Journal of Polish Safety and Reliability Association
Summer Safety and Reliability Seminars, Volume 8, Number 3, 2017

Bogalecka Magda

Kołowrocki Krzysztof
Maritime University, Gdynia, Poland

General model of critical infrastructure accident consequences application to chemical spill consequences generated by dynamic ship critical infrastructure network operating at the Baltic Sea waters. Part 2. Process of environment threats

Keywords

Baltic Sea region, critical infrastructure, sea accident, accident consequences, environment threats

Abstract

In the paper, the process of environment threats at the Baltic Sea area identification is performed. Next, the main characteristics of this process are predicted.

1. Introduction

The risk analysis of chemical spills at sea and their consequences is proposed to be based on the General Model of Critical Infrastructure Accident Consequences (GMCIAC) [Bogalecka, Kołowrocki, 2016], [Bogalecka, Kołowrocki, 2017] of mutual interactions between three processes: the process of the sea accident initiating events [Bogalecka, 2010], [Bogalecka, Kołowrocki, 2015a], the process of the sea environment threats [Bogalecka, Kołowrocki, 2015b] and the process of the sea environment degradation.

2. Application of the model of the process of environment threats to the Baltic Sea waters

We assume, as in [EU-CIRCLE Report D3.3-GMU21, 2016], that the process of environment threats of the sub-region D_k, $k = 1,2,\ldots,n_3$, is taking υ_k, $\upsilon_k \in N$, different states of environment threats $s^1_{(k)}, s^2_{(k)}, \ldots, s^{\upsilon_k}_{(k)}$. Next, we mark by $S_{(k/l)}(t)$, $t \in <0,\infty)$, the sub-process of environment threats of the sub-region while the process of initiating events $E(t)$, is at the state e^l, $l = 1,2,\ldots,\omega$. The sub-process $S_{(k/l)}(t)$, is a function defined on the time interval $t \in <0,\infty)$, depending on the states of the process of initiating events $E(t)$, and taking discrete values in the set $\{s^1_{(k/l)}, s^2_{(k/l)}, \ldots, s^{\upsilon_k}_{(k/l)}\}$ of the environment threats states. We assume a semi-Markov model [Grabski, 2015], [Kołowrocki, 2004], [Kołowrocki, 2014], [Kołowrocki, Soszyńska-Budny, 2008], [Kołowrocki, Soszyńska-Budny, 2011], [Limnios, Oprisan, 2005], [Macci, 2008], [Mercier, 2008] of the sub-process of environment threats $S_{(k/l)}(t)$, and we mark by $\eta^{ij}_{(k/l)}$ its random conditional sojourn times at the states $s^i_{(k/l)}$, when its next state is $s^j_{(k/l)}$, $i, j = 1,2,\ldots,\upsilon_k$, $i \neq j$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$.

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

2.1. Parameters evaluation of the process of environment threats at the Baltic Sea waters

To identify the unknown parameters of the process of environment threats the suitable statistical data coming from realization should be collected. The statistical identification of the environment threats was performed on the base on the ship accidents around the Baltic Sea in a period of 11 years (2004-2014). The initial moment $t = 0$ of the process of environment threat was fixed at the moment when the initiating event causing ship accident generated one of the distinguished environment threat states.
Unfortunately, the less accurate identification of the process of environment threats is performed for the Baltic Sea waters because of the less sufficiently numerous set of statistical data.

2.1.1. States of the process of environment threats

Taking into account the expert opinion on varying in time the process of environment threats, we distinguished its states for particular sub-regions. There are $\upsilon_1 = 35$ states of the process of environment threats in the air (D_1 sub-region):

state $s^1_{(1)}$ – accident has happened without the dangerous substance spill or a chemical substance has released, but the substance is not dangerous,

state $s^2_{(1)}$ – the released chemical substance causes the fire and its flashpoint [°C] belongs to the interval (61,∞),

state $s^3_{(1)}$ – the released chemical substance causes the fire and its flashpoint [°C] belongs to the interval (23,61>,

state $s^4_{(1)}$ – the released chemical substance causes the fire and its flashpoint [°C] belongs to the interval (-18,23>,

state $s^5_{(1)}$ – the released chemical substance causes the fire and its flashpoint [°C] belongs to the interval (-∞,-18>,

state $s^6_{(1)}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (10,∞),

state $s^7_{(1)}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (2,10>,

state $s^8_{(1)}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0.5,2>,

state $s^9_{(1)}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0,0.5>,

state $s^{10}_{(1)}$ – the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval (60,∞),

state $s^{11}_{(1)}$ – the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval (3,60>,

state $s^{12}_{(1)}$ – the released chemical substance bioaccumulates in living organisms and its log P belongs to the interval (3,4>, or its BCF belongs to the interval (100,500>,

state $s^{13}_{(1)}$ – the released chemical substance bioaccumulates in living organisms and its log P belongs to the interval (2,3>, or its BCF belongs to the interval (10,100>, and simultaneously the released chemical substance causes other threats ,

state $s^{14}_{(1)}$ – the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval (3,60>, and simultaneously the released chemical substance causes other threats ,

state $s^{15}_{(1)}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (10,∞), and simultaneously the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval (0,3>,

state $s^{16}_{(1)}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (2,10>, and simultaneously the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval (0,3>,

state $s^{17}_{(1)}$ – the released chemical substance causes the fire and its flashpoint [°C] belongs to the interval (23,61>, and simultaneously the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0.5,2>, state $s_{(1)}^{18}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0.5,2>, and simultaneously the released chemical substance causes other threats,

state $s_{(1)}^{19}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0.5,2>, and simultaneously the released chemical substance bioaccumulates in living organisms and its log P belongs to the interval (2,3>, or its BCF belongs to the interval (10,100>,

state $s_{(1)}^{20}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0.5,2>, and simultaneously the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval (60,∞),

state $s_{(1)}^{21}$ – the released chemical substance causes the fire and its flashpoint [°C] belongs to the interval (-18,23>, and simultaneously the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (2,10>,

state $s_{(1)}^{22}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0.5,2>, and simultaneously the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval (3,60>,

state $s_{(1)}^{23}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0,0.5>, and simultaneously the released chemical substance bioaccumulates in living organisms and its log P belongs to the interval (1,2>, or its BCF belongs to the interval (1,10>,

state $s_{(1)}^{24}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (2,10>, and simultaneously the released chemical substance causes other threats ,

state $s_{(1)}^{25}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0.5,2>, and simultaneously the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval (0,3>,

state $s_{(1)}^{26}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (2,10>, and simultaneously the released chemical substance bioaccumulates in living organisms and its log P belongs to the interval (1,2>, or its BCF belongs to the interval (1,10>, and additionally the released chemical substance causes other threats,

state $s_{(1)}^{27}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (2,10>, and simultaneously the released chemical substance bioaccumulates in living organisms and its log P belongs to the interval (3,4>, or its BCF belongs to the interval (100,500>, and additionally the released chemical substance causes other threats,

state $s_{(1)}^{28}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0.5,2>, and simultaneously the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval (60,∞), and additionally the released chemical substance causes other threats,

state $s_{(1)}^{29}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0.5,2>, and simultaneously the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval (3,60>, and additionally the released chemical substance bioaccumulates in living organisms and its log P belongs to the interval (3,4>, or its BCF belongs to the interval (100,500>,

state $s_{(1)}^{30}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0,0.5>, and simultaneously the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval (0,3>,

state $s_{(1)}^{31}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0,0.5>, and simultaneously the released chemical substance bioaccumulates in living organisms and its log P belongs to the interval (1,2>, or its BCF belongs to the interval (1,10>, and additionally the released chemical substance causes other threats ,

state $s_{(1)}^{32}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0,0.5>, and simultaneously the released chemical substance bioaccumulates in living organisms and its log P belongs to the interval (5,∞), or its BCF belongs to the interval (4000,∞), and additionally the released chemical substance causes other threats ,

state $s_{(1)}^{33}$ – the released chemical substance caused the air contamination and its LC_{50} [mg/dm^3] belongs to the interval (0,0.5>, and simultaneously the released chemical substance is corrosive and its time of causing the skin necrosis belongs to the interval (3,60>, and additionally the released chemical substance bioaccumulates in living organisms and its log P belongs to the interval (2,3>, or its BCF belongs to the interval (10,100>,

state $s^{34}_{(1)}$ – the released chemical substance causes the explosion and belongs to class 1.4 of IMDG Code and simultaneously the released chemical substance causes the fire and its flashpoint [°C] belongs to the interval (-18,23>,
state $s^{35}_{(1)}$ – the released chemical substance causes the explosion and belongs to class 1.4 of IMDG Code and simultaneously the released chemical substance causes the fire and its flashpoint [°C] belongs to the interval (-∞,-18>,
Moreover, there are υ_2 = 33 states for the water surface (D_2 sub-region), υ_3 = 29 states for the water column (D_3 sub-region), υ_4 = 29 states for the sea floor (D_4 sub-region), and υ_5 = 29 states for the coast (D_5 sub-region) that are given in [EU-CIRCLE Report D3.3-GMU21, 2016].

2.1.2. Probabilities of transitions between states of the process of environment threats

On the basis of the statistical data, it is possible to evaluate the following unknown basic parameters of the process of environment threats at the Baltic Sea waters:
- the vectors of the initial probabilities $p^i_{(k/l)}(0)$ of the environment threats sub-process at the particular states at the moment $t = 0$ as follows:

$$[p_{(1/l)}(0)]_{1x35} = [1, 0, \ldots, 0],\ l = 1,2,\ldots,16,$$

$$[p_{(2/l)}(0)]_{1x33} = [1, 0, \ldots, 0],\ l = 1,2,\ldots,16,$$

$$[p_{(3/l)}(0)]_{1x29} = [1, 0, \ldots, 0],\ l = 1,2,\ldots,16,$$

$$[p_{(4/l)}(0)]_{1x29} = [1, 0, \ldots, 0],\ l = 1,2,\ldots,16,$$

$$[p_{(5/l)}(0)]_{1x29} = [1, 0, \ldots, 0],\ l = 1,2,\ldots,16; \quad (1)$$

- the matrix $[p^{ij}_{(k/l)}]$ $i, j = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots, 5$, $l = 1,2,\ldots,16$ of the probabilities of transitions of the sub-process $S_{(k/l)}(t)$ from the state $s^i_{(k/l)}$ into the state $s^j_{(k/l)}$, during the experimental time. The probabilities of transitions that are not equal to 0 are as follows:

$$p^{1\,27}_{(1/2)} = 1,\ p^{27\,1}_{(1/2)} = 1; \quad (2)$$

$$p^{1\,27}_{(1/3)} = 0.5,\ p^{1\,30}_{(1/3)} = 0.5;\ p^{27\,1}_{(1/3)} = 1,\ p^{30\,1}_{(1/3)} = 1; \quad (3)$$

$$p^{1\,6}_{(1/8)} = 1,\ p^{6\,1}_{(1/8)} = 1; \quad (4)$$

$$p^{1\,33}_{(2/2)} = 1,\ p^{33\,1}_{(2/2)} = 1; \quad (5)$$

$$p^{1\,17}_{(2/3)} = 0.5,\ p^{1\,33}_{(2/3)} = 0.5,\ p^{17\,1}_{(2/3)} = 1,\ p^{33\,1}_{(2/3)} = 1; \quad (6)$$

$$p^{1\,24}_{(3/2)} = 1,\ p^{24\,1}_{(3/2)} = 1; \quad (7)$$

$$p^{1\,14}_{(3/3)} = 0.5,\ p^{1\,24}_{(3/3)} = 0.5,\ p^{14\,1}_{(3/3)} = 1,\ p^{24\,1}_{(3/3)} = 1; \quad (8)$$

$$p^{1\,14}_{(4/3)} = 1,\ p^{14\,1}_{(4/3)} = 1. \quad (9)$$

Some of the values of the probabilities existing in the vector $[p_{(k/l)}(0)]$ and in the matrix $[p^{ij}_{(k/l)}]$, besides of that standing on the main diagonal, and equal to zero does not mean that the events they are concerned with, can not appear. They are evaluated on the basis of real statistical data and their values may change and become more precise if the time of the experiment is longer.

2.1.3. Evaluation of distributions and mean values of the process of environment threats conditional sojourn times

Because we only have the number of realizations of the sub-process of environment threats and its all realizations are equal to an approximate value, we assume that this time has the uniform distribution in the interval from this value minus its half to this value plus its half.
The uniform distribution functions of the sub-process of environment threats for particular conditional sojourn times $\eta^{ij}_{(k/l)}$ are identified on the basis of statistical data coming from its process realizations at the Baltic Sea waters given in Appendix 4 in [EU-CIRCLE Report D3.3-GMU22, 2016]. For instance, the sub-process of environment threats the conditional sojourn time $\eta^{1\,27}_{(1/2)}$ assumed $n^{1\,27}_{(1/2)}$ = 1 value equals to 1, we assume that it has the uniform distribution function given by

$$H^{1\,27}_{(1/2)}(t) = \begin{cases} 0, & t < 0.5 \\ t, & 0.5 \le t < 1.5 \\ 1, & t \ge 1.5. \end{cases} \quad (10)$$

We have proceeded with the remaining conditional times at the states of the sub-process of environment threats in the same way and approximately fix they distribution.

Further, for distributions identified in this section by application general formulae for the mean value given by (3.17) in [EU-CIRCLE Report D3.3-GMU21, 2016], the mean values $M^{ij}_{(k/l)} = E[\eta^{ij}_{(k/l)}]$, $i, j = 1,2,\ldots,\upsilon_k$, $i \neq j$, $k = 1,2,\ldots,5$, $l = 1,2,\ldots,16$, $\upsilon_1 = 35$, $\upsilon_2 = 33$, $\upsilon_3 = 29$, $\upsilon_4 = 29$, $\upsilon_5 = 29$, of the process of environment threats conditional sojourn times at particular states at the Baltic Sea waters can be determined and they are as follows:

$$M^{1\,27}_{(1/2)} = 1,\ M^{27\,1}_{(1/2)} = 300,\ M^{1\,27}_{(1/3)} = 1,\ M^{1\,30}_{(1/3)} = 1,$$

$$M^{27\,1}_{(1/3)} = 180,\ M^{30\,1}_{(1/3)} = 240,\ M^{1\,6}_{(1/8)} = 1,$$

$$M^{6\,1}_{(1/8)} = 240,\ M^{1\,33}_{(2/2)} = 1,\ M^{33\,1}_{(2/2)} = 1440,$$

$$M^{1\,17}_{(2/3)} = 1,\ M^{1\,33}_{(2/3)} = 1,\ M^{17\,1}_{(2/3)} = 10080,$$

$$M^{33\,1}_{(2/3)} = 1440,\ M^{1\,24}_{(3/2)} = 1,\ M^{24\,1}_{(3/2)} = 1440,$$

$$M^{1\,14}_{(3/3)} = 1,\ M^{1\,24}_{(3/3)} = 1,\ M^{14\,1}_{(3/3)} = 10080,$$

$$M^{24\,1}_{(3/3)} = 1440,\ M^{1\,14}_{(4/3)} = 1,\ M^{14\,1}_{(4/3)} = 10080. \quad (11)$$

2.1.4. Prediction of the process of environment threats

Using the identified parameters of the process of environment threats in Section 2.1.2 and 2.1.3, it is possible to predict its characteristics [EU-CIRCLE Report D3.3-GMU23, 2016]. Namely, considering (2)-(9) and (11), the mean values of the process of environment threats at the Baltic Sea waters unconditional sojourn times at the particular states are:

$$M^{1}_{(1/2)} = 1,\ M^{27}_{(1/2)} = 300; \quad (12)$$

$$M^{1}_{(1/3)} = 1,\ M^{27}_{(1/3)} = 180,\ M^{30}_{(1/3)} = 240; \quad (13)$$

$$M^{1}_{(1/8)} = 1,\ M^{6}_{(1/8)} = 240; \quad (14)$$

$$M^{1}_{(2/2)} = 1,\ M^{33}_{(2/2)} = 1440; \quad (15)$$

$$M^{1}_{(2/3)} = 1,\ M^{17}_{(2/3)} = 10080,\ M^{33}_{(2/3)} = 1440; \quad (16)$$

$$M^{1}_{(3/2)} = 1,\ M^{24}_{(3/2)} = 1440; \quad (17)$$

$$M^{1}_{(3/3)} = 1,\ M^{14}_{(3/3)} = 10080,\ M^{24}_{(3/3)} = 1440; \quad (18)$$

$$M^{1}_{(4/3)} = 1,\ M^{14}_{(4/3)} = 10080. \quad (19)$$

Since from the system of equations (3.29) in [EU-CIRCLE Report D3.3-GMU21, 2016] takes the following form

$$\begin{cases} [\pi^{i}_{(k/l)}]_{1\mathrm{x}\upsilon_k} = [\pi^{i}_{(k/l)}]_{1\mathrm{x}\upsilon_k}[p^{ij}_{(k/l)}]_{\upsilon_k\mathrm{x}\upsilon_k} \\ \sum_{j=1}^{\upsilon_k} \pi^{j}_{(k/l)} = 1, \end{cases}$$

where

$k = 1,2,\ldots,5$, $l = 1,2,\ldots,16$, $\upsilon_1 = 35$, $\upsilon_2 = 33$, $\upsilon_3 = 29$, $\upsilon_4 = 29$, $\upsilon_5 = 29$,

we get its following solution:

$$\pi^{1}_{(1/2)} = 0.5,\ \pi^{27}_{(1/2)} = 0.5; \quad (20)$$

$$\pi^{1}_{(1/3)} = 0.5,\ \pi^{27}_{(1/3)} = 0.25,\ \pi^{30}_{(1/3)} = 0.25; \quad (21)$$

$$\pi^{1}_{(1/8)} = 0.5,\ \pi^{6}_{(1/8)} = 0.5; \quad (22)$$

$$\pi^{1}_{(2/2)} = 0.5,\ \pi^{33}_{(2/2)} = 0.5; \quad (23)$$

$$\pi^{1}_{(2/3)} = 0.5,\ \pi^{17}_{(2/3)} = 0.25,\ \pi^{33}_{(2/3)} = 0.25; \quad (24)$$

$$\pi^{1}_{(3/2)} = 0.5,\ \pi^{24}_{(3/2)} = 0.5; \quad (25)$$

$$\pi^{1}_{(3/3)} = 0.5,\ \pi^{14}_{(3/3)} = 0.25,\ \pi^{24}_{(3/3)} = 0.25; \quad (26)$$

$$\pi^{1}_{(4/3)} = 0.5,\ \pi^{14}_{(4/3)} = 0.5. \quad (27)$$

Then after considering (12)-(19) respectively and applying (3.28) in [EU-CIRCLE Report D3.3-GMU21, 2016], we get the approximate limit values of transient probabilities at the particular states of the process of environment threats:

$$p^{1}_{(1/2)} = 0.00332,\ p^{27}_{(1/2)} = 0.99668; \quad (28)$$

$$p^{1}_{(1/3)} = 0.00474,\ p^{27}_{(1/3)} = 0.42654;$$
$$p^{30}_{(1/3)} = 0.56872; \quad (29)$$

$$p^{1}_{(1/8)} = 0.00415,\ p^{6}_{(1/8)} = 0.99585; \qquad (30)$$

$$p^{1}_{(2/2)} = 0.00069,\ p^{33}_{(2/2)} = 0.99931; \qquad (31)$$

$$p^{1}_{(2/3)} = 0.00017,\ p^{17}_{(2/3)} = 0.87485,$$
$$p^{33}_{(2/3)} = 0.12498; \qquad (32)$$

$$p^{1}_{(3/2)} = 0.00069,\ p^{24}_{(3/2)} = 0.99931; \qquad (33)$$

$$p^{1}_{(3/3)} = 0.00017,\ p^{14}_{(3/3)} = 0.87485,$$
$$p^{24}_{(3/3)} = 0.12498; \qquad (34)$$

$$p^{1}_{(4/3)} = 0.00010,\ p^{14}_{(4/3)} = 0.99990. \qquad (35)$$

Further, by (3.30) in [EU-CIRCLE Report D3.3-GMU21, 2016] and considering (28)-(35) respectively, the approximate mean values of the sojourn total times $\hat{\eta}^{i}_{(k/l)}$ of the process of environment threats $S_{(k/l)}(t)$ at the Baltic Sea waters in the time interval $\eta_{(k/l)}$ = 1 month = 43200 minutes at the particular states $s^{i}_{(k/l)}$ expressed in minutes are:

$$\hat{M}^{1}_{(1/2)} = 143.52,\ \hat{M}^{27}_{(1/2)} = 43056.48; \qquad (36)$$

$$\hat{M}^{1}_{(1/3)} = 204.74,\ \hat{M}^{27}_{(1/3)} = 18426.54,$$
$$\hat{M}^{30}_{(1/3)} = 24568.72; \qquad (37)$$

$$\hat{M}^{1}_{(1/8)} = 179.25,\ \hat{M}^{6}_{(1/8)} = 43020.75; \qquad (38)$$

$$\hat{M}^{1}_{(2/2)} = 29.98,\ \hat{M}^{33}_{(2/2)} = 43170.02; \qquad (39)$$

$$\hat{M}^{1}_{(2/3)} = 7.50,\ \hat{M}^{17}_{(2/3)} = 37793.44,$$
$$\hat{M}^{33}_{(2/3)} = 5399.06; \qquad (40)$$

$$\hat{M}^{1}_{(3/2)} = 29.98,\ \hat{M}^{24}_{(3/2)} = 43170.02; \qquad (41)$$

$$\hat{M}^{1}_{(3/3)} = 7.50,\ \hat{M}^{14}_{(3/3)} = 37793.44,$$
$$\hat{M}^{24}_{(3/3)} = 5399.06; \qquad (42)$$

$$\hat{M}^{1}_{(4/3)} = 4.29,\ \hat{M}^{14}_{(4/3)} = 43195.71. \qquad (43)$$

3. Conclusion

The results (28)-(35) and (36)-(43) are main characteristics of the considered process of environment threats that is the second part of the integrated model of critical infrastructure accident consequences [Bogalecka, Kołowrocki, 2017]. This characteristics are necessary for the prediction of the remaining third part of the integrated model, i.e. for the prediction of the characteristics of the process of environment degradation.

Acknowledgments

The paper presents the results developed in the scope of the EU-CIRCLE project titled "A pan – European framework for strengthening Critical Infrastructure resilience to climate change" that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653824. http://www.eu-circle.eu/.

References

Bogalecka M., Analysis of sea accidents initial events, Polish Journal of Environmental Studies, 19(4A), 5-8, 2010

Bogalecka M., Kołowrocki K., Modelling, identification and prediction of environment degradation initial events process generated by critical infrastructure accidents. Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars, 6(1), 47-66, 2015a

Bogalecka M., Kołowrocki K., The process of sea environment threats generated by hazardous chemicals release. Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars, 6(1), 67-74, 2015b

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

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

EU-CIRCLE Report D3.3-GMU21, Modelling critical infrastructure accident consequences –

designing the General Model of Critical Infrastructure Accident Consequences (GMCIAC), 2016

EU-CIRCLE Report D3.3-GMU22, Identification of unknown parameters of the General Model of Critical Infrastructure Accident Consequences (GMCIAC), 2016

EU-CIRCLE Report D3.3-GMU23, Adaptation of the general model of critical infrastructure accident consequences (GMCIAC) to the prediction of critical infrastructure accident consequences, 2016

Grabski F., Semi-Markov processes: applications in system reliability and maintenance. Elsevier, 2015

Kołowrocki K., Reliability of large systems. Amsterdam, Boston, Heidelberd, London, New York, Oxford, Paris, San Diego, San Francisco, Singapore, Sidney, Tokyo, Elsevier, 2004

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

Kołowrocki K., Soszyńska-Budny J., A general model of industrial systems operation processes related to their environment and infrastructure. Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars, 2(2), 223-226, 2008

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

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

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

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