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Chemical spill due to extreme sea surges – critical infrastructure chemical accident (spill) consequences related to climate-weather change

Keywords

shipping, dangerous good, sea accident, environment degradation, cost analysis, climate-weather impact

Abstract

The paper contains the detailed description, preparatory work and necessary data for conduction of Case Study 2: Storm and Sea Surge at Baltic Sea Port, Scenario 2: Chemical Spill Due to Extreme Sea Surges – Critical Infrastructure Chemical Accident (Spill) Consequences Related to Climate-Weather Change in the scope of the EU-CIRCLE project. The general model of critical accident consequences was applied to chemical spill consequences generated by dynamic ship critical infrastructure network operating at the Baltic Sea waters. The approach to the prediction of critical infrastructure accident consequences is proposed. Moreover, the cost analysis of losses associated with the consequences of chemical spill, without and with considering the climate-weather impact, is proposed.

1. Introduction

The critical infrastructure is a complex system in its operating environment that significant features are its inside and outside dependencies, that in the case of its degradation have significant destructive influence on the health, safety and security, economics and social conditions of large human communities and territory areas. The critical infrastructure accident is understand as an event that causes changing the critical infrastructure safety state into the safety state worse than the critical safety state that is dangerous for the critical infrastructure itself and its operating environment as well. The general model of a critical infrastructure accident consequences was constructed as a joint probabilistic model including the process of initiating events generated either by its accident or by its loss of safety critical level, the process of environment threats and the process of environment degradation [Bogalecka & Kołowrocki, 2016b], [Blokus-Roszkowska et al., 2017] (*Figure 1*).

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 should be defined and the methods and procedures of estimating these processes unknown parameters should be developed. Under these 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 [Bogalecka & Kołowrocki, 2016b, 2017e].

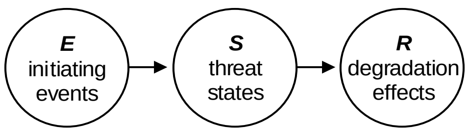

Figure 1. Interrelations of the critical infrastructure accident consequences general model.

2. Process of initiating events

The procedures for modeling, identification and prediction of the process of initiating events is based on methods and algorithms presented in [Kołowrocki & Soszyńska-Budny, 2011], [Bogalecka & Kołowrocki, 2015a, 2016b, 2017b,e,g].

To model the process of initiating events we should distinguish and fix the following preliminary characteristics:

- E_i – event initiating the dangerous situation for the critical infrastructure operating environment,
- e^l – state of the process of initiating events,
- ω – number of initiating event states.

Example – application of the process of initiating events to accidents within sea waters

Based on the analysis and the maritime authorities classification of the initial events caused by sea accidents, seven initiating events that generate dangerous situations for the sea environment were distinguished. There are 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.

The states of the process of initiating events were defined as the vector where 1 means the initiating event occurs, and 0 means the initiating event does not occur.

For instance, the vector:

- [0,0,0,0,0,0,0] means no initiating event dangerous for the environment takes place,
- [0,1,0,0,0,0,0] means the grounding takes place (1 is on the 2nd place in the vector, therefore initiating event E_2 occurred),
- [0,1,0,1,0,0,0] means the grounding and fire occurred simultaneously (1 is on the 2nd and 4th place in the vector, therefore initiating events E_2 and E_4 occurred).

Finally, we fixed $\omega = 16$ states of initiating events that are given in Section 2.3 in [Bogalecka & Kołowrocki, 2016b].

The identification and prediction of the process of initiating events allow to estimate inter alia:

- conditional approximate values of transient probabilities p^l, $l = 1,2,\ldots,\omega$, at the particular states of the process of initiating events given by (3) in [Bogalecka & Kołowrocki, 2017e].

The examples of modeling, identification and prediction of the process of initiating events for critical infrastructure accidents within the Baltic Sea and the world sea waters are given respectively in [Bogalecka & Kołowrocki, 2017b,g].

3. Process of environment threats

The procedures for modeling, identification and prediction of the process of environment threats is based on methods and algorithms presented in [Kołowrocki & Soszyńska-Budny, 2011], [Bogalecka & Kołowrocki, 2015b, 2016b, 2017c,e,i].

To model the process of environment threats we should distinguish and fix the following preliminary characteristics:

- D_k – environment sub-region of the considered critical infrastructure operating environment region that may be degraded by the environment threats,
- n_3 – number of sub-regions D_k,
- H_i – threat as the consequences of initiating events that may cause the sea environment degradation,
- f^i – parameter characterising a particular environment threat,
- l_i – range of a particular parameter characterising each environment threat,
- $s^i_{(k)}$ – state of the process of environment threats of the environment sub-region D_k,
- υ_k – number of environment threat states of the environment sub-region D_k.

Example – application of the process of environment threats to accidents within sea waters

There are distinguished five sub-regions that may be degraded by the environment threats as follows:

D_1 – air,
D_2 – water surface,
D_3 – water column,
D_4 – sea floor,
D_5 – coast (shoreline).

Based on the analysis of chemical substances properties, six possible environment threats caused by released substances within the neighbourhood region of the ship accident area were distinguished. There are as follows:

H_1 – explosion of the chemical substance in the accident area,
H_2 – fire of the chemical substance in the accident area,
H_3 – toxic chemical substance presence in the accident area,
H_4 – corrosive chemical substance presence in the accident area,
H_5 – bioaccumulative substance presence in the accident area,
H_6 – other dangerous chemical substances presence in the accident area.

Each environment threat is characterised by one parameter as follows:

f^1 – explosiveness range of the substance causing the explosion,
f^2 – flashpoint of the substance causing the fire,

f^3 – toxicity of the chemical substance,

f^4 – time of corrosive substance causing the skin necrosis,

f^5 – ability to bioaccumulation in living organisms,

f^6 – ability to cause other threats.

These parameters are expressed in the rising from 0 scale (l_i ranges).

The states of the process of environment threats were defined as the vector where 0 means the threat does not appear but other digit means the threat appears and its value expresses the range of the threat.

For instance, the vector:

- [0,0,0,0,0,0] means the sea accident has happened without the dangerous substance spill or a chemical substance has released, but the substance is not dangerous, in other words, the environment region of the accident area is not threatened,
- [0,0,0,1,0,0] means the released chemical substance is corrosive (a digit on the 4th place in the vector, therefore environment threat H_4 appears) and the corrosiveness range is slight (digit equals to 1),
- [0,0,0,3,0,0] means the released chemical substance is corrosive (a digit on the 4th place in the vector, therefore environment threat H_4 appears) and the corrosiveness range is high (digit equals to 3),
- [0,1,0,1,0,0] means the released chemical substance is simultaneously flammable and corrosive (a digit on the 2nd and 4th place in the vector, therefore environment threat H_2 and H_4 appear), and the flammability and corrosiveness range is slight (both digits equal to 1).

When two or more dangerous substances have released as a result of sea accident caused the same kind of threat but with different ranges l_i of its parameters f^i we set the parameter with the highest range.

Finally, we fixed $\upsilon_1 = 35$, $\upsilon_2 = 33$, $\upsilon_3 = 29$, $\upsilon_4 = 29$, $\upsilon_5 = 29$ states of environment threats for particular sub-regions that are given in Section 3.3 in [Bogalecka & Kołowrocki, 2016b].

Moreover, the process of environment threats of the each sub-region is involved with the process of initiating evens. Namely, the state of the process of environment threats is conditional upon the state of the process of initiating event that caused the previous one. Then $s^i_{(k/l)}$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$, mean the state of the process of environment threats of the environment sub-region D_k, $k = 1,2,\ldots,n_3$, when the process of initiating event is in the state e^l.

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

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

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

$$i = 1,2,\ldots,\upsilon_k,\ k = 1,2,\ldots,n_3.$$

The examples of modeling, identification and prediction of the process of environment threats for critical infrastructure accidents within the Baltic Sea and the world sea waters are given respectively in [Bogalecka & Kołowrocki, 2017c,h].

4. Process of environment degradation

The procedures for modeling, identification and prediction of the process of environment degradation is based on methods and algorithms presented in [Kołowrocki & Soszyńska-Budny, 2011], [Bogalecka & Kołowrocki, 2016b, 2017d-e,i].

To model the process of environment degradation we should distinguish and fix the following preliminary characteristics:

- R^m – degradation effect caused by the threats as the consequences of initiating events,
- v^m – level of a particular degradation effect,
- $r^i_{(k)}$ – state of the process of environment degradation of the environment sub-region D_k,
- ℓ_k – number of environment degradation states of the environment sub-region D_k.

Example – application of the process of environment degradation to accidents within sea waters

The process of environment degradation is considered for the same five sub-regions distinguished in the process of environment threats that were mentioned in Section 3.

We distinguished five possible environment degradation effects in the neighbourhood region of the ship accident area. There are as follows:

R_1 – the increase of temperature in the accident area,

R_2 – the decrease of oxygen concentration,

R_3 – the disturbance of the air pH regime,

R_4 – the aesthetic nuisance (caused by smells, fume, discoloration etc.) in the accident area,
R_5 – pollution in the accident area.

Each environment degradation effect may reach one of few levels. For instance, the air temperature in the accident area can increase the value from one of three intervals: (10°C, 20°C>, (20°C, 30°C>, or (30°C, ∞). Thus, the air temperature in the accident area can reach 1, 2 or 3 level.

Similarly, the remaining environment degradation effects for particular sub-regions are expressed in the scale from 1 (slight) up to 3 (extreme). Moreover, 0 means there are no degradation effects.

The states of the process of environment degradations were defined as the vector where 0 means the degradation effect does not appear but other digit means the level of appeared degradation effect.

For instance, the vector:

- [0,0,0,0,0] means there are no degradation effects and the environment region of the accident area is not degraded,
- [1,0,0,0,0] means the temperature in the accident area has changed, (a digit on the 1st place in the vector, therefore degradation effect R_1 appears and temperature in the accident area increased the value up to 1 level (10°C, 20°C>),
- [2,0,0,0,0] means the temperature in the accident area has changed, (a digit on the 1st place in the vector, therefore degradation effect R_1 appears and temperature in the accident area increased the value up to 2 level (20°C, 30°C>),
- [1,0,1,0,0] means the temperature and pH in the accident area have changed, (a digit on the 1st and 3rd place in the vector, therefore degradation effect R_1 and R_3 appear and both temperature and pH in the accident area increased the value up to 1 level (20°C, 30°C> and ±1 unit) respectively.

Finally, we fixed $\ell_1 = 30$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ states of environment degradation for particular sub-regions that are given in Section 4.3 in [Bogalecka & Kołowrocki, 2016b].

Moreover, the process of environment degradation of the each sub-region is involved with the process of environment threats. Namely, the state of the process of environment degradation is conditional upon the state of the process of environment threats that caused the previous one. Then $r^i_{(k/\upsilon)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$, $\upsilon = 1,2,\ldots,\upsilon_k$, mean the state of the process of environment degradation of the environment sub-region D_k, $k = 1,2,\ldots,n_3$, when the process of environment threats is at the state $s^\upsilon_{(k)}$, $\upsilon = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$.

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

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

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

$$i = 1,2,...,\ell_k,\ k = 1,2,\ldots,n_3. \qquad (2)$$

The examples of modeling, identification and prediction of the process of environment degradation for critical infrastructure accidents within the Baltic Sea and the world sea waters are given respectively in [Bogalecka & Kołowrocki, 2017d,i].

5. Critical infrastructure accident losses

The losses associated with particular environment degradation states are involved with negative consequences in the accident area. The types of consequences are various for different kinds of accident and accident area. The losses can be expressed by the cost of the negative consequences. In the case of negative consequences like people death, the losses can be expressed as the number of loss of life [Bogalecka & Kołowrocki, 2017e].

Example – critical infrastructure accident losses within sea waters area

In the paper we only consider the accident consequences that can be expressed by cost – K^i. In the shipping, we distinguished the $\xi = 7$ following negative consequences of critical infrastructure accident within the sea waters area:

K^1 – closure of fishery area,
K^2 – closure of beaches,
K^3 – closure of hotels,
K^4 – closure of port,
K^5 – hold up shipping,
K^6 – evacuation of people,
K^7 – cleanup of accident area.

We estimated the cost of above particular negative consequences applying the procedures given in [Kontovas et al, 2011], [Goldstein & Ritterling, 2001], Etkin, 1999], [Psaraftis, 2008] as well as considering the comments and opinions coming from experts.

Thus, a single loss $L^i_{(k)}(t)$, $i = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$, for the sub-region D_k, $k = 1,2,\ldots,n_3$, is expressed by the total cost of all consequences lasting t in the sub-region D_k [Bogalecka & Kołowrocki, 2018]

$$L^i_{(k)}(t) \cong \sum_{j=1}^{\xi} [K^i_{(k)}(t)]^{(j)}, \ t \in <0,+\infty), \tag{3}$$

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

where ξ means the number of kinds of accident consequences.

The expected value of the losses $L_{(k)}(t)$ associated with the process of the environment degradation of the sub-region D_k, $k = 1,2,\ldots,n_3$, is defined by [Bogalecka & Kołowrocki, 2018]

$$L_{(k)}(t) \cong \sum_{i=1}^{\ell_k} q^i_{(k)} \cdot L^i_{(k)}(t), \tag{4}$$

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

and finally, a sum of losses given by (4) expresses total losses $L(t)$ in all sub-regions of the considered critical infrastructure operating environment region that is given in [Bogalecka & Kołowrocki, 2018]

$$L(t) \cong \sum_{k=1}^{n_3} L_{(k)}(t), \ t \in <0,+\infty). \tag{5}$$

6. Critical infrastructure accident losses related to the climate-weather change process impact

We consider that the climate-weather change process (C-WCP) [Kołowrocki & Soszyńska-Budny, 2016] affects the losses associated with the process of the environment degradation [Bogalecka & Kołowrocki, 2017f].

There are $w = 6$ climate-weather states c_b, $b = 1,2,\ldots,w$, distinguished for the ship operating area at the open and restricted waters:

c_1 – the wave height belongs to the interval <0, 2) m and the wind speed belongs to the interval <0, 17) m/s,
c_2 – the wave height belongs to the interval <2, 5) m and the wind speed belongs to the interval <0, 17) m/s,
c_3 – the wave height belongs to the interval <5, 14) m and the wind speed belongs to the interval <0, 17) m/s,
c_4 – the wave height belongs to the interval <0, 2) m and the wind speed belongs to the interval <17, 33) m/s,
c_5 – the wave height belongs to the interval <2, 5) m and the wind speed belongs to the interval <17, 33) m/s,
c_6 – the wave height belongs to the interval <5, 14) m and the wind speed belongs to the interval <17, 33) m/s;

and $w = 6$ climate-weather states c_b, $b = 1,2,\ldots,w$ for the ship operating area at the port waters:

c_1 – the wind speed belongs to the interval <0, 17) m/s and the wind direction belongs to the interval <0, 22.5) or <67.5, 112.5) or <337.5, 360)°,
c_2 – the wind speed belongs to the interval <17, 33) m/s and the wind direction belongs to the interval <0, 22.5) or <67.5, 112.5) or <337.5, 360)°,
c_3 – the wind speed belongs to the interval <0, 17) m/s and the wind direction belongs to the interval <22.5, 67.5) or <112.5, 247.5)°,
c_4 – the wind speed belongs to the interval <17, 33) m/s and the wind direction belongs to the interval <22.5, 67.5) or <112.5, 247.5)°,
c_5 – the wind speed belongs to the interval <17, 33) m/s and the wind direction belongs to the interval <247.5, 337.5)°,
c_6 – the wind speed belongs to the interval <17, 33) m/s and the wind direction belongs to the interval <247.5, 337.5)°.

The limit values of transient probabilities q_b, $b = 1,2,\ldots,w$ of C-WCP at particular states c_b, $b = 1,2,\ldots,w$ are given in [Kołowrocki et al, 2018].

The environmental losses, impacted by C-WCP [Kołowrocki & Soszyńska-Budny, 2016, 2017], in the considered sub-region D_k, $k = 1,2,\ldots,n_3$, are defined by [Bogalecka & Kołowrocki, 2018]

$$[L^i_{(k)}(t)]^{(b)} = [\rho^i_{(k)}]^{(b)} \cdot L^i_{(k)}(t), \ t \in <0,+\infty), \tag{6}$$

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

and are understood as losses without considering climate-weather impact determined by (3) and coefficient $[\rho^i_{(k)}]^{(b)}$, $i = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$, $b = 1,2,\ldots,w$, given by (14) in [Bogalecka & Kołowrocki, 2018] expresses the climate-weather change process impact on these losses. The value of coefficient $[\rho^i_{(k)}]^{(b)}$, $i = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$,

$b = 1,2,\ldots,w$ of the climate-weather impact on losses according to the states c_b, $b = 1,2,\ldots,w$ of the C-WCP at the open waters are given in *Table 1*.

Table 1. The coefficient of the climate-weather impact on environment losses at the open waters

Sub-region D_k	State of C-WCP c_b	Coefficient of C-WCP impact $[\rho^i_{(k)}]^{(b)}$
D_1	c_1, c_2, c_3	1
	c_4, c_5, c_6	2
D_2	c_1	1
	c_2	2
	c_3, c_5	2.5
	c_4	1.8
	c_6	3
D_3	$c_1, c_4,$	1
	$c_2, c_5,$	2
	c_3, c_6	3
D_4	$c_1, c_2, c_3, c_4, c_5, c_6$	1
D_5	$c_1, c_2, c_3, c_4, c_5, c_6$	1

Moreover, by (3) and (6) the conditional expected value of the losses associated with the process of the environment degradation of the sub-region D_k, $k = 1,2,\ldots,n_3$, impacted by the C-WCP is expressed by [Bogalecka & Kołowrocki, 2018]

$$[L_{(k)}(t)]^{(b)} \cong \sum_{i=1}^{\ell_k} q^i_{(k)} \cdot [L^i_{(k)}(t)]^{(b)}, \quad (7)$$

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

The unconditional approximate expected value of the environmental losses, impacted by the C-WCP, associated with the process of the environment degradation of the sub-region D_k, $k = 1,2,\ldots,n_3$ is expressed by [Bogalecka & Kołowrocki, 2018]

$$\bar{L}_{(k)}(t) \cong \sum_{b=1}^{w} q_b \cdot [L_{(k)}(t)]^{(b)}, \quad (8)$$

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

and finally, a sum of losses given by (8) expresses the total losses $\bar{L}(t)$ impacted by C-WCP in all sub-regions of the considered critical infrastructure operating environment region that is given by [Bogalecka & Kołowrocki, 2018]

$$\bar{L}(t) \cong \sum_{k=1}^{n_3} \bar{L}_{(k)}(t), \quad t \in < 0,+\infty). \quad (9)$$

Other practically interesting characteristics of the environment degradation caused by critical infrastructure accident consequences related to the climate-weather are the indicators of the environment of the sub-regions D_k, $k = 1,2,\ldots,n_3$, resilience to the losses associated with the critical infrastructure accident related to the climate-weather change that is given by [Bogalecka & Kołowrocki, 2018]

$$RI_{(k)}(t) = L_{(k)}(t) / \bar{L}_{(k)}(t), \quad (10)$$

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

and the indicator of the environment of the entire region D resilience to the total losses associated with the critical infrastructure accident consequences related to the climate-weather change that is given by [Bogalecka & Kołowrocki, 2018]

$$RI(t) = L(t) / \bar{L}(t), \quad t \in < 0,+\infty). \quad (11)$$

7. Application of general model of critical infrastructure accident consequences to Case Study 2: chemical spill due to extreme sea surges

The Case Study is concern with the framework of EU-CIRCLE project [Bogalecka & Kołowrocki, 2017a]. The probabilistic general model of critical infrastructure accident consequences including three processes: the process of initiating events, process of environment threats and process of environment degradation are applied in the Scenario 2 of the Case Study. The models of critical infrastructure accident losses with considering climate-weather change process impact are applied as well.

7.1. Experiment description

On the basis of the statistical data coming from reports of chemical accidents at sea, the risk of dangerous chemicals accidents at sea and their dangerous consequences are modelled, identified and predicted. Further, under the assumption of the stress of weather influence on the operation conditions in the form of maritime storm and/or other hard sea conditions existence, the risk of chemical spills at sea and their consequences are examined and the results are compared with the previous results.
The risk of chemical spills at sea and the consequences of environment degradation

optimization and mitigation will be performed and practical suggestions and procedures decreasing the risk of the environment degradation will be worked out.

7.2. Experiment area dimension and description

The experiment area is placed in the neighbourhood of the maritime ferry route. The considered maritime ferry is a passenger Ro-Ro ship operating at the Baltic Sea between Gdynia and Karlskrona ports on regular everyday line. The approximate length of the maritime ferry sea water route is equal to 250 km (*Figure 2*).

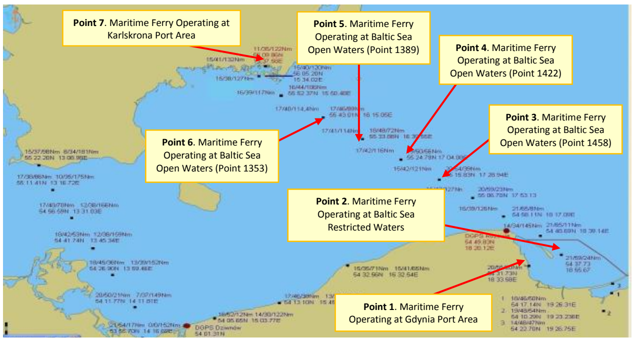

Figure 2. Maritime ferry route between Karlskrona Port and Gdynia Port.

In *Figure 2*, there are shown additionally, the measurement points from which data describing the climate-weather change process at the maritime ferry operating area were collected.

7.3. Application of the GMU Safety Interactive Platform in Case Study 2

The GMU Safety Interactive Platform is accessed throw the Gdynia Maritime University (GMU) website (http://gmu.safety.am.gdynia.pl) and contains the computer software supports the Case Study 2.

7.3.1. Input data

On the basis of statistical data coming from experts, the process of initiating events, the process of environment threats and the process of environment degradation was identified and its main characteristics were predicted. The conditional approximate values of transient probabilities p^l, $l = 1,2,\ldots,\omega$, $p^i_{(k/l)}$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$, and $q^i_{(k/\upsilon)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$, $\upsilon = 1,2,\ldots, \upsilon_k$, at the particular states of the process of initiating events, process of environment threats and process of environment degradation are the final result of the prediction of these processes respectively. The results are the main input data to perform the Scenario 2 of Case Study 2 supported with the GMU Safety Interactive Platform as well.

Additionally, the cost of accident consequences associated with particular environment degradation states, during the time t for the particular sub-regions have to be estimated.

Moreover, to examine the climate-weather impact on the critical infrastructure accident consequences, the following data are necessary:

– states c_b, $b = 1,2,\ldots,w$ of the C-WCP and the limit values of transient probabilities of C-WCP at the particular climate-weather states [Kołowrocki & Soszyńska-Budny, 2016, 2017], [Kołowrocki et al, 2018],
– coefficient $[\rho^i_{(k)}]^{(b)}$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$, $b = 1,2,\ldots,w$ of the climate-weather impact on environmental total losses.

7.3.2. Output data

The input data mentioned in Section 7.3.1 allow to get the output data. There are as follows:

– limit forms of total probabilities $q^i_{(k)}$, $k = 1,2,\ldots,n_3$, $i = 1,2,\ldots,\ell_k$ of the joined process of environment degradation, process of environment threats and process of initiating events, applying (1)-(2),
– the single loss $L^i_{(k)}(t)$, $i = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$, and conditional losses $L_{(k)}(t)$, $k = 1,2,\ldots,n_3$, associated with the process of the environment degradation for the fixed time in the particular sub-regions as well as total losses $L(t)$ within the entire region D, applying (3), (4) and (5) respectively,
– the single loss $[L^i_{(k)}(t)]^{(b)}$, $k = 1,2,\ldots,n_3$, $i = 1,2,\ldots,\ell_k$, $b = 1,2,\ldots,w$ and conditional losses $[L_{(k)}(t)]^{(b)}$, $k = 1,2,\ldots,n_3$, $b = 1,2,\ldots,w$ associated with the process of the environment degradation impacted by C-WCP in the considered sub-region D_k, $k = 1,2,\ldots,n_3$, applying (6) and (7) respectively,
– the unconditional approximate expected value of the environmental losses $\bar{L}_{(k)}(t)$, $k = 1,2,\ldots,n_3$, impacted by C-WCP in the particular sub-regions as well as total losses $\bar{L}(t)$ impacted by C-WCP within the entire region D, applying (8) and (9) respectively,
– the indicators of the environment of the sub-regions D_k, $k = 1,2,\ldots,n_3$, and the entire region D, resilience to the losses associated with the critical infrastructure accident related to the climate-

weather change, applying (10) and (11) respectively.

7.3.3. Example of GMU Safety Interactive Platform application in Case Study 2

The below example concerns the Baltic Sea open waters and only one environment sub-region (D_1 – air) that may be degraded by the environment threats.
The input data are:

– the conditional approximate values of transient probabilities p^l, l = 1,2,…,16 (that are not equal to 0), at the particular states of the process of initiating events:

$$p^1 = 0.9998607108,\ p^2 = 0.0000000738,$$

$$p^3 = 0.0001288857,\ p^4 = 0.0000000062,$$

$$p^5 = 0.0000015165,\ p^6 = 0.0000072805,$$

$$p^7 = 0.0000015008,\ p^8 = 0.0000000051,$$

$$p^{10} = 0.0000000102,\ p^{13} = 0.0000000102; \quad (12)$$

– the conditional approximate values of transient probabilities $p^i_{(k/l)}$, i = 1,2,…,35, k = 1, l = 1,2,…,16, (that are not equal to 0) at the particular states of the process of environment threats for the sub-region D_1:

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

$$p^1_{(1/3)} = 0.00474,\ p^{27}_{(1/3)} = 0.42654,$$

$$p^{30}_{(1/3)} = 0.56872,\ p^1_{(1/4)} = 1,\ p^1_{(1/5)} = 1,$$

$$p^1_{(1/6)} = 1,\ p^1_{(1/7)} = 1,\ p^1_{(1/8)} = 0.00415,$$

$$p^6_{(1/8)} = 0.99585,\ p^1_{(1/10)} = 1,\ p^1_{(1/13)} = 1; \quad (13)$$

– the conditional approximate values of transient probabilities $q^i_{(k/\upsilon)}$, i = 1,2,…,30, k = 1, υ_1 = 35, (that are not equal to 0) at the particular states of the process of environment degradation for the sub-region D_1:

$$q^1_{(1/1)} = 1,\ q^1_{(1/6)} = 0.00415,\ q^2_{(1/6)} = 0.99585,$$

$$q^1_{(1/27)} = 0.00415,\ q^6_{(1/27)} = 0.99585,$$

$$q^1_{(1/30)} = 0.00415,\ q^{11}_{(1/30)} = 0.99585; \quad (14)$$

– the losses $L^i_{(k)}(t)$, i = 1,2,…,35, k = 1, expressed by the total cost of all consequences, associated with particular environment degradation states, during the time t = 1 hour, for the sub-region D_1:

$$L^1_{(1)}(1) = \sum_{j=1}^{7}[K^1_{(1)}(1)]^{(j)} = 0 \text{ PLN},$$

$$L^2_{(1)}(1) = \sum_{j=1}^{7}[K^2_{(1)}(1)]^{(j)} = 5000 \text{ PLN},$$

$$L^6_{(1)}(1) = \sum_{j=1}^{7}[K^6_{(1)}(1)]^{(j)} = 5000 \text{ PLN},$$

$$L^{11}_{(1)}(1) = \sum_{j=1}^{7}[K^{11}_{(1)}(1)]^{(j)} = 7000 \text{ PLN}; \quad (15)$$

– the coefficient $[\rho^i_{(k)}]^{(b)}$, i = 1,2,…,35, k = 1, b = 1,2,…,6 of the climate-weather impact on losses according to the states c_b, b = 1,2,…,6 of the C-WCP are given in *Table 1*.
– the approximate limit values of transient probabilities q_b, b = 1,2,…,6 of the C-WCP, at the climate-weather states for the open waters operating area [Kołowrocki et al., 2018]:

$$q_1 = 0.834,\ q_2 = 0.149,\ q_3 = 0,\ q_4 = 0,$$

$$q_5 = 0.015,\ q_6 = 0.002. \quad (16)$$

The output data are:

– considering (12)-(14) and applying (1)-(2), the unconditional approximate values of transient probabilities $q^i_{(k)}$, i = 1,2,…,30, k = 1 (that are not equal to 0) of the process of the environment degradation, for the sub-region D_1, at its particular states for sufficiently large t:

$$q^1_{(1)} = 0.999872179003445,$$

$$q^2_{(1)} = 0.000000005069726,$$

$$q_{(1)}^{6} = 0.000054820128704,$$

$$q_{(1)}^{11} = 0.000072995798125; \quad (17)$$

– considering (15), (17) and applying (3)-(4), the value of losses $L_{(k)}(t)$, $k = 1$, associated with process of the environment degradation during the time $t = 1$ hour, in the sub-region D_1 amounts:

$$L_{(1)}(1) \cong 0.999872179003445 \cdot 0 + 0.000000005069726 \cdot 5000 + 0.000054820128704 \cdot 5000 + 0.000072995798125 \cdot 7000 \cong 0.785 \text{ PLN}; \quad (18)$$

– considering (15) and data given in *Table 1*, and applying (3), (6), the conditional approximate expected value of the losses $[L_{(k)}^{i}(t)]^{(b)}$, $i = 1,2,\ldots,30$, $k = 1$, $b = 1,2\ldots6$, during the time $t = 1$ hour, associated with the process of the environment degradation, in the sub-region D_1, according to the state c_b, $b = 1,2\ldots6$, of the C-WCP at the open waters amounts:

$$[L_{(1)}^{i}(1)]^{(b)} \cong 1.0 \cdot 0 = 0 \text{ PLN},$$

for $b = 1,2,3,4,5,6$, $i = 1$,

$$[L_{(1)}^{i}(1)]^{(b)} \cong 1.0 \cdot 5000 = 5000 \text{ PLN},$$

for $b = 1,2,3$, $i = 2,6$,

$$[L_{(1)}^{i}(1)]^{(b)} \cong 1.0 \cdot 7000 = 7000 \text{ PLN},$$

for $b = 1,2,3$, $i = 11$,

$$[L_{(1)}^{i}(1)]^{(b)} \cong 2.0 \cdot 5000 = 10000 \text{ PLN},$$

for $b = 4,5,6$, $i = 2,6$,

$$[L_{(1)}^{i}(1)]^{(b)} \cong 2.0 \cdot 7000 = 14000 \text{ PLN},$$

for $b = 4,5,6$, $i = 11$; (19)

– considering (17), (19) and applying (7), the conditional approximate expected value of the environmental losses $[L_{(k)}(t)]^{(b)}$, $b = 1,2\ldots6$, $k = 1$, during the time $t = 1$ hour, associated with the process of the environment degradation of the sub-region D_1, impacted by the C-WCP, at the open waters, amounts:

$$[L_{(1)}(1)]^{(b)} \cong 0.999872179003445 \cdot 0 + 0.000000005069726 \cdot 5000 + 0.000054820128704 \cdot 5000 + 0.000072995798125 \cdot 7000 \cong 0.785 \text{ PLN},$$

for $b = 1,2,3$,

$$[L_{(1)}(1)]^{(b)} \cong 0.999872179003445 \cdot 0 + 0.000000005069726 \cdot 10000 + 0.000054820128704 \cdot 10000 + 0.000072995798125 \cdot 14000 \cong 1.570 \text{ PLN},$$

for $b = 4,5,6$; (20)

– considering (16), (20) and applying (8), the unconditional approximate expected value of the environmental losses $\overline{L}_{(k)}(t)$, $k = 1$, during the time $t = 1$ hour, impacted by the C-WCP amounts:

$$\overline{L}_{(1)}(1) \cong 0.834 \cdot 0.785 + 0.149 \cdot 0.785 + 0 \cdot 0.785 + 0 \cdot 1.570 + 0.015 \cdot 1.570 + 0.002 \cdot 1.570 \cong 0.798 \text{ PLN}; \quad (21)$$

– considering (18), (21) and applying (10), the indicator of the environment of the sub-regions D_k, $k = 1,2,\ldots,n_3$, resilience to the losses associated with the critical infrastructure accident related to the climate-weather change amounts:

$$RI_{(1)}(1) = \frac{0.785}{0.798} = 0.984 = 98.4\%. \quad (22)$$

7.3.4. Other results and discussion

The results presented in Section 7.3.3 are concerned to the sub-region D_1 (air) at the Baltic Sea open waters operating area. For the time $t = 1$ hour, the value of losses associated with the process of the environment degradation without considering the climate-weather impact calculated in (18) is $L_{(1)}(1) \cong 0.785$ PLN, whereas the value of losses impacted by C-WCP increases and according to (21) is $\overline{L}_{(1)}(1) \cong 0.798$ PLN.

The value of losses does not increase when C-WCP is at the state c_1, c_2 or c_3, because the wind speed at these states is soft in the opposite to wind speed when C-WCP is at the state c_4, c_5 or c_6. It causes the stagnation in the air then the air degradation effects do not spread off. Thus, the degradation effects occur on a smaller area. The wave height is not significant for the critical infrastructure accident losses in the air.
The results (output data) for the other sub-regions were obtained in the same way as presented in Section 7.3.3. The results are as follows:

– the unconditional approximate values of transient probabilities $q_{(k)}^{i}$, $i = 1,2,...,\ell_k$, $k = 2,3,4,5$, $\ell_2 = 28$, $\ell_3 = 28$, $\ell_4 = 31$, $\ell_5 = 23$ (that are not equal to 0) of the process of the environment degradation, for the sub-region D_k, $k = 2,3,4,5$ at its particular states for sufficiently large t:

$q_{(2)}^{1} = 0.999871085266778,$

$q_{(2)}^{6} = 0.000016170471066,$

$q_{(2)}^{12} = 0.000032213681563,$

$q_{(2)}^{16} = 0.000042280457051,$

$q_{(2)}^{21} = 0.000032213681563,$

$q_{(2)}^{25} = 0.000003353578877,$

$q_{(2)}^{27} = 0.000002682863102;$

$q_{(3)}^{1} = 0.999871085266778,$

$q_{(3)}^{6} = 0.000016170471066,$

$q_{(3)}^{12} = 0.000032213681563,$

$q_{(3)}^{16} = 0.000042280457051,$

$q_{(3)}^{21} = 0.000032213681563,$

$q_{(3)}^{25} = 0.000003353578877,$

$q_{(3)}^{27} = 0.000002682863102;$

$q_{(4)}^{1} = 0.999871139828533,$

$q_{(4)}^{12} = 0.000036818375059,$

$q_{(4)}^{16} = 0.000048324117265,$

$q_{(4)}^{21} = 0.000036818375059,$

$q_{(4)}^{28} = 0.000003832946714,$

$q_{(4)}^{30} = 0.000003066357371;$

$q_{(5)}^{1} = 1; \quad (23)$

– the value of losses $L_{(k)}(t)$, $k = 2,3,4,5$, associated with the process of the environment degradation, during the time $t = 1$ hour, in the sub-region D_k, $k = 2,3,4,5$, amounts:

$L_{(2)}(1) \cong 2.467$ PLN,

$L_{(3)}(1) \cong 3.091$ PLN,

$L_{(4)}(1) \cong 3.072$ PLN,

$L_{(5)}(1) = 0$ PLN; (24)

– the conditional approximate expected value of the environmental losses $[L_{(k)}(t)]^{(b)}$, $b = 1,2\ldots6$, $k = 2,3,4,5$, during the time $t = 1$ hour, associated with the process of the environment degradation of the sub-region D_k, $k = 2,3,4,5$, impacted by the C-WCP, at the open waters, amounts:

$[L_{(2)}(1)]^{(b)} \cong$ 2.467 PLN, for b = 1,

$[L_{(2)}(1)]^{(b)} \cong$ 4.934 PLN, for b = 2,

$[L_{(2)}(1)]^{(b)} \cong$ 6.167 PLN, for b = 3,5,

$[L_{(2)}(1)]^{(b)} \cong$ 4.440 PLN, for b = 4,

$[L_{(2)}(1)]^{(b)} \cong$ 7.401 PLN, for b = 6; (25)

$[L_{(3)}(1)]^{(b)} \cong$ 3.091 PLN, for b = 1,4,

$[L_{(3)}(1)]^{(b)} \cong$ 6.183 PLN, for b = 2,5,

$[L_{(3)}(1)]^{(b)} \cong$ 9.274 PLN, for b = 3,5; (26)

$[L_{(4)}(1)]^{(b)} \cong$ 3.072 PLN, for b = 1,2,...,6; (27)

$[L_{(5)}(1)]^{(b)} =$ 0 PLN, for b = 1,2,...,6; (28)

– the unconditional approximate expected value of the environmental losses $\bar{L}_{(k)}(t)$, k = 2,3,4,5, during the time t = 1 hour, impacted by the C-WCP amounts:

$$\bar{L}_{(2)}(1) \cong 2.900 \text{ PLN}, \quad \bar{L}_{(3)}(1) \cong 3.611 \text{ PLN},$$

$$\bar{L}_{(4)}(1) \cong 3.072 \text{ PLN}, \quad \bar{L}_{(5)}(1) = 0 \text{ PLN}; \tag{29}$$

– the indicators of the environment of the sub-regions D_k, k = 2,3,4,5, resilience to the losses associated with the critical infrastructure accident related to the climate-weather change amount:

$$RI_{(2)}(1) = 0.851 = 85.1\%,$$

$$RI_{(3)}(1) = 0.856 = 85.6\%,$$

$$RI_{(4)}(1) = 1 = 100\%,$$

$$RI_{(5)}(1) = 1 = 100\%. \tag{30}$$

Additional results, regarding the entire region D are as follows:

– considering (18), (24) and according to (5), the total expected value of losses $L(t)$, during the time t = 1 hour, associated with the process of the environment degradation in all sub-regions of the considered critical infrastructure operating environment region D, is

$$L(1) = 9.415 \text{ PLN}; \tag{31}$$

– considering (21), (29) and according to (9), the total expected value of losses $\bar{L}(t)$, during the time t = 1 hour, impacted by the C-WCP, associated with the process of the environment degradation in all sub-regions of the considered critical infrastructure operating environment region D, is

$$\bar{L}(1) \cong 10.381 \text{ PLN}; \tag{32}$$

– considering (31)-(32) and according to (11), the indicator $RI(t)$, of the environment of the entire region D resilience to the losses associated with the critical infrastructure accident related to the climate-weather change is

$$RI(1) = 0.907 = 90.7\%. \tag{33}$$

We assume that the value of losses associated with process of the environment degradation is the same at any given moment of the particular environment degradation state duration. Thus, the each next hour of environment degradation state duration causes the losses where the value is a multiple of state time duration and (18) and (24) or (21) and (29) respectively. Taking this into account, the graph of the function of environmental total losses associated with the process of the environment degradation no impacted and impacted by C-WCP is given in *Figure 3*.

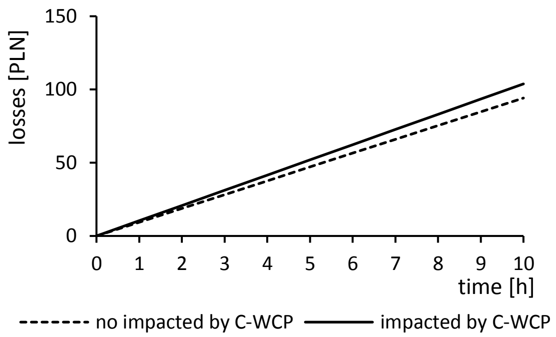

Figure 3. The graph of the function of environmental total losses associated with the process of the environment degradation no impacted and impacted by C-WCP.

8. Conclusion

The general model of critical infrastructure accident consequences proposed in [Bogalecka & Kołowrocki, 2016b], [Blokus-Roszkowska et al., 2017] was applied to prediction of the critical infrastructure accident consequences generated by the critical infrastructure defined as a ship operating in the Baltic Sea area and to cost analysis of losses associated with these consequences as well. Moreover, the losses of critical infrastructure accident consequences impacted by the climate-weather change process were analysied and compare with losses without considering the climate-weather impact.

The application of this model is supported by suitable computer software that is placed at the GMU Safety Interactive Platform http://gmu.safety.am.gdynia.pl/.

The results will be applied to the accident consequences cost optimization through the accident losses minimizing [Bogalecka & Kołowrocki, 2018].

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/.

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