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Modelling operation process of Global Baltic Network of Critical Infrastructure Networks

Keywords

critical infrastructure, critical infrastructure network, operation process, network of critical infrastructure networks

Abstract

The paper presents an approach to modelling operation process of critical infrastructure networks located within certain area. The approach has been conducted basing on networks located within the Baltic Sea area, being however also general concept of network of critical infrastructure networks operational process analysis. Operation process of particular critical infrastructure network has been defined, and then its characteristics described, by applying a semi-Markov processes modelling approach. Further, similar approach has been conducted to model operation process of network of critical infrastructure networks. On the base of models of operation processes of certain critical infrastructure network, and network of critical infrastructure networks, general approach to Global Baltic Network of Critical Infrastructure Networks modelling is presented as well.

1. Introduction

Critical infrastructure systems protection has become last years very important part of many public institutions and entrepreneurs activities. This is coming out of both: increasing menace of terrorist attacks usually concentrated on critical infrastructures, and increasing amount of different kinds of elemental disasters taking place in the near past, that also caused significant negative impact on critical infrastructure systems [7]). It is also predicted, forecasted climate changes will significantly impact on critical infrastructure assets, too. Thus, intensive works on adapting infrastructures to possible climate fluctuations, have been processed for last couple of years [17]-[18].

The Baltic Sea area is a region significantly fitted with various critical infrastructure systems. Additionally, geographical conditions of the area, cause potential failure of one of the systems, can lead to a massive negative impact on natural environment and societies located within and around. Also, predicted climate changes do have significant meaning for the Baltic Sea and critical infrastructures located within: one of the greatest (within Europe) increases in sea surface temperature; decreasing trend in the Baltic Sea's ice cover; falling level of the Baltic in the northern shores and rising to the south; increased beach erosion due to increased storminess in the eastern Baltic Sea; and increasing eutrophication problems in coastal waters [7]. Main socio-economic implications coming out of forecasted climate changes are: high vulnerability of southern part of the Baltic coast to sea level rise flooding; impact on sea-life and therefore on fisheries and aquaculture of warmer, more acidic seawater; increasing risks of inundation and erosion of coastal road transport networks, causing disruptions in the transport of goods and in the mobility of local communities; energy production located in coastal areas, threatened by climate change induced storm surges, sea-level rise and flooding; impacts on agriculture, resulting in extreme cases, a reduction in suitable areas for cultivation in certain European regions; and erosion and flooding of sensitive coastal ecosystems such as brackish waters and tidal pools [17].

In terms of the Baltic Sea area, following matters are pointed concerning critical infrastructure systems reflecting predicted climate changes: protecting built environments against floods or ensuring water and energy supply during consumption peaks; infrastructure in coastal areas as well as off-shore

installations (e.g. transmission lines, wind turbines), affected by sea level rise; increasing frequency and intensity of extreme weather events (e.g. storms, heat waves, flooding) having significant impact on the functioning of transport infrastructure; consequences of climate change for transport infrastructure such as for rail, road, shipping and aviation; increased frequency of extreme weather events or changing water and air temperatures having effects on energy transmission, distribution, generation and demand; and floods, identified as a particular threat to electricity generators and related physical assets [18].
Basing on above mentioned issues, the analysis of industry installations and other systems performing activities within the Baltic Sea area, including prognosis of their developments has been performed. Moreover, the specification of criteria determining particular systems as the critical infrastructure subsystems, reflecting climate influence on their operation was done as well [2]. After that, 8 Baltic critical infrastructure networks for various existing in the region industrial installations were defined and analysed [1], [3]-[6], [21]-[23] and 1 network of 3 most natural and typical for Baltic Sea Region critical infrastructure networks was defined and its operation process was primarily modelled [20].
The intention of the article is to make an effort in order to conceptualize a global network of all considered critical infrastructures within the Baltic Sea area and create it as Baltic critical infrastructure "network of networks".
To do this generally, we consider a certain fixed area of the Baltic Sea Region and suppose there is a number of critical, interacting and interconnected infrastructure networks, operating within.

2. Operation processes of Baltic critical infrastructure networks

We assume, that there are $k, k \in N$ of interconnected and interdependent Baltic critical infrastructure networks $BCIN^{(i)}$, $i = 1,2,...,k$, interacting directly and indirectly at various levels of their complexity and operating activity within this area. Moreover, we suppose that the operation processes of these critical infrastructure networks have an influence on their safety and on their operating environment safety as well.
To describe this influence, we start with constructing a general model of the Global Baltic Network of Critical Infrastructure Networks (GBNCIN) and its general operation process. To do this, we assume that the GBNCIN is composed of k Baltic Critical Infrastructure Networks (BCIN) marked by

$$BCIN^{(i)}, \ i = 1,2,...,k,$$

that during their operation process can take respectively $\nu^{(i)}, \nu^{(i)} \in N,$ different operation states

$$z_1^{(i)}, z_2^{(i)}, ..., z_{\nu^{(i)}}^{(i)},$$

Further, we define respectively those critical infrastructure networks' operation processes

$$Z^{(i)}(t), \ t \in \langle 0,+\infty), \ i = 1,2,...,k, \tag{1}$$

with discrete operation states from the sets

$$Z^{(i)} = \{z_1^{(i)}, z_2^{(i)}, ..., z_{\nu^{(i)}}^{(i)}\}, \ i = 1,2,...,k. \tag{2}$$

To model this processes, we can assume that the critical infrastructure operation processes $Z^{(i)}(t)$, $t \in \langle 0,+\infty)$, $i = 1,2,...,k,$ are semi-Markov processes [19], [24], [25]-[27] with the conditional sojourn times $\theta_{bl}^{(i)}$ at the operation states $z_b^{(i)}$ when its next operation state is $z_l^{(i)}$, $b, l = 1,2,..., \nu^{(i)}$, $b \neq l.$
Under these assumptions, the particular critical infrastructure network $BCIN^{(i)}$, $i = 1,2,...,k,$ operation process $Z^{(i)}(t)$, $t \in \langle 0,+\infty)$, $i = 1,2,...,k,$ may be described by the following parameters:
- the vector

$$[p_b^{(i)}(0)]_{1 \times \nu^{(i)}} = [p_1^{(i)}(0), p_2^{(i)}(0), ..., p_{\nu^{(i)}}^{(i)}(0)] \tag{3}$$

of the initial probabilities

$$p_b^{(i)}(0) = P(Z^{(i)}(0) = z_b^{(i)}), \ b = 1,2,..., \nu^{(i)},$$
$$i = 1,2,...,k, \tag{4}$$

of the critical infrastructure network $BCIN^{(i)}$, $i = 1,2,...,k,$ operation process $Z^{(i)}(t)$ staying at particular operation states at the moment $t = 0;$
- the matrix

$$[p_{bl}^{(i)}]_{\nu^{(i)} \times \nu^{(i)}} = \begin{bmatrix} p_{11}^{(i)} & p_{12}^{(i)} & \cdots & p_{1\nu^{(i)}}^{(i1)} \\ p_{21}^{(i)} & p_{22}^{(i)} & \cdots & p_{2\nu^{(i)}}^{(i)} \\ \cdots & & & \\ p_{\nu^{(i)}1}^{(i)} & p_{\nu^{(i)}2}^{(i)} & \cdots & p_{\nu^{(i)}\nu^{(i)}}^{(i)} \end{bmatrix} \tag{5}$$

of the probabilities

$$p_{bl}^{(i)}, \ b, l = 1,2,..., \nu^{(i)}, \ b \neq l, \tag{6}$$

of the critical infrastructure network operation process $Z^{(i)}(t)$ transitions between the operation states $z_b^{(i)}$ and $z_l^{(i)}$, where by formal agreement

$$p_{bb}^{(i)} = 0 \text{ for } b = 1,2,...,\nu^{(i)}; \tag{7}$$

- the matrix

$$[H_{bl}^{(i)}(t)]_{\nu^{(i)} \times \nu^{(i)}} = \begin{bmatrix} H_{11}^{(i)}(t) & H_{12}^{(i)}(t) & \cdots & H_{1\nu^{(i)}}^{(i)}(t) \\ H_{21}^{(i)}(t) & H_{22}^{(i)}(t) & \cdots & H_{2\nu^{(i)}}^{(i)}(t) \\ \cdots & & & \\ H_{\nu^{(i)}1}^{(i)}(t) & H_{\nu^{(i)}2}^{(i)}(t) & \cdots & H_{\nu^{(i)}\nu^{(i)}}^{(i)}(t) \end{bmatrix} \tag{8}$$

of the conditional distribution functions

$$H_{bl}^{(i)}(t) = P(\theta_{bl}^{(i)} < t), \; b,l = 1,2,...,\nu^{(i)}, \; b \neq l, \tag{9}$$

of the critical infrastructure network operation process $Z^{(i)}(t)$ conditional sojourn times $\theta_{bl}^{(i)}$ at the operation states $z_b^{(i)}$ when the next operation state is and $z_l^{(i)}$, where by formal agreement

$$H_{bb}^{(i)}(t) = 0 \text{ for } b = 1,2,...,\nu^{(i)}.$$

3. Operation process of the Global Baltic Network of Critical Infrastructure Networks

As it has been assumed in chapter 2 above, the GBNCIN is a set composed of *k* critical infrastructure networks, i.e.

$$GBNCIN = \{BCIN^{(i)}; \; i = 1,2,...,k, \, k \in N\}$$

Further, we define respectively the GBNCIN operation process

$$Z_{GBNCIN}(t) = \left[Z^{(1)}(t), Z^{(2)}(t), \ldots, Z^{(k)}(t)\right], \tag{10}$$

for $t \in \langle 0, +\infty)$, with the following discrete operation states in the form of a vector from the set

$$Z_{GBNCIN} = \{[z^{(1)}, z^{(2)}, ..., z^{(k)}] : k \in N\} \;\; k \in N, \tag{11}$$

where the vector coordinates $z^{(i)}$ are the discrete operation states of the *i*-th critical infrastructure networks $BCIN^{(i)}$, $i = 1,2,...,k$, respectively from the sets

$$Z^{(i)} = \{z_1^{(i)}, z_2^{(i)}, ..., z_{\nu^{(i)}}^{(i)}\}, \; i = 1,2,...,k, \tag{12}$$

Thus, the number ι of all operation states of the GBNCIN is equal to

$$\iota = \nu^{(1)} \cdot \nu^{(2)} \cdot \ldots \cdot \nu^{(k)}.$$

To simplify the notation, we number the vector operation states from 1 up to ι and we assume that the operation process $Z_{GBNCIN}(t)$, of the GBNCIN is taking the following operation states

$$z_1, z_2, ..., z_\iota. \tag{13}$$

Further, to model the operation process $Z_{GBNCIN}(t)$, $t \in \langle 0, +\infty)$, of the *GBNCIN* it is assumed that this process is a semi-Markov process [19], [24], [25]-[27] with the conditional sojourn times θ_{bl} at the operation states z_b when its next operation state is z_l, $b,l = 1,2,...,\iota$, $b \neq l$.

Under this assumption, the *GBNCIN* operation process $Z_{GBNCIN}(t)$, $t \in \langle 0, +\infty)$, may be described by the following parameters:

- the vector

$$[p_b(0)]_{1 \times \iota} = [p_1(0), p_2(0), ..., p_\iota(0)] \tag{14}$$

of the initial probabilities

$$p_b(0) = P(Z_{GBNCIN}(0) = z_b), \; b = 1,2,...,\iota, \tag{15}$$

of the *GBNCIN* operation process $Z_{GBNCIN}(t)$, $t \in \langle 0, +\infty)$, staying at particular operation states at the moment $t = 0$;

- the matrix

$$[p_{bl}]_{\iota \times \iota} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1\iota} \\ p_{21} & p_{22} & \cdots & p_{2\iota} \\ \cdots & & & \\ p_{\iota 1} & p_{\iota 2} & \cdots & p_{\iota\iota} \end{bmatrix} \tag{16}$$

of the probabilities

$$p_{bl}, \; b,l = 1,2,...,\iota, \; b \neq l, \tag{17}$$

of the *GBNCIN* operation process $Z_{GBNCIN}(t)$, $t \in \langle 0, +\infty)$, transitions between the operation states z_b and z_l, where by formal agreement

$$p_{bb} = 0 \text{ for } b = 1,2,...,\iota; \quad (18)$$

- the matrix

$$[H_{bl}(t)]_{\iota \times \iota} = \begin{bmatrix} H_{11}(t) & H_{12}(t) & \cdots & H_{1\iota}(t) \\ H_{21}(t) & H_{22}(t) & \cdots & H_{2\iota}(t) \\ \cdots \\ H_{\iota 1}(t) & H_{\iota 2}(t) & \cdots & H_{\iota\iota}(t) \end{bmatrix} \quad (19)$$

of the conditional distribution functions

$$H_{bl}(t) = P(\theta_{bl} < t), \; b,l = 1,2,...,\iota, \; b \neq l, \quad (20)$$

of the *GBNCIN* operation process $Z_{GBNCIN}(t)$, $t \in \langle 0, +\infty)$, conditional sojourn times θ_{bl} at the operation states z_b when the next operation state is z_l, where by formal agreement

$$H_{bb}(t) = 0 \text{ for } b = 1,2,...,\iota.$$

4. Detailed approach to Global Baltic Network of Critical Infrastructure Networks modelling

Going into details and considering findings of [1], [3]-[6], [21]-[23], the above general approach to the GBNCIN operation process modelling, we assume the number of this network of networks is composed of $k = 8$ critical infrastructure networks and we mark them respectively as follows:
- the Baltic Port Critical Infrastructure Network (BPCIN) is marked by $BCIN^{(1)}$;
- the Baltic Shipping Critical Infrastructure Network (BSCIN) is marked by $BCIN^{(2)}$;
- the Baltic Oil Rig Critical Infrastructure Network (BORCIN) is marked by $BCIN^{(3)}$;
- the Baltic Wind Farm Critical Infrastructure Network (BWFCIN) is marked by $BCIN^{(4)}$;
- the Baltic Electric Cable Critical Infrastructure Network (BECCIN) is marked by $BCIN^{(5)}$;
- the Baltic Gas Pipeline Critical Infrastructure Network (BGPCIN) is marked by $BCIN^{(6)}$;
- the Baltic Oil Pipeline Critical Infrastructure Network (BOPCIN) is marked by $BCIN^{(7)}$;
- the Baltic Ship Traffic and Port Operation Information Critical Infrastructure Network (BSTPOICIN) by $BCIN^{(8)}$.

Further, we can describe the operation processes

$$Z^{(i)}(t), \; t \in < 0, +\infty), \; i = 1,2,...,8,$$

and the operation states

$$z_1^{(i)}, z_2^{(i)}, ..., z_{\nu^{(i)}}^{(i)},$$

of particular critical infrastructure networks

$$BCIN^{(i)}, \; i = 1,2,...,8,$$

as the introduced in this paper semi-Markov procesess by defining:
- their vectors

$$[p_b^{(i)}]_{1x\nu^{(i)}}, \; i = 1,2,...,8,$$

of the probabilities of initial operation states at the moment $t = 0$;
- their matricies

$$[p_{bl}^{(i)}]_{\nu^{(i)} \times \nu^{(i)}}, \; t \in < 0, +\infty), \; i = 1,2,...,8,$$

of the probabilities of transitions between their operation states.
- their matricies

$$[H_{bl}^{(i)}(t)]_{\nu^{(i)} \times \nu^{(i)}}, \; t \in < 0, +\infty), \; i = 1,2,...,8,$$

of the conditional sojourn times in their operation states.

The next steps in modelling the *GBNCIN* operation process, taking into account just defined processes $Z^{(i)}(t)$, $t \in < 0, +\infty)$, $i = 1,2,...,8$, interactions and interdependences, the joint operation process of this network of critical infrastructure networks can be defined in the form of the vector

$$Z_{GBNCIN}(t) = [Z^{(1)}(t), Z^{(2)}(t), ..., Z^{(8)}(t)],$$
$$t \in < 0, +\infty).$$

According to (13)-(20), the *GBNCIN* operation process $Z_{GBNCIN}(t)$, $t \in \langle 0, +\infty)$, may assume the number

$$\iota = \nu^{(1)} \cdot \nu^{(2)} \cdot \ldots \cdot \nu^{(8)} \qquad (21)$$

of the operation states $z_1, z_2, ..., z_\iota$, and may be described by the following parameters:
- the vector

$$[p_b(0)]_{1\times\iota} \qquad (22)$$

of the initial probabilities of the *GBNCIN* operation process $Z_{GBNCIN}(t),\ t \in \langle 0, +\infty)$, staying at particular operation states at the moment $t = 0$;
- the matrix

$$[p_{bl}]_{\iota\times\iota} \qquad (23)$$

of the probabilities of the *GBNCIN* operation process $Z_{GBNCIN}(t),\ t \in \langle 0, +\infty)$, transitions between the operation states z_b and z_l;
- the matrix

$$[H_{bl}(t)]_{\iota\times\iota} \qquad (24)$$

of the conditional distribution functions of the *GBNCIN* operation process $Z_{GBNCIN}(t),\ t \in \langle 0, +\infty)$, conditional sojourn times θ_{bl} at the operation states z_b when the next operation state is z_l.

The results of this section will be developed in [12] where *GBNCIN* will be finally defined and modelled.

3. Conclusion

Modelling presented in the paper is the basis of the next steps concerned with the *GBNCIN* operation process unknown parameters identification, its characterictics prediction and optimization with respect to the GBNCIN safety and its resilience to climate/weather change that are going to be done in further EU-CIRCLE GMU reports.

Practical applications of the proposed model will be done in [12] to describe the operation process of the *GBNCIN* covering interconnections and interdependences of critical infrastructures this network is composed of and with the climate-weather process change influence using the Critical Infrastructure Operation Process General Model (CIOPGM) related to Operating Environment Threats (OET) and Extreme Weather Hazards (EWE). Further developments of the defined and initially modelled operation process of the GBNCIN will be done in the reports prepared in the next steps of the project research.

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

[1] Blokus-Roszkowska, A., Bogalecka, M., Dziula, P. et al. (2016). Gas pipelines critical infrastructure network. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 7, 2, 1-6.

[2] Blokus-Roszkowska, A., Bogalecka, M. & Kołowrocki, K. (2016). Critical infrastructure networks at Baltic Sea and its seaside. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 7, 2, 7-14.

[3] Blokus-Roszkowska, A., Guze, S., Kołowrocki, K. et al. (2016). Port Critical Infrastructure Network. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 7, 2, 15-28.

[4] Blokus-Roszkowska, A., Kołowrocki, K. & Soszyńska-Budny, J. (2016). Baltic Electric Cables Critical Infrastructure Network. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 7, 2, 29-36.

[5] Bogalecka, M., Kołowrocki, K., Soszyńska-Budny, J., et al. (2016). Shipping critical infrastructure network. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 7, 2, 43-52.

[6] Drzazga, M., Kołowrocki, K., & Soszyńska-Budny, J. (2016). Oil pipeline critical infrastructure network. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 7, 2, 53-60.

[7] Dziula, P. (2015). Selected aspects of acts of law concerning critical infrastructure protection within the Baltic Sea area, *Scientific Journals of the Maritime University of Szczecin*, 44, 116, 173-181.

[8] EU-CIRCLE Report D1.4-GMU2, (2016), *Selected critical infrastructures at the Southern Baltic Sea area and its surroundings identification and their parameters analysis - port, maritime transport and information critical infrastructures network defining*.

[9] EU-CIRCLE Report D2.1-GMU2, (2016), *Modelling outside dependences influence on Critical Infrastructure Safety (CIS) – Modelling Critical Infrastructure Operation Process (CIOP) including Operating Environment Threats (OET).*

[10] EU-CIRCLE Report D2.1-GMU3, (2016), *Modelling outside dependences influence on Critical Infrastructure Safety (CIS) – Modelling Climate-Weather Change Process (C-WCP) including Extreme Weather Events (EWE).*

[11] EU-CIRCLE Report D2.1-GMU4, (2016), *Modelling outside dependences influence on Critical Infrastructure Safety (CIS) - Designing Critical Infrastructure Operation Process General Model (CIOPGM) related to Operating Environment Threats (OET) and Extreme Weather Events (EWE) by linking CIOP and C-WCP models*.

[12] EU-CIRCLE Report D2.2-GMU4, (2016), *Modeling the operation process of the Baltic Sea critical infrastructures general network of interconnected and interdependent critical infrastructures located within the Baltic Sea and ashore around that function collaboratively using the Critical Infrastructure Operation Process General Model (CIOPGM) related to Operating Environment Threats (OET) and Extreme Weather Events (EWE) in its operating environment ("network of networks" approach)*.

[13] EU-CIRCLE Report D2.3-GMU1, (2016), *Identification methods and procedures of Critical Infrastructure Operation Process (CIOP) including Operating Environment Threats (OET).*

[14] EU-CIRCLE Report D2.3-GMU2, (2016), *Identification methods and procedures of Climate-Weather Change Process (C-WCP) including Extreme Weather Events (EWE)*.

[15] EU-CIRCLE Report D2.3-GMU3, (2016), *Identification methods and procedures of unknown parameters of Critical Infrastructure Operation Process General Model (CIOPGM) related to Operating Environment Threats (OET) and Extreme Weather Events*.

[16] EU-CIRCLE Report D2.3-GMU7, (2016), *Evaluation of unknown parameters of the Baltic Sea critical infrastructures global/general network ("network of networks") of interconnected and interdependent critical infrastructures located within the Baltic Sea and ashore around that function collaboratively using the Critical Infrastructure Operation Process General Model (CIOPGM) related to Operating Environment Threats (OET) and Extreme Wheather Events (EWE) in its operating environment*.

[17] European Union, European Commission (2013). Commission Staff working document: *Climate change adaptation, coastal and marine issues,* SWD(2013) 133 final. Brussels.

[18] European Union, European Commission (2013). Commission Staff working document: *Adapting infrastructure to climate change,* SWD (2013) 137 final. Brussels.

[19] Grabski, F. (2015). *Semi-Markov Processes: Applications in System Reliability and Maintenance,* Elsevier.

[20] Guze S. & Kołowrocki K. (2016). Joint Network of Port, Shipping, Ship Traffic and Port Operation Information Critical Infrastructure Network. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 7, 2, 61-64.

[21] Guze, S. & Ledóchowski, M. (2016). Ship Traffic and Port Operation Information Critical Infrastructure Network. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 7, 2, 65-72.

[22] Kołowrocki, K., Kuligowska, E. & Reszko, M. (2016). Methodology for oil rig critical infrastructure network safety and resilience to climate change analysis. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 7, 2, 187-195.

[23] Kołowrocki, K., Kuligowska, E. & Reszko, M. (2016). Methodology for wind farms critical infrastructure network safety and resilience to climate change analysis. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars* 7, 2, 179-186.

[24] Kołowrocki, K., Soszyńska-Budny, J. (2011). *Reliability and Safety of Complex Technical Systems and Processes: Modeling - Identification - Prediction - Optimization*. Springer, London, Dordrecht, Heildeberg, New York.

[25] Limnios, N., Oprisan, G. (2005). *Semi-Markov Processes and Reliability*. Birkhauser, Boston.

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

[27] Soszyńska, J. (2007). *Systems reliability analysis in variable operation conditions.* PhD Thesis. Gdynia Maritime University – System Research Institute Warsaw, (in Polish).