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Optimization of Operation and Safety of Baltic Port and Shipping Critical Infrastructure Network with Considering Climate-Weather Change Influence – Maximizing Lifetime in the Set of Safety States Not Worse Than a Critical Safety State

Keywords

critical infrastructure network, operation process, climate-weather change process, safety lifetime maximization, port, shipping

Abstract

The paper is devoted the optimization of operation process and maximization of safety lifetimes for Baltic Port and Shipping Critical Infrastructure Network (BPSCIN) at variable operation conditions related to the climate-weather change. For this network, the optimal transient probabilities of BPSCIN operation process at operation states related to climate-weather change that maximize the mean value of BPSCIN safety lifetimes are found. Finally, the optimal safety and resilience indicators of considered network are presented.

1. Introduction

Adaptation and mitigation of climate change is one of the greatest challenges for scientific research in the Europe [EU, 2013a], [2013b]. The changes have the influence for the safety and operation process of complex technical systems [Kołowrocki, 2014], [Kołowrocki, Soszyńska-Budny, 2011]. Most of them are important to ensure the basic needs of people and are called the critical infrastructures(CIs) or critical infrastructure networks (CINs). The main problem is how to describe the changes of climate and its influence to operation process of complex technical systems. One of the approach to investigate the critical infrastructure safety including its operation process is the usage of the semi-Markov process models [Grabski, 2015], [Kołowrocki, Soszyńska-Budny, 2011], The operation process related to the climate-weather change can be described in the same way [Kołowrocki st al., 2017a],. These two processes have influence to safety of technical systems, critical infrastructures and critical infrastructure networks. This influence can be described by the general safety model of the multistate critical infrastructure network changing its safety structure and its components safety parameters during variable operation process [Kołowrocki, Soszyńska-Budny, 2011, 2014, 2012a-b] and at different climate-weather states of the critical infrastructure operating area [Kołowrocki, et al., 2017b-c]. The combination of these models and the linear programming [Klabjan, Adelman, 2006], [Kołowrocki, Soszyńska-Budny, 2011] gives possibility to find the optimal values of the limit transient probabilities of the critical infrastructure operation process that maximize the unconditional CI lifetimes in the safety state subsets. These results also can be apply to find the optimal values of limit transient probabilities of CI operation process related to the climate-weather change, to maximize CI network lifetime in the set of safety states not worse than a critical safety state.

The main aim of the paper is the optimization of operation and safety lifetime of Baltic Port and Shipping Critical Infrastructure Network (BPSCIN) defined in [Guze&Kołowrocki, 2017a,b]. The optimal values of limit transient probabilities of BPSCIN operation process related to the climate-weather change, to maximize BPSCIN lifetime in the set of safety states not worse than a critical safety state are determined. Thus, the BPSCIN optimal safety and resilience indicators can be introduced and estimated the following:

- the BPSCIN optimal unconditional safety function,
- the optimal BPSCIN risk function,and the optimal moment when the risk exceeds a permitted level,
- the optimal intensities of degradation,
- the optimal coefficients of the operation process related to the climate-weather change impact on the BPSCIN intensities of degradation and the optimal indicator of BPSCIN resilience to operation process related to climate-weather change impact.

2. Baltic Port and Shipping Critical Infrastructure Network Operation Process Related to Climate-Weather Change Process

In the paper, we consider the impact of the operation process related to the climate-weather change process $ZC(t)$, $t \in < 0,\infty)$, in a various way at this process states zc_{bl}, $\upsilon = 1,2,3$, $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, on Baltic Port and Shipping Critical Infrastructure Network. Furthermore, according to results given in [Kołowrocki, et al., 2017c], we assume that the changes of the states of operation process related to the climate-weather change process $ZC(t)$, $t \in < 0,\infty)$, at BPSCIN operating area have an influence on its safety structure and on the safety of its assets A_i, $i = 1,2,...,n^{(\upsilon)}$, $\upsilon = 1,2,3$, as well.

Taking into account results in [Kołowrocki, et al., 2017b-c], we assume, that Baltic Port and Shipping Critical Infrastructure Network during its operation process is taking $V = \nu^{(1)} \cdot \nu^{(2)} \cdot \nu^{(3)}, V \in N$, different operation states $z_1, z_2, \ldots, z_V$. Moreover, we define the BPSCIN operation process $Z(t)$, $t \in < 0,+\infty)$, with discrete operation states from the set $\{z_1, z_2, \ldots, z_V\}$. In the next step, we make the assumption that we have either calculated analytically or evaluated approximately by experts the vector of limit values of transient probabilities of the Baltic Port and Shipping Critical Infrastructure Network operation process $Z(t)$ at the particular operation states z_b, $\upsilon = 1,2,3$, $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$.

We also assume that the climate-weather change process $C(t)$, $t \in < 0, +\infty)$, at the BPSCIN operating area is taking $W = w^{(1)} \cdot w^{(2)} \cdot w^{(3)}, W \in N$, different climate-weather states $c_1, c_2, \ldots, c_W$. The vector of limit values of transient probabilities of the climate-weather change process $C(t)$ at the particular climate-weather states c_l, $\upsilon = 1,2,3$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, is defined similarly to [Kołowrocki, et al., 2017c].

According to these assumptions about the Baltic Port and Shipping Critical Infrastructure Network operation process $Z(t)$, $t \in < 0,+\infty)$, and the climate-weather change process $C(t)$, we introduce the Baltic Port and Shipping Critical Infrastructure Network joint process of operation process and climate-weather change process called the joint Baltic Port and Shipping Critical Infrastructure Network operation process related to climate-weather change marked by $ZC(t)$, $t \in < 0,+\infty)$, and we assume that it can take $V \cdot W, V, W \in N$, different operation states related to the climate-weather change $zc_{11}, zc_{12}, \ldots, zc_{VW}$. Next, we make the assumption that the Baltic Port and Shipping Critical Infrastructure Network operation process related to climate-weather change $ZC(t)$, at the moment $t \in < 0,+\infty)$, is at the state zc_{bl}, $\upsilon = 1,2,3$, $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, if and only if at that moment, the operation process $Z(t)$ is at the operation states z_b, $\upsilon = 1,2,3$, $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, and the climate-weather change process $C(t)$ is at the climate-weather state c_l, $\upsilon = 1,2,3$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, what we express as follows:

$$(ZC(t) = zc_{bl}) \Leftrightarrow (Z(t) = z_b \cap C(t) = c_l),$$
$$t \in < 0,+\infty), \ \upsilon = 1,2,3, \ b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)},$$
$$l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}. \quad (1)$$

The transient probabilities of the BPSCIN operation process related to climate-weather change $ZC(t)$ at the operation states zc_{bl}, $b = 1,2,...,\nu$, $l = 1,2,..., w$, are defined in [Kołowrocki, et al., 2017c]:

$$pq_{bl}(t) = P(ZC(t) = zc_{bl}), \ t \in < 0,+\infty), \ \upsilon = 1,2,3,$$
$$b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}, \ l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}. \quad (2)$$

Hence the limit values of the transient probabilities of the joint Baltic Port and Shipping Critical Infrastructure Network operation process related to climate-weather change $ZC(t)$ at the operation states zc_{bl}, $\upsilon = 1,2,3$, $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, are given as

$$pq_{bl} = \lim_{t\to\infty} pq_{bl}(t),\ \upsilon = 1,2,3,$$
$$b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)},\ l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}, \quad (3)$$

and in case when the processes $Z(t)$ and $C(t)$ are independent, they can be found in [Kołowrocki, et al., 2017b]:

$$pq_{bl} = p_b q_l,\ \upsilon = 1,2,3,\ b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)},$$
$$l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}, \quad (4)$$

where p_b, $\upsilon = 1,2,3,$ $b = 1,2,...,v^{\upsilon}$, are the limit transient probabilities of the operation process $Z(t)$ at the particular operation states z_b, $\upsilon = 1,2,3,$ $b = 1,2,...,v^{\upsilon}$, and q_l, $\upsilon = 1,2,3,$ $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, are the limit transient probabilities of the climate-weather change process $C(t)$ at the particular climate-weather startes c_l, $\upsilon = 1,2,3,$ $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$.

Other interesting characteristics of the joint Baltic Port and Shipping Critical Infrastructure Network operation process $ZC_{bl}(t)$ are its total sojourn times $\hat{\theta}\hat{C}_{bl}$, $\upsilon = 1,2,3,$ $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, at the particular operation states zc_{bl}, $\upsilon = 1,2,3,$ $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, during the fixed sufficiently large Baltic Port and Shipping Critical Infrastructure Network operation time θ. They have approximately normal distributions with the expected values given by

$$\hat{M}\hat{N}_{bl} = E[\hat{\theta}\hat{C}_{bl}] = pq_{bl}\theta, \quad (5)$$

where pq_{bl}, $\upsilon = 1,2,3,$ $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, are defined by (3) and given by (4) in the case the processes $Z(t)$ and $C(t)$ are independent.

3. Optimization of Operation and Safety of BPSCIN

3.1. Optimal Transient Probabilities of BPSCIN Operation Process at Operation States Related to Climate-Weather Change Process

It is natural to assume that the Baltic Port and Shipping Critical Infrastructure Network operation process has a significant influence on its safety.

We consider the coordinates of the unconditional safety function of the Baltic Port and Shipping Critical Infrastructure Network impacted by the operation process related to the climate-weather change process $ZC(t)$, $t \in <0,\infty)$, which are given by

$$\boldsymbol{S}^4(t,u) \cong \sum_{b=1}^{V}\sum_{l=1}^{W} pq_{bl}[\boldsymbol{S}^4(t,u)]^{(bl)} \text{ for } t \ge 0,$$
$$u = 1,2,...,z,$$

where $[\boldsymbol{S}^4(t,u)]^{(bl)}$, $u = 1,2,...,z,$ $\upsilon = 1,2,3,$ $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, are the coordinates of the BPSCIN impacted by the operation process related to the climate-weather change process $ZC(t)$, $t \in <0,\infty)$, conditional safety functions defined by (1)-(2) and pq_{bl}, $\upsilon = 1,2,3,$ $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, are the operation process related to the climate-weather change process $ZC(t), t \in <0,\infty)$, at the BPSCIN operating area limit transient probabilities at the states zc_{bl}, $\upsilon = 1,2,3,$ $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$.

The influence of operation process is also clearly expressed in the equation for the mean lifetime of the critical infrastructure in the safety state subset $\{u, u+1, ..., z\}$, u = 1,2,...,z, given by

$$\boldsymbol{\mu}^4(u) = \int_0^\infty [\boldsymbol{S}^4(t,u)]dt \cong \sum_{b=1}^{V}\sum_{l=1}^{W} pq_{bl}[\mu^4(u)]^{(bl)},$$
$$u = 1,2,...,z,$$

where $[\boldsymbol{\mu}^4(r)]^{(bl)}$, $u = 1,2,...,z,$ $\upsilon = 1,2,3,$ $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, are the mean values of the BPSCIN conditional lifetimes $[T^4(u)]^{(bl)}$, $u = 1,2,...,z,$ $\upsilon = 1,2,3,$ $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, in the safety state subset $\{u, u+1, ..., z\}$, $u = 1,2,...,z,$ at the BPSCIN operating process related to the climate-weather change process state zc_{bl}, $\upsilon = 1,2,3,$ $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, given by

$$[\mu^4(u)]^{(b)} = \int_0^\infty [\boldsymbol{S}^4(t,u)]^{(bl)}dt,\ u = 1,2,...,z,\ \upsilon = 1,2,3,$$
$$b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)},\ l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}. \quad (8)$$

From the linear equation

$$\boldsymbol{\mu}^4(u) \cong \sum_{b=1}^{V}\sum_{l=1}^{W} pq_{bl}[\mu^4(u)]^{(bl)}, \; u=1,2,...,z, \tag{9}$$

we can see that the mean value of the Baltic Port and Shipping Critical Infrastructure Network unconditional lifetime $\boldsymbol{\mu}^4(u)$, $u=1,2,...,z,$ is determined by the limit values of transient probabilities pq_{bl}, $\upsilon=1,2,3,$ $b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}$, $l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)}$, of the Baltic Port and Shipping Critical Infrastructure Network operation process at the operation states given by (2.4) and the mean values $[\boldsymbol{\mu}^4(r)]^{(bl)}$, $u=1,2,...,z,$ $\upsilon=1,2,3,$ $b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}$, $l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)}$, are the mean values of the Baltic Port and Shipping Critical Infrastructure Network conditional lifetimes in the safety state subset $\{u,u+1,...,z\}$ at the BPSCIN operating process related to the climate-weather change process state zc_{bl}, $\upsilon=1,2,3,$ $b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}$, $l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)}$.

Therefore, the Baltic Port and Shipping Critical Infrastructure Network lifetime optimization approach based on the linear programming [Klabjan, Adelman, 2006], [Kołowrocki, Soszyńska-Budny, 2011] can be proposed We may look for the corresponding optimal values the limit values of transient probabilities $\dot{p}q_{bl}$, $\upsilon=1,2,3,$ $b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}$, $l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)}$, of the Baltic Port and Shipping Critical Infrastructure Network operation process at the operation states pq_{bl}, $\upsilon=1,2,3,$ $b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}$, $l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)}$, of the BPSCIN operation process at the operation states to maximize the mean value $\boldsymbol{\mu}^4(u)$, $u=1,2,...,z,$ of the unconditional BPSCIN lifetimes in the safety state subsets $\{u,u+1,...,z\}$, $u=1,2,...,z,$ under the assumption that the mean values $[\boldsymbol{\mu}^4(u)]^{(bl)}$, $u=1,2,...,z,$ $\upsilon=1,2,3,$ $b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}$, $l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)}$, of the BPSCIN conditional lifetimes in the safety state subsets are fixed.

As a special case of the above formulation of the Baltic Port and Shipping Critical Infrastructure Network lifetime optimization problem, if r, $r=1,2,...,z,$ is the Baltic Port and Shipping Critical Infrastructure Network critical safety state, we want to find the optimal values $\dot{p}q_{bl}$, $\upsilon=1,2,3,$ $b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}$, $l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)}$, of the BPSCIN operation process at the operation states pq_{bl}, $\upsilon=1,2,3,$ $b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}$, $l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)}$, of the BPSICN operation process at the operation states to maximize the mean value $\boldsymbol{\mu}^4(r)$ of the unconditional BPSCIN lifetimes in the safety state subsets $\{u,u+1,...,z\}$, $u=1,2,...,z,$ under the assumption that the mean values $[\boldsymbol{\mu}^4(r)]^{(bl)}$, $\upsilon=1,2,3,$ $b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}$, $l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)}$, of the Baltic Port and Shipping Critical Infrastructure Network conditional lifetimes in the safety state subsets are fixed. Taking into account formulae (5.10) – (5.27), we formulate the optimization problem as a linear programming model, with the objective function of the following form

$$\boldsymbol{\mu}^4(r) \cong \sum_{b=1}^{V}\sum_{l=1}^{W} pq_{bl}[\mu^4(r)]^{(bl)},$$

for a fixed $r \in \{1,2,...,z\}$ and with the following bound constraints

$$\breve{p}q_{bl} \le pq_{bl} \le \hat{p}q_{bl}, \; \upsilon=1,2,3, \; b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}, \; l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)},$$

$$\sum_{b=1}^{V}\sum_{l=1}^{W} pq_{bl} = 1,$$

where

$$[\boldsymbol{\mu}^4(r)]^{(bl)}, \; [\boldsymbol{\mu}^4(r)]^{(bl)} \ge 0, \; \upsilon=1,2,3, \; b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}, \; l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)},$$

are fixed mean values of the Baltic Port and Shipping Critical Infrastructure Network conditional lifetimes in the safety state subset $\{r,r+1,...,z\}$ and

$$\breve{p}q_{bl}, \; 0 \le \breve{p}q_{bl} \le 1 \text{ and } \hat{p}q_{bl}, \; 0 \le \hat{p}q_{bl} \le 1, \; \breve{p}q_{bl} \le \hat{p}q_{bl}, \; \upsilon=1,2,3, \; b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}, \; l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)},$$

are lower and upper bounds of the transient probabilities pq_{bl}, $\upsilon=1,2,3,$ $b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}$, $l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)}$, respectively.

Now, we can obtain the optimal solution of the formulated by (10)-(14) the linear programming problem, i.e. we can find the optimal values $\dot{p}q_{bl}$, $\upsilon=1,2,3,$ $b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}$, $l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)}$, of the limit transient probabilities pq_{bl} that maximize the objective function given by (10). The procedure of finding the optimal values $\dot{p}q_{bl}$, $\upsilon=1,2,3,$ $b=1^{(\upsilon)},2^{(\upsilon)},...,v^{(\upsilon)}$, $l=1^{(\upsilon)},2^{(\upsilon)},...,w^{(\upsilon)}$, is the same as the procedure presented in Section 5.2.1 in [Kołowrocki, et al., 2017c].

Maximizing the Baltic Port and Shipping Critical Infrastructure Network mean lifetime in the safety state subset $\{r, r+1, ..., z\}$, defined by the linear form (10), giving its maximum value in the following form

$$\dot{\boldsymbol{\mu}}^4(r) \cong \sum_{b=1}^{V}\sum_{l=1}^{W} \dot{p}q_{bl}[\mu^4(r)]^{(bl)} \quad (15)$$

for a fixed $r \in \{1,2,...,z\}$.

3.2. Baltic Port and Shipping Critical Infrastructure Network Optimal Safety and Resilience Indicators

Taking into account the expressions (15) for the maximum mean value $\dot{\boldsymbol{\mu}}^4(r)$ of the Baltic Port and Shipping Critical Infrastructure Network unconditional lifetime in the safety state subset $\{r, r+1, ..., z\}$, replacing in it the critical safety state r by the safety state $u, u = 1,2,...,z,$ we obtain the corresponding optimal solutions for the mean values of the Baltic Port and Shipping Critical Infrastructure Network unconditional lifetimes in the safety state subsets $\{u, u+1, ..., z\}$ of the form

$$\dot{\mu}^4(u) = \sum_{b=1}^{V}\sum_{l=1}^{W} \dot{p}q_b[\mu^4(u)]^{(bl)} \text{ for } u = 1,2,...,z. \quad (16)$$

Further, according to (8), the corresponding optimal unconditional multistate safety function of the Baltic Port and Shipping Critical Infrastructure Network is the vector

$$\dot{\boldsymbol{S}}(t,\cdot) = [1, \dot{\boldsymbol{S}}(t,1), ..., \dot{\boldsymbol{S}}(t,z)], \quad (17)$$

with the coordinates given by

$$\dot{\boldsymbol{S}}^4(t,u) \cong \sum_{b=1}^{v}\sum_{l=1}^{w} \dot{p}q_{bl}[\boldsymbol{S}^4(t,u)]^{(bl)} \text{ for } t \geq 0, \quad u = 1,2,...,z. \quad (18)$$

By applying (3.16) from [Kołowrocki, et al., 2017b], the corresponding optimal values of the variances of the CI network unconditional lifetimes in the critical infrastructure safety state subsets are

$$\dot{\boldsymbol{\sigma}}^{4^2}(u) = 2\int_0^{\infty} t \; \dot{\boldsymbol{S}}^4(t,u)dt - [\dot{\boldsymbol{\mu}}^4(u)]^2, \quad u = 1,2,...,z, \quad (19)$$

where $\dot{\boldsymbol{\mu}}^4(u)$ is given by (16) and $\dot{\boldsymbol{S}}^4(t,u)$ is given by (18).

And, by (3.17) from [Kołowrocki, et al., 2017b], the optimal solutions for the mean values of the Baltic Port and Shipping Critical Infrastructure Network unconditional lifetimes in the particular safety states are

$$\dot{\bar{\boldsymbol{\mu}}}^4(u) = \dot{\boldsymbol{\mu}}^4(u) - \dot{\boldsymbol{\mu}}^4(u+1), \; u = 1,...,z-1, \quad \dot{\bar{\boldsymbol{\mu}}}^4(z) = \dot{\boldsymbol{\mu}}^4(z). \quad (20)$$

Moreover, considering (3.19) from [Kołowrocki, et al., 2017b],], the corresponding optimal Baltic Port and Shipping Critical Infrastructure Network risk function and the optimal moment when the risk exceeds a permitted level δ, respectively are given by

$$\dot{\boldsymbol{r}}^4(t) = 1 - \dot{\boldsymbol{S}}^4(t,r), \; t \geq 0, \quad (21)$$

and

$$\dot{\boldsymbol{\tau}}^4 = \dot{\boldsymbol{r}}^{4^{-1}}(\boldsymbol{\delta}), \quad (22)$$

where $\dot{\boldsymbol{S}}^4(t,r)$ is given by (18) for $u = r$ and $\dot{\boldsymbol{r}}^{4^{-1}}(t)$, if it exists, is the inverse function of the optimal risk function $\dot{\boldsymbol{r}}^4(t)$.

The optimal intensities of degradation of the Baltic Port and Shipping Critical Infrastructure Network the optimal intensities of the Baltic Port and Shipping Critical Infrastructure Network departure from the safety state subset $\{u, u+1, ..., z\}$, $u = 1,2,...,z,$ impacted by the operation process related to the climate-weather change process impact, i.e. the coordinates of the vector

$$\dot{\boldsymbol{\lambda}}^4(t,\cdot) = [0, \dot{\boldsymbol{\lambda}}^4(t,1), ..., \dot{\boldsymbol{\lambda}}^4(t,z)], \quad t \in <0,+\infty), \quad (23)$$

are given by

$$\dot{\boldsymbol{\lambda}}^4(t,u) = \frac{-\frac{d\dot{\boldsymbol{S}}^4(t,u)}{dt}}{\dot{\boldsymbol{S}}^4(t,u)}, \quad t \in <0,+\infty), \quad u = 1,2,...,z. \quad (24)$$

The optimal coefficients of the operation process related to the climate-weather change process impact on the Baltic Port and Shipping Critical Infrastructure Network intensities of degradation / the coefficients of the operation process related to the climate-weather change process impact on the Baltic Port and Shipping Critical Infrastructure Network intensities of departure from the safety state subset $\{u, u+1, ..., z\}$, i.e. the coordinates of the vector are given by

$$\dot{\boldsymbol{\rho}}^4(t,\cdot) = [0,\ \dot{\boldsymbol{\rho}}^4(t,1),\ \ldots,\ \dot{\boldsymbol{\rho}}^4(t,z)\ ],$$
$$t \in <0,+\infty), \quad (25)$$

where

$$\dot{\boldsymbol{\lambda}}^4(t,u) = \dot{\boldsymbol{\rho}}^4(t,u) \cdot \boldsymbol{\lambda}^{\mathbf{0}}(t,u),\ u = 1,2,...,z, \quad (26)$$

i.e.

$$\dot{\boldsymbol{\rho}}^4(t,u) = \frac{\dot{\boldsymbol{\lambda}}^4(t,u)}{\boldsymbol{\lambda}^0(t,u)},\ \ u = 1,2,...,z, \quad (27)$$

and $\boldsymbol{\lambda}^{\mathbf{0}}(t,u)$, $t \in <0,+\infty)$, $u = 1,2,...,z,$ are the intensities of degradation of the Baltic Port and Shipping Critical Infrastructure Network without of the operation process related to the climate-weather change process impact, i.e. the coordinate of the vector

$$\boldsymbol{\lambda}^{\mathbf{0}}(t,\cdot) = [0,\ \boldsymbol{\lambda}^{\mathbf{0}}(t,1),,\ \ldots, \boldsymbol{\lambda}^{\mathbf{0}}(t,z)\ ],$$
$$t \in <0,+\infty), \quad (28)$$

and $\dot{\boldsymbol{\lambda}}^4(t,u)$, $t \in <0,+\infty)$, $u = 1,2,...,z,$ are the optimal intensities of degradation of the Baltic Port and Shipping Critical Infrastructure Network impacted by the operation process related to the climate-weather change process, i.e. the coordinate of the vector

$$\dot{\boldsymbol{\lambda}}^4(t,\cdot) = [0,\ \dot{\boldsymbol{\lambda}}^4(t,1),\ \ldots,\ \dot{\boldsymbol{\lambda}}^4(t,z)\ ],$$
$$t \in <0,+\infty). \quad (29)$$

The optimal indicator of Baltic Port and Shipping Critical Infrastructure Network resilience to operation process related to climate-weather change process impact is given by

$$\dot{\boldsymbol{RI}}^4(t,r) = \frac{1}{\dot{\boldsymbol{\rho}}^4(t,r)},\quad t \in <0,+\infty), \quad (30)$$

where $\dot{\boldsymbol{\rho}}^4(t,r)$, $t \in <0,+\infty)$, is the optimal coefficients of operation process related to climate-weather change process impact on the Baltic Port and Shipping Critical Infrastructure Network intensities of degradation for $u = r$.

3.3. Optimal Sojourn Times of BPSCIN Operation Process at Operation States Related to Climate-Weather Change Process

Assuming that the Baltic Port and Shipping Critical Infrastructure Network operation process and the climate-weather change process are independent and replacing in (2.4) in [Kołowrocki et al., 2017a] the limit transient probabilities p_b of the Baltic Port and Shipping Critical Infrastructure Network operation process at the operation states by

$$\dot{p}_b = \frac{\dot{p}b_{bl}}{b_l} = \frac{\dot{p}_b \cdot b_l}{b_l} = \dot{p}_b,\ \upsilon = 1,2,3,$$
$$b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)},$$
(31)

where

$$\dot{p}q_{bl} = \dot{p}_b \cdot q_l,\qquad \upsilon = 1,2,3,\qquad b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)},$$
$$l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)},$$

are the optimal values of transient probabilities pq_{bl}, $\upsilon = 1,2,3,$ $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., w^{(\upsilon)}$, and the mean values M_b of the unconditional sojourn times at the operation states by their corresponding unknown optimal values $\dot{M}_b$ maximizing the mean value of the Baltic Port and Shipping Critical Infrastructure Network lifetime in the safety states subset $\{r, r+1, ..., z\}$ defined in [Kołowrocki et al., 2017a], we get the following system of equations

$$\dot{p}_b = \frac{\pi_b \dot{M}_b}{\sum_{l=1}^{v} \pi_l \dot{M}_l},\ \ \upsilon = 1,2,3,\ \ b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)},$$

After simple transformations the above system takes the form

$$(\dot{p}_1 - 1)\pi_1 \dot{M}_1 + \dot{p}_1 \pi_2 \dot{M}_2 + ... + \dot{p}_1 \pi_v \dot{M}_v = 0$$

$$\dot{p}_2 \pi_1 \dot{M}_1 + (\dot{p}_2 - 1)\pi_2 \dot{M}_2 + ... + \dot{p}_2 \pi_v \dot{M}_v = 0$$

$$\vdots$$

$$\dot{p}_v \pi_1 \dot{M}_1 + \dot{p}_v \pi_2 \dot{M}_2 + ... + (\dot{p}_v - 1)\pi_v \dot{M}_v = 0, \quad (33)$$

where $\dot{M}_b$ are unknown variables we want to find, $\dot{p}_b$ are optimal transient probabilities determined by (32) and π_b are steady probabilities determined in [Kołowrocki et al., 2017a].

Since the system of equations (33) is homogeneous and it can be proved that the determinant of its main matrix is equal to zero, then it has nonzero solutions and moreover, these solutions are ambiguous. Thus, if we fix some of the optimal values $\dot{M}_b$ of the mean values M_b of the unconditional sojourn times at the operation states, for instance by arbitrary fixing one or a few of them, we may find the values of the remaining once and this way to get the solution of this equation.

Having this solution, it is also possible to look for the optimal values $\dot{M}_{bl}$ of the mean values M_{bl} of the conditional sojourn times at the operation states using the following system of equations

$$\sum_{l=1}^{v} p_{bl}\dot{M}_{bl} = \dot{M}_b, \ \ \upsilon = 1,2,3, \ \ b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}, \quad (34)$$

obtained from (2.3) in [Kołowrocki et al., 2017b] by replacing M_b by $\dot{M}_b$ and M_{bl} by $\dot{M}_{bl}$, were p_{bl} are known probabilities of the Baltic Port and Shipping Critical Infrastructure Network operation process transitions between the operation states z_b i z_l, $\upsilon = 1,2,3$, $b,l = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, $b \neq l$, defined in [Kołowrocki et al., 2017a-c].

The knowledge of the optimal values $\dot{M}_b$ of the mean values M_b of the unconditional sojourn times at the operation states and the conditional optimal values $\dot{M}_{bl}$ of the mean values M_{bl} of the conditional sojourn times at the operation states maximizing the mean value of the Baltic Port and Shipping Critical Infrastructure Network lifetime in the safety states subset not worse than the critical safety state can help in the planning better strategy in the Baltic Port and Shipping Critical Infrastructure Network operation processes resulting in higher safety of this network operation.

Another very useful and much easier to be applied in practice tool that can help in planning more reliable and safe operation process of BPSCIN is its operation process optimal mean values of the total operation process sojourn times $\hat{\theta}_b$ at the particular operation states z_b, $\upsilon = 1,2,3$, $b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}$, during the fixed BPSCIN operation time θ, that can be obtain by the replacing in the formula (2.6) in [Kołowrocki&Soszyńska-Budny, 2011] the transient probabilities p_b at the operation states z_b by their optimal values $\dot{p}_b$ and resulting in the following expession

$$\dot{E}[\hat{\boldsymbol{\theta}}_b] = \dot{p}_b\boldsymbol{\theta}, \ \ \upsilon = 1,2,3, \ \ b = 1^{(\upsilon)}, 2^{(\upsilon)}, ..., v^{(\upsilon)}. \quad (35)$$

The knowledge of the optimal values $\dot{M}_b$ of the mean values of the unconditional sojourn times and the optimal values $\dot{M}_{bl}$ of the mean values of the conditional sojourn times at the operation states and the optimal mean values $\dot{E}[\hat{\theta}_b]$ of the total sojourn times at the particular operation states during the fixed BPSCIN operation time may be more safe by the basis for changing its operation processes in order to ensure this network operation. It also may be useful for cost analysis of the Baltic Port and Shipping Critical Infrastructure Network.

4. Conclusion

In this paper optimization of operation and safety of Baltic Port and Shipping Critical Infrastructure Network at variable operation conditions related to the climate-weather change have been presented. Namely, for BPSCIN the optimal unconditional safety function, the optimal critical infrastructure risk function and the optimal moment when the risk exceeds a permitted level, the optimal intensities of degradation, the optimal coefficients of the operation process related to the climate-weather change impact on the BPSCIN intensities of degradation and the optimal indicator of its resilience to operation process related to climate-weather change impact can be estimated according to results given in [Kołowrocki, et al., 2017c].

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