contamination and its LC_{50} [mg/dm^3] belongs to the interval $(1, 10 >$, or if the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval $(0.5, 2 >$,

$f_{34} = 4$ – the released chemical substance causes the water contamination and its LC_{50} [mg/dm^3] belongs to the interval $(0.1, 1 >$, or if the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval $(0, 0.5 >$,

$f_{35} = 5$ – the released chemical substance causes the water contamination and its LC_{50} [mg/dm^3] belongs to the interval $(0.01, 0.1 >$,

$f_{36} = 6$ – the released chemical substance causes the water contamination and its LC_{50} [mg/dm^3] belongs to the interval $(0, 0.01 >$.

The f_4 parameter (time of corrosive substance causing the skin necrosis) may reach the $l_4 = 3$ ranges:

$f_{41} = 1$ – the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval $(60, \infty)$,

$f_{42} = 2$ – the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval $(3, 60 >$,

$f_{43} = 3$ – the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval $(0, 3 >$.

The f_5 parameter (ability to bioaccumulation in living organisms) may be in the $l_5 = 5$ ranges:

$f_{51} = 1$ – the released chemical substance log P (partition coefficient) belongs to the interval $(1, 2 >$, or the released chemical substance BCF (bio-concentration factor) belongs to the interval $(1, 10 >$,

$f_{52} = 2$ – the released chemical substance log P belongs to the interval $(2, 3 >$, or the released chemical substance BCF belongs to the interval $(10, 100 >$,

$f_{53} = 3$ – the released chemical substance log P belongs to the interval $(3, 4 >$, or the released chemical substance BCF belongs to the interval $(100, 500>$,

$f_{54} = 4$ – the released chemical substance log P belongs to the interval $(4, 5>$, or the released chemical substance BCF belongs to the interval $(500, 4000>$,

$f_{55} = 5$ – the released chemical substance log P belongs to the interval $(5, \infty)$, or the released chemical substance BCF belongs to the interval $(4000, \infty)$.

The f_6 parameter (ability to cause other threats) may reach $l_6 = 1$ range:

$f_{61} = 1$ – the released chemical substance causes other threats.

3.3. States of environment threats process

There is a lack of exhausting and completed documents on chemical substances (other than crude oil and its petroleum products) spills after the sea accidents. Some of them were well documented whereas a lot of them were poorly documented or basically ignored [34]. The last two decades data show more than 100 accidents and incidents at the Baltic Sea every year. HELCOM reported approximately 1840 accidents with 1960 vessels at the Baltic Sea in 1989-2013. On average 4.7% of them (in 2004-2013) occurred the sea environment pollution with usually no more than 0.1-1 tons of oil substances rather than others chemicals [18]. The pollution with substance other than oil has noted only once since 1996 (a leakage of 0.5 m^3 of orthoxylene in Gothenburg on 13th February 1996) [17].

Thus, last decades some accessible reports of accidental spills of hazardous substances at seas were analysed [5], [7], [13], [35], [39]. Based on them, we distinguished more than fifty kinds of dangerous chemicals released into the sea environment as a result of sea accidents that caused the environment threats (such as: acetone, ammonia, benzene, chlorine, crude oil and petroleum products, epichlorohydrin, ethanol, hydrochloric acid, phenol, sulfuric acid, xylene).

Next, we distinguished $n_3 = 4$ sub-regions that may be degraded by the environment threats H_i, $i = 1,2,...,6$, as follows:

D_1 – air,
D_2 – water surface,
D_3 – water column,
D_4 – sea floor.

Considering (6) and (7) we distinguish the following threat states $s_\upsilon^{(k)}$, $\upsilon = 1,2,...,\upsilon_k$, for each environment sub-region D_k, $k = 1,2,...,4$.

The sea environment is not threatened as long as any hazardous substances is presented in the marine ecosystem. When the sea accident has happened without the dangerous substance spill or a chemical substance has released, but the substance is not dangerous, the sea environment threat process for particularly sub-region D_k is at the states

$$s_1^{(1)} = [0,0,0,0,0,0],\ s_1^{(2)} = [0,0,0,0,0,0],$$
$$s_1^{(3)} = [0,0,0,0,0,0],\ s_1^{(4)} = [0,0,0,0,0,0].$$

The other environment threat states for each sub-regions are as follows.

For sub-region D_1 – air:

$$s_2^{(1)} = [0,1,0,0,0,0],\ s_3^{(1)} = [0,2,0,0,0,0],$$
$$s_4^{(1)} = [0,3,0,0,0,0],\ s_5^{(1)} = [0,4,0,0,0,0],$$
$$s_6^{(1)} = [0,0,1,0,0,0],\ s_7^{(1)} = [0,0,2,0,0,0],$$
$$s_8^{(1)} = [0,0,3,0,0,0],\ s_9^{(1)} = [0,0,4,0,0,0],$$
$$s_{10}^{(1)} = [0,0,0,1,0,0],\ s_{11}^{(1)} = [0,0,0,2,0,0],$$
$$s_{12}^{(1)} = [0,0,0,0,3,0],\ s_{13}^{(1)} = [0,0,0,0,1,1],$$
$$s_{14}^{(1)} = [0,0,0,0,2,1],\ s_{15}^{(1)} = [0,0,0,2,0,1],$$
$$s_{16}^{(1)} = [0,0,1,3,0,0],\ s_{17}^{(1)} = [0,0,2,3,0,0],$$
$$s_{18}^{(1)} = [0,0,3,0,0,1],\ s_{19}^{(1)} = [0,0,3,0,2,0],$$
$$s_{20}^{(1)} = [0,0,3,1,0,0],\ s_{21}^{(1)} = [0,0,3,2,0,0],$$
$$s_{22}^{(1)} = [0,0,4,0,1,0],\ s_{23}^{(1)} = [0,0,2,0,0,1],$$
$$s_{24}^{(1)} = [0,0,3,3,0,0],\ s_{25}^{(1)} = [0,0,2,0,1,1],$$
$$s_{26}^{(1)} = [0,0,2,0,3,1],\ s_{27}^{(1)} = [0,0,3,1,0,1],$$
$$s_{28}^{(1)} = [0,0,3,2,3,0],\ s_{29}^{(1)} = [0,0,3,3,0,1],$$
$$s_{30}^{(1)} = [0,0,4,0,1,1],\ s_{31}^{(1)} = [0,0,4,0,5,1],$$
$$s_{32}^{(1)} = [0,0,4,2,2,0],\ s_{33}^{(1)} = [3,3,0,0,0,0].$$

For sub-region D_2 – water surface:

$$s_2^{(2)} = [0,0,1,0,0,0],\ s_3^{(2)} = [0,0,0,2,0,0],$$
$$s_4^{(2)} = [0,0,2,0,0,0],\ s_5^{(2)} = [0,0,3,0,0,0],$$
$$s_6^{(2)} = [0,0,4,0,0,0],\ s_7^{(2)} = [0,0,5,0,0,0],$$
$$s_8^{(2)} = [0,1,0,0,0,0],\ s_9^{(2)} = [0,2,0,0,0,0],$$
$$s_{10}^{(2)} = [0,3,0,0,0,0],\ s_{11}^{(2)} = [0,4,0,0,0,0],$$
$$s_{12}^{(2)} = [0,0,0,0,1,1],\ s_{13}^{(2)} = [0,0,0,2,0,1],$$
$$s_{14}^{(2)} = [0,0,2,0,1,0],\ s_{15}^{(2)} = [0,0,2,1,0,1],$$
$$s_{16}^{(2)} = [0,0,2,2,0,0],\ s_{17}^{(2)} = [0,0,2,3,0,1],$$
$$s_{18}^{(2)} = [0,0,3,0,1,0],\ s_{19}^{(2)} = [0,0,3,0,2,0],$$
$$s_{20}^{(2)} = [0,0,3,0,2,1],\ s_{21}^{(2)} = [0,0,3,0,3,0],$$
$$s_{22}^{(2)} = [0,0,3,0,3,1],\ s_{23}^{(2)} = [0,0,3,1,0,0],$$
$$s_{24}^{(2)} = [0,0,3,2,2,0],\ s_{25}^{(2)} = [0,0,3,2,3,0],$$

$s_{26}^{(2)}=[0,0,4,2,0,0],\ s_{27}^{(2)}=[0,0,5,0,5,1],$
$s_{28}^{(2)}=[3,3,0,0,0,0],\ s_{29}^{(2)}=[0,0,1,3,0,0],$
$s_{30}^{(2)}=[0,0,2,0,0,1],\ s_{31}^{(2)}=[0,0,2,0,1,1],$
$s_{32}^{(2)}=[0,0,2,3,0,0].$

For sub-region D_3 – water column:

$s_{2}^{(3)}=[0,0,1,0,0,0],\ s_{3}^{(3)}=[0,0,2,0,0,0],$
$s_{4}^{(3)}=[0,0,3,0,0,0],\ s_{5}^{(3)}=[0,0,4,0,0,0],$
$s_{6}^{(3)}=[0,0,5,0,0,0],\ s_{7}^{(3)}=[0,0,0,2,0,0],$
$s_{8}^{(3)}=[0,0,0,0,1,1],\ s_{9}^{(3)}=[0,0,0,2,0,1],$
$s_{10}^{(3)}=[0,0,1,3,0,0],\ s_{11}^{(3)}=[0,0,2,0,0,1],$
$s_{12}^{(3)}=[0,0,2,0,1,0],\ s_{13}^{(3)}=[0,0,2,0,2,0],$
$s_{14}^{(3)}=[0,0,2,3,0,0],\ s_{15}^{(3)}=[0,0,3,0,1,0],$
$s_{16}^{(3)}=[0,0,3,0,0,1],\ s_{17}^{(3)}=[0,0,3,0,2,0],$
$s_{18}^{(3)}=[0,0,3,0,3,0],\ s_{19}^{(3)}=[0,0,3,1,0,0],$
$s_{20}^{(3)}=[0,0,4,0,0,1],\ s_{21}^{(3)}=[0,0,4,0,2,0],$
$s_{22}^{(3)}=[0,0,2,0,1,1],\ s_{23}^{(3)}=[0,0,2,1,0,1],$
$s_{24}^{(3)}=[0,0,2,3,0,1],\ s_{25}^{(3)}=[0,0,3,0,2,1],$
$s_{26}^{(3)}=[0,0,3,0,3,1],\ s_{27}^{(3)}=[0,0,3,2,2,0],$
$s_{28}^{(3)}=[0,0,3,2,3,0],\ s_{29}^{(3)}=[0,0,5,0,5,1].$

For sub-region D_4 – sea floor:

$s_{2}^{(4)}=[0,0,1,0,0,0],\ s_{3}^{(4)}=[0,0,2,0,0,0],$
$s_{4}^{(4)}=[0,0,3,0,0,0],\ s_{5}^{(4)}=[0,0,4,0,0,0],$
$s_{6}^{(4)}=[0,0,5,0,0,0],\ s_{7}^{(4)}=[0,0,0,2,0,0],$
$s_{8}^{(4)}=[0,0,0,0,1,1],\ s_{9}^{(4)}=[0,0,0,2,0,1],$
$s_{10}^{(4)}=[0,0,1,3,0,0],\ s_{11}^{(4)}=[0,0,2,0,0,1],$
$s_{12}^{(4)}=[0,0,2,0,1,0],\ s_{13}^{(4)}=[0,0,2,0,2,0],$
$s_{14}^{(4)}=[0,0,2,3,0,0],\ s_{15}^{(4)}=[0,0,3,0,1,0],$
$s_{16}^{(4)}=[0,0,3,0,0,1],\ s_{17}^{(4)}=[0,0,3,0,2,0],$
$s_{18}^{(4)}=[0,0,3,0,3,0],\ s_{19}^{(4)}=[0,0,3,1,0,0],$
$s_{20}^{(4)}=[0,0,4,0,0,1],\ s_{21}^{(4)}=[0,0,4,0,2,0],$
$s_{22}^{(4)}=[0,0,2,0,1,1],\ s_{23}^{(4)}=[0,0,2,1,0,1],$
$s_{24}^{(4)}=[0,0,2,3,0,1],\ s_{25}^{(4)}=[0,0,3,0,2,1],$
$s_{26}^{(4)}=[0,0,3,0,3,1],\ s_{27}^{(4)}=[0,0,3,2,2,0],$
$s_{28}^{(4)}=[0,0,3,2,3,0],\ s_{29}^{(4)}=[0,0,5,0,5,1].$

Note: when two or more dangerous substances have released as a result of sea accident caused the same kind of threat but with different ranges of its parameters f_i, we set the parameter with the highest range.

4. Process of environment degradation

4.1. Process of environment degradation modelling

The particular states of the process of the environment threats $S^{(k)}(t)$ of the sub-region D_k, $k=1,2,...,n_3$, defined in Section 3, may lead to dangerous effects degrading the environment at this sub-region. Thus, we assume that there are m_k different dangerous degradation effects for the environment sub-region D_k, $k=1,2,...,n_3$, and we mark them by

$$R_1^{(k)}, R_2^{(k)}, ..., R_{m_k}^{(k)}.$$

This way the set

$$R^{(k)}=\{R_1^{(k)}, R_2^{(k)}, ..., R_{m_k}^{(k)}\},\quad k=1,2,...,n_3,$$

is the set of degradation effects for the environment of the sub-region D_k.

These degradation effects may attain different levels. Namely, the degradation effect

$$R_m^{(k)},\quad m=1,2,...,m_k,$$

may reach $\nu_m^{(k)}$ levels

$$R_{m1}^{(k)}, R_{m2}^{(k)}, ..., R_{m\nu_m^{(k)}}^{(k)},\quad m=1,2,...,m_k,$$

that are called the states of this degradation effect. The set

$$R_m^{(k)}=\{R_{m1}^{(k)}, R_{m2}^{(k)}, ..., R_{m\nu_m^{(k)}}^{(k)}\},\quad m=1,2,...,m_k,$$

is called the set of states of the degradation effect

$$R_m^{(k)},\quad m=1,2,...,m_k,\quad k=1,2,...,n_3$$

for the environment of the sub-region D_k, $k=1,2,...,n_3$.

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

$$R^{(k)}(t)=[R_1^{(k)}(t), R_2^{(k)}(t), ..., R_{m_k}^{(k)}(t)],\ t\in<0,+\infty),\quad (8)$$

where

$$R_m^{(k)}(t),\quad t\in<0,+\infty),\quad m=1,2,...,m_k,\quad k=1,2,...,n_3,$$

are the processes of degradation effects for the environment of the sub-region D_k, defined on the time interval $t \in < 0,+\infty)$, and having their values in degradation the state sets

$$R_m^{(k)}, \ m = 1,2,\ldots,m_k, \ t \in < 0,+\infty), \qquad (9)$$

is called the degradation process of the environment of the sub-region D_k.

The conditional environment sub-region degradation process dependent on the sub-region process of the environment threats is a function

$$R_{m\upsilon}^{(k)}(t), \ t \in < 0,+\infty), \ m = 1,2,\ldots,m_k, \ \upsilon = 1,2,\ldots,\upsilon_k,$$
$$k = 1,2,\ldots,n_3,$$

defined on the time interval $t \in < 0,+\infty)$, and having values in the degradation effect states set $R^{(k)}$, $k = 1,2,\ldots,n_3$, is called the conditional sub-process of the environment degradation of the sub-region D_k, $k = 1,2,\ldots,n_3$, while the process of environment threats $S^{(k)}(t)$ of the sub-region D_k, is in the state $S_\upsilon^{(k)}$ $\upsilon = 1,2,\ldots,\upsilon_k$.

We assume a semi-Markov model of the conditional environment sub-region degradation process

$$R_{m\upsilon}^{(k)}(t), \ t \in < 0,+\infty), \ k = 1,2,\ldots,n_3, \ m = 1,2,\ldots m_k,$$
$$\upsilon = 1,2,\ldots,\upsilon_k,$$

and denote by $\zeta_{mk\upsilon}^{ij}$ its random conditional sojourn times in the state $R_{mi}^{(k)}$ while its next transition will be done to the state $R_{mj}^{(k)}$, $i, j = 1,2,\ldots,v_m^{(k)}$, $i \neq j$, $m = 1,2,\ldots,m_k$, $\upsilon = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$.

This sub-process is defined by:

– the vector $[p_{mk\upsilon}^i(0)]_{1xv_m^{(k)}}$ of probabilities

$$p_{mk\upsilon}^i(0) = P(R_{m\upsilon}^{(k)}(0) = R_{mi}^{(k)}), \ i = 1,2,\ldots,v_m^{(k)},$$
$$m = 1,2,\ldots,m_k, \ \upsilon = 1,2,\ldots,\upsilon_k, \ k = 1,2,\ldots,n_3,$$

of its initial states at the moment $t = 0$;

– the matrix $[p_{mk\upsilon}^{ij}]_{v_m^{(k)}xv_m^{(k)}}$ of probabilities

$$p_{mk\upsilon}^{ij}, \ i, j = 1,2,\ldots,v_m^{(k)}, \ m = 1,2,\ldots,m_k,$$
$$\upsilon = 1,2,\ldots,\upsilon_k, \ k = 1,2,\ldots,n_3,$$

of transitions between the degradation states $R_{mi}^{(k)}$ and $R_{mj}^{(k)}$, $i, j = 1,2,\ldots,v_m^{(k)}$, $m = 1,2,\ldots,m_k$, $k = 1,2,\ldots,n_3$, where $p_{mk\upsilon}^{ii} = 0 \ \forall i = 1,2,\ldots,v_m^{(k)}$;

– the matrix $[G_{mk\upsilon}^{ij}(t)]_{v_m^{(k)}xv_m^{(k)}}$ of conditional distribution functions

$$G_{mk\upsilon}^{ij}(t) = P(\zeta_{mk\upsilon}^{ij} < t), \ t \in < 0,+\infty), \ i \neq j,$$
$$i, j = 1,2,\ldots,v_m^{(k)}, \ m = 1,2,\ldots,m_k, \ \upsilon = 1,2,\ldots,\upsilon_k,$$
$$k = 1,2,\ldots,n_3,$$

of sojourn times $\zeta_{mk\upsilon}^{ij}$ of the degradation sub-process $R_{m\upsilon}^{(k)}(t)$ in the degradation state $R_{mi}^{(k)}$ while is next transition will be done to the degradation state $R_{mj}^{(k)}$, $i, j = 1,2,\ldots,v_m^{(k)}$, $i \neq j$, $m = 1,2,\ldots,m_k$, $\upsilon = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, where $G_{mk\upsilon}^{ii}(t) = 0$, $i = 1,2,\ldots,v_m^{(k)}$.

4.2. Degradations coming from chemical releases into the marine environment

We distinguished $m_k = 5$, possible environment degradations in the neighbourhood region of a critical infrastructure (a ship) accident area that may be caused by threats coming from chemical substance released into the marine environment as a result of a sea accident. These environment degradations are marked by $R_m^{(k)}$, $m = 1,2,\ldots,5$, and they are as follows.

For sub-region D_1 – air in the accident area:

$R_1^{(1)}$ – the increase of air temperature in the accident area,

$R_2^{(1)}$ – the decrease of oxygen concentration in the air in the accident area,

$R_3^{(1)}$ – the disturbance of the air pH regime in the accident area,

$R_4^{(1)}$ – the aesthetic nuisance of air (caused by smells, fume, discoloration etc.) in the accident area,

$R_5^{(1)}$ – the pollution of air in the accident area.

For sub-region D_2 – water surface in the accident area:

$R_1^{(2)}$ – increase of the water surface temperature in the accident area,

$R_2^{(2)}$ – the decrease of oxygen concentration of the water surface in the accident area,

$R_3^{(2)}$ – the disturbance of the water surface pH regime in the accident area,

$R_4^{(2)}$ – the aesthetic nuisance of the water surface (caused by smells, litter, discoloration etc.) in the accident area,

$R_5^{(2)}$ – the pollution of water surface in the accident area.

For sub-region D_3 – water column in the accident area:

$R_1^{(3)}$ – the increase of the water column temperature in the accident area,

$R_2^{(3)}$ – the decrease of oxygen concentration in the water column in the accident area,

$R_3^{(3)}$ – the disturbance of the water column pH regime in the accident area,

$R_4^{(3)}$ – the aesthetic nuisance of the water column (caused by smells, litter, discoloration etc.) in the accident area,

$R_5^{(3)}$ – the pollution of water column in the accident area.

For sub-region D_4 – sea floor in the accident area:

$R_1^{(4)}$ – the increase of bottom the water temperature in the accident area,

$R_2^{(4)}$ – the decrease of oxygen concentration of bottom water in the accident area,

$R_3^{(4)}$ – the disturbance of the bottom water pH regime in the accident area,

$R_4^{(4)}$ – the aesthetic nuisance of the sea floor (caused by smells, litter, discoloration etc.) in the accident area,

$R_5^{(4)}$ – the pollution of the sea floor in the accident area.

We also distinguished that each degradation effect may reach $\nu_m^{(k)} = 3$ levels as follows.

$R_{11}^{(1)}$ – the air temperature in the accident area increased of the value from the interval (10°C, 20°C>,

$R_{12}^{(1)}$ – the air temperature in the accident area increased of the value from the interval (20°C, 30°C>,

$R_{13}^{(1)}$ – the air temperature in the accident area increased of the value more than 30°C,

$R_{11}^{(2)}$ – the water surface temperature in the accident area increased of the value from the interval (10°C, 20°C>,

$R_{12}^{(2)}$ – the water surface temperature in the accident area increased of the value from the interval (10°C, 20°C>,

$R_{13}^{(2)}$ – the water surface temperature in the accident area increased of the value more than 30°C,

$R_{11}^{(3)}$ – the water column temperature in the accident area increased of the value from the interval (10°C, 20°C>,

$R_{12}^{(3)}$ – the water column temperature in the accident area increased of the value from the interval (20°C, 30°C>,

$R_{13}^{(3)}$ – the water column temperature in the accident area increased of the value more than 30°C,

$R_{11}^{(4)}$ – the sea floor water temperature in the accident area increased of the value from the interval (10°C, 20°C>,

$R_{12}^{(4)}$ – the sea floor water temperature in the accident area increased of the value from the interval (20°C, 30°C>,

$R_{13}^{(4)}$ – the sea floor water column temperature in the accident area increased of the value more than 30°C,

$R_{21}^{(1)}$ – the oxygen concentration in the air of the accident area decreased the value up to 2%,

$R_{22}^{(1)}$ – the oxygen concentration in the air of the accident area decreased the value from the interval 2-5%,

$R_{23}^{(1)}$ – the oxygen concentration in the air of the accident area decreased the value more than 5%,

$R_{21}^{(2)}$ – the oxygen concentration in the water surface of the accident area decreased the value up to 2 mg/dm^3,

$R_{22}^{(2)}$ – the oxygen concentration in the water surface of the accident area decreased the value from the interval 2-5 mg/dm^3,

$R_{23}^{(2)}$ – the oxygen concentration in the water surface of the accident area decreased the value more than 5 mg/dm^3,

$R_{21}^{(3)}$ – the oxygen concentration in the water column of the accident area decreased the value up to 2 mg/dm^3,

$R_{22}^{(3)}$ – the oxygen concentration in the water column of the accident area decreased the value from the interval 2-5 mg/dm^3,

$R_{23}^{(3)}$ – the oxygen concentration in the water column of the accident area decreased the value more than 5 mg/dm^3,

$R_{21}^{(4)}$ – the oxygen concentration at the sea floor of the accident area decreased the value up to 2 mg/dm^3,

$R_{22}^{(4)}$ – the oxygen concentration at the sea floor of the accident area decreased the value from the interval 2-5 mg/dm^3,

$R_{23}^{(4)}$ – the oxygen concentration at the sea floor of the accident area decreased the value more than 5 mg/dm^3,

$R_{31}^{(1)}$ – the air pH regime in the accident area changed not more than ±1 unit,

$R_{32}^{(1)}$ – the air pH regime in the accident area changed ±1-2 units,

$R_{33}^{(1)}$ – the air pH regime in the accident area changed ±2 units or more,

$R_{31}^{(2)}$ – the water surface pH regime in the accident area changed not more than ±1 unit,

$R_{32}^{(2)}$ – the water surface pH regime in the accident area changed ±1-2 units,

$R_{33}^{(2)}$ – the water surface pH regime in the accident area changed ±2 units or more,

$R_{31}^{(3)}$ – the water column pH regime in the accident area changed not more than ±1 unit,

$R_{32}^{(3)}$ – the water column pH regime in the accident area changed ±1-2 units,

$R_{33}^{(3)}$ – the water column pH regime in the accident area changed ±2 units or more,

$R_{31}^{(4)}$ – the sea floor pH regime in the accident area changed not more than ±1 unit,

$R_{32}^{(4)}$ – the sea floor pH regime in the accident area changed ±1-2 units,

$R_{33}^{(4)}$ – the sea floor pH regime in the accident area changed ±2 units or more,

$R_{41}^{(1)}$ – the aesthetic nuisance of air of the accident area is presented but the closure of area is not required,

$R_{42}^{(1)}$ – the aesthetic nuisance of air of the accident area is presented and the closure of area is required for not more than 2 days,

$R_{43}^{(1)}$ – the aesthetic nuisance of air of the accident area is presented and the closure of area is required for
2 days or more,

$R_{41}^{(2)}$ – the aesthetic nuisance of water surface in the accident area is presented but the closure of area is not required,

$R_{42}^{(2)}$ – the aesthetic nuisance of water surface in the accident area is presented and the closure of area is required for not more than 2 days,

$R_{43}^{(2)}$ – the aesthetic nuisance of water surface in the accident area is presented and the closure of area is required for 2 days or more,

$R_{41}^{(3)}$ – the aesthetic nuisance of water column in the accident area is presented but the closure of area is not required,

$R_{42}^{(3)}$ – the aesthetic nuisance of water column in the accident area is presented and the closure of area is required for not more than 2 days,

$R_{43}^{(3)}$ – the aesthetic nuisance of water column in the accident area is presented and the closure of area is required for 2 days or more,

$R_{41}^{(4)}$ – the aesthetic nuisance of sea floor and beaches in the accident area is presented but the closure of area is not required,

$R_{42}^{(4)}$ – the aesthetic nuisance of sea floor and beaches in the accident area is presented and the closure of area is required for not more than 2 days,

$R_{43}^{(4)}$ – the aesthetic nuisance of sea floor and beaches in the accident area is presented and the closure of area is required for 2 days or more,

$R_{51}^{(1)}$ – the concentration of chemical substance in the air in the accident area belongs to the interval $(0, LC_{50}/2>$,

$R_{52}^{(1)}$ – the concentration of chemical substance in the air in the accident area belongs to the interval $(LC_{50}/2, LC_{50}>$,

$R_{53}^{(1)}$ – the concentration of chemical substance in the air in the accident area belongs to the interval (LC_{50}, ∞),

$R_{51}^{(2)}$ – the concentration of chemical substance in the water surface in the accident area belongs to the interval $(0, LC_{50}/2>$,

$R_{52}^{(2)}$ – the concentration of chemical substance in the water surface in the accident area belongs to the interval $(LC_{50}/2, LC_{50}>$,

$R_{53}^{(2)}$ – the concentration of chemical substance in the water surface in the accident area belongs to the interval (LC_{50}, ∞),

$R_{51}^{(3)}$ – the concentration of chemical substance in the water column in the accident area belongs to the interval $(0, LC_{50}/2>$,

$R_{52}^{(3)}$ – the concentration of chemical substance in the water column in the accident area belongs to the interval $(LC_{50}/2, LC_{50}>$,

$R_{53}^{(3)}$ – the concentration of chemical substance in the water column in the accident area belongs to the interval (LC_{50}, ∞),

$R_{51}^{(4)}$ – the concentration of chemical substance in the sea floor water in the accident area belongs to the interval $(0, LC_{50}/2 >$,

$R_{52}^{(4)}$ – the concentration of chemical substance in the sea floor water in the accident area belongs to the interval $(LC_{50}/2, LC_{50} >$,

$R_{53}^{(4)}$ – the concentration of chemical substance in the sea floor water in the accident area belongs to the interval (LC_{50}, ∞).

4.3. States of environment degradation process

Considering (8) and (9) we distinguish the following environment degradation states $R_m^{(k)}$, $m = 1,2,\dots,m_k$, $m_k = 5$, for the sub-regions D_k, $k = 1,2,\dots,n_3$, $n_3 = 4$, environment degradation processes $R_{m\upsilon}^{(k)}(t)$, $t \in < 0,+\infty)$, $m = 1,2,3,4,5$, $k = 1,2,3,4$, in all states $S_\upsilon^{(k)}$, $\upsilon = 1,2,\dots,\upsilon_k$, $k = 1,2,3,4$, $\upsilon_1 = 33$, $\upsilon_2 = 32$, $\upsilon_3 = 29$, $\upsilon_4 = 29$, of the process of environment threats.

For sub-region D_1 – air:

$R_1^{(1)} = [0,0,0,0,0]$, $R_2^{(1)} = [0,0,0,0,1]$,
$R_3^{(1)} = [0,0,0,0,2]$, $R_4^{(1)} = [0,0,0,0,3]$,
$R_5^{(1)} = [0,0,0,1,0]$, $R_6^{(1)} = [0,0,0,1,1]$,
$R_7^{(1)} = [0,0,0,1,2]$, $R_8^{(1)} = [0,0,0,1,3]$,
$R_9^{(1)} = [0,0,0,2,2]$, $R_{10}^{(1)} = [0,0,0,2,3]$,
$R_{11}^{(1)} = [0,0,1,0,2]$, $R_{12}^{(1)} = [0,0,2,3,3]$,
$R_{13}^{(1)} = [3,3,0,2,0]$.

For sub-region D_2 – water surface:

$R_1^{(2)} = [0,0,0,0,0]$, $R_2^{(2)} = [0,0,0,0,1]$,
$R_3^{(2)} = [0,0,0,0,2]$, $R_4^{(2)} = [0,0,0,0,3]$,
$R_5^{(2)} = [0,0,0,1,0]$, $R_6^{(2)} = [0,0,0,1,1]$,
$R_7^{(2)} = [0,0,0,1,2]$, $R_8^{(2)} = [0,0,0,1,3]$,
$R_9^{(2)} = [0,0,0,2,0]$, $R_{10}^{(2)} = [0,0,0,2,1]$,
$R_{11}^{(2)} = [0,0,0,2,2]$, $R_{12}^{(2)} = [0,0,0,2,3]$,
$R_{13}^{(2)} = [0,0,1,0,1]$, $R_{14}^{(2)} = [0,0,1,0,3]$,
$R_{15}^{(2)} = [0,0,1,1,1]$, $R_{16}^{(2)} = [0,0,2,0,1]$,
$R_{17}^{(2)} = [0,0,2,0,2]$, $R_{18}^{(2)} = [0,0,2,0,3]$,
$R_{19}^{(2)} = [0,0,2,1,0]$, $R_{20}^{(2)} = [0,0,2,1,2]$,
$R_{21}^{(2)} = [0,0,2,2,3]$, $R_{22}^{(2)} = [0,0,2,3,3]$,
$R_{23}^{(2)} = [0,0,3,0,3]$, $R_{24}^{(2)} = [0,0,3,1,1]$,
$R_{25}^{(2)} = [0,0,3,2,1]$, $R_{26}^{(2)} = [0,0,3,2,3]$,
$R_{27}^{(2)} = [0,2,2,1,2]$, $R_{28}^{(2)} = [0,3,0,0,3]$,
$R_{29}^{(2)} = [3,0,0,3,0]$.

For sub-region D_3 – water column:

$R_1^{(3)} = [0,0,0,0,0]$, $R_2^{(3)} = [0,0,0,0,1]$,
$R_3^{(3)} = [0,0,0,0,2]$, $R_4^{(3)} = [0,0,0,0,3]$,
$R_5^{(3)} = [0,0,0,1,0]$, $R_6^{(3)} = [0,0,0,1,1]$,
$R_7^{(3)} = [0,0,0,1,2]$, $R_8^{(3)} = [0,0,0,1,3]$,
$R_9^{(3)} = [0,0,0,2,0]$, $R_{10}^{(3)} = [0,0,0,2,1]$,
$R_{11}^{(3)} = [0,0,0,2,2]$, $R_{12}^{(3)} = [0,0,0,2,3]$,
$R_{13}^{(3)} = [0,0,1,0,1]$, $R_{14}^{(3)} = [0,0,1,0,3]$,
$R_{15}^{(3)} = [0,0,1,1,1]$, $R_{16}^{(3)} = [0,0,2,0,1]$,
$R_{17}^{(3)} = [0,0,2,0,2]$, $R_{18}^{(3)} = [0,0,2,0,3]$,
$R_{19}^{(3)} = [0,0,2,1,0]$, $R_{20}^{(3)} = [0,0,2,1,2]$,
$R_{21}^{(3)} = [0,0,2,2,3]$, $R_{22}^{(3)} = [0,0,2,3,3]$,
$R_{23}^{(3)} = [0,0,3,0,3]$, $R_{24}^{(3)} = [0,0,3,1,1]$,
$R_{25}^{(3)} = [0,0,3,2,1]$, $R_{26}^{(3)} = [0,0,3,2,3]$,
$R_{27}^{(3)} = [0,2,2,1,2]$, $R_{28}^{(3)} = [0,3,0,0,3]$,
$R_{29}^{(3)} = [2,0,0,3,0]$.

For sub-region D_4 – sea floor:

$R_1^{(4)} = [0,0,0,0,0]$, $R_2^{(4)} = [0,0,0,0,1]$,
$R_3^{(4)} = [0,0,0,0,2]$, $R_4^{(4)} = [0,0,0,0,3]$,
$R_5^{(4)} = [0,0,0,1,0]$, $R_6^{(4)} = [0,0,0,1,1]$,
$R_7^{(4)} = [0,0,0,1,2]$, $R_8^{(4)} = [0,0,0,1,3]$,
$R_9^{(4)} = [0,0,0,2,0]$, $R_{10}^{(4)} = [0,0,0,2,1]$,
$R_{11}^{(4)} = [0,0,0,2,2]$, $R_{12}^{(4)} = [0,0,0,2,3]$,
$R_{13}^{(4)} = [0,0,1,0,1]$, $R_{14}^{(4)} = [0,0,1,0,3]$,
$R_{15}^{(4)} = [0,0,1,1,1]$, $R_{16}^{(4)} = [0,0,2,0,1]$,
$R_{17}^{(4)} = [0,0,2,0,2]$, $R_{18}^{(4)} = [0,0,2,0,3]$,
$R_{19}^{(4)} = [0,0,2,1,0]$, $R_{20}^{(4)} = [0,0,2,1,2]$,
$R_{21}^{(4)} = [0,0,2,2,3]$, $R_{22}^{(4)} = [0,0,2,3,3]$,
$R_{23}^{(4)} = [0,0,3,0,3]$, $R_{24}^{(4)} = [0,0,3,1,1]$,
$R_{25}^{(4)} = [0,0,3,2,1]$, $R_{26}^{(4)} = [0,0,3,2,3]$,
$R_{27}^{(4)} = [0,2,2,1,2]$, $R_{28}^{(4)} = [0,3,0,0,3]$,
$R_{29}^{(4)} = [2,0,0,3,0]$.

5. Conclusion

The modelling critical infrastructure accident consequences through designing the General Model of Critical Infrastructure Accident Consequences (GMCIAC) presented in this paper and the identification of its unknown parameters will be performed in [9]. Further, the GMCIAC adaptation to the prediction of critical infrastructure accident consequences will be done in [10] and its practical applications will be performed in [11] to the chemical spill consequences generated by the accident of one of the ships of the shipping critical infrastructure network operating at the Baltic Sea waters (the preparatory approach to the EU-CIRCLE Case Study 2, scenario 2 [12]).

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