Kołowrocki Krzysztof

Soszyńska-Budny Joanna
Maritime University, Gdynia, Poland

Modelling critical infrastructure operation process including operating environment threats

Keywords

critical infrastructure, operation process, operating environment threats

Abstract

In the article the traditional semi-Markov approach to a complex technical system operation process modeling is developed to modelling a critical infrastructure operation process including operating environment threats. The method of defining the parameters of this operation process is presented and a new procedure of their determining in the case when the critical infrastructure operating threats are not explicit sepatated in this process is proposed.

1. Introduction

The operation process of a critical infrastructure is very complex and often it is difficult to analyze these critical infrastructure safety with respect to changing in time its operation process states and operating environment conditions that are essential in this analysis. The complexity of the critical infrastructure operation process and its influence on changing in time the critical infrastructure structure and its components' safety parameters are essential in critical infrastructure safety analysis and protection. Usually, the critical infrastructure environment have either an explicit or an implicit strong influence on the critical infrastructure operation process. As a rule, some of the environmental events together with the infrastructure operation conditions define a set of different operation states of the critical infrastructure in which the critical infrastructure change its safety structure and its components safety parameters. In this report, we propose a convenient tool for analyzing this problem applying the semi-Markov model [13]-[15], [17], [23]-[24] of the critical infrastructure operation process, both without including critical infrastructure environment threats and with including them into this model.

2. Modelling critical infrastructure operation process

We assume that the critical infrastructure during its operation process is taking $v, v \in N$, different operation states $z_1, z_2,...z_v$. Further, we define the critical infrastructure operation process $Z(t)$, $t \in < 0, \infty)$, with discrete operation states from the set $\{z_1, z_2, ..., z_v\}$. Moreover, we assume that the critical infrastructure operation process $Z(t)$ is a semi-Markov process [15], [22], [23]-[25] with the conditional sojourn times θ_{bl} at the operation states z_b when its next operation state is z_l, $b, l = 1,2,..., v,$ $b \neq l.$ Under these assumptions, the critical infrastructure operation process may be described by:

- the vector $[p_b(0)]_{1 \times v}$ of the initial probabilities $p_b(0) = P(Z(0) = z_b)$, $b = 1,2,..., v$, of the critical infrastructure operation process $Z(t)$ staying at particular operation states at the moment $t = 0$;
- the matrix $[p_{bl}]_{v \times v}$ of probabilities p_{bl}, $b, l = 1,2,..., v,$ of the critical infrastructure operation process $Z(t)$ transitions between the operation states z_b and z_l, ;
- the matrix $[H_{bl}(t)]_{v \times v}$ of conditional distribution functions $H_{bl}(t) = P(\theta_{bl} < t)$, $b, l = 1,2,..., v,$ of the

critical infrastructure operation process $Z(t)$ conditional sojourn times θ_{bl} at the operation states.

3. Modelling critical infrastructure operation process including operating environment threats

The companies (stakeholders, operators) using different critical infrastructures often have very different organizational environments. The critical infrastructures organizational environments are composed of forces or institutions surrounding an organization that affect performance, operations and resources. They include all of the elements that exist outside of the organization's boundaries and have the potential to affect a portion or all of the organization, for instance government regulatory agencies, competitors, customers, suppliers and pressure from the public. To manage the organization effectively, managers need to properly understand the environment. It is reasonable to divide environmental factors into two parts, namely, internal and external environments. An organization's internal environment consists of the entities, conditions, events, and factors within the organization that influence choices and activities, especially in employee behaviour. It exposes the strengths and weaknesses found within the organization. Factors that are frequently considered part of the internal environment include the organization's culture, mission statement, and leadership styles. An organization's external environment consists of the entities, conditions, events, and factors surrounding the organization that influence choices and activities and determine its opportunities and threats. It is also called an operating environment. Examples of factors affecting an organization's external environment include customers, public opinion, economic conditions, government regulations, and competition. Thus, taking into account the above analysis, the critical infrastructure operating environment threat can be defined as an unnatural event that may cause the critical infrastructure damage and/or change its operation activity in the way unsafe for it and its operating environment, [1]-[2]. For instance, the critical infrastructure unnatural threats coming from its operating environment are another critical infrastructure activity in its operating environment that can result in an accident with serious consequences for the critical infrastructure and its operating environment, a human error an act of vandalism and a terrorist attack changing the critical infrastructure operation process in an unsafe way.

3.1. Semi-Markov model of critical infrastructure operation process including operating environment threats

We assume that the critical infrastructure operation process modelled in Section 2 can be affected by a number w, $w \in N$, of unnatural threats coming from the critical infrastructure operating environment and mark them by ut_i, $i = 1,2,...,w$. We define new operation states considering the critical nfrastructure operating environment threats as follows:

- the operation states without including operating environment threats

$$z_i^{'} = z_i,\ i = 1,2,...,v,\ v \in N; \qquad (1)$$

- the operation states including at least 1 and maximum w of operating environment threats

$$z_i^{'},\ i = v+1, v+2,..., v^{'},\ v^{'} \in N. \qquad (2)$$

The maximum value of the number of operation states $v^{'}$ is

$$v \cdot [\binom{w}{0} + \binom{w}{1} + ... + \binom{w}{w}] = v \cdot 2^w, \qquad (3)$$

This way, we can have:

$$- v \cdot \binom{w}{0} = v \qquad (4)$$

operation states without including operating environment threats

$$z_i^{'} = z_i,\ i = 1,2,...,v; \qquad (5)$$

$$- v \cdot \binom{w}{1} = vw \qquad (6)$$

operation states including 1 of the operating environment threats ut_i, $i = 1,2,...,w$,

$$z_i^{'},\ i = v+1, v+2,..., v+vw; \qquad (7)$$

$$- v \cdot \binom{w}{2} = vw(w-1)/2 \qquad (8)$$

operation states including different 2 of the operating environment threats ut_i, $i = 1,2,...,w$,

$$z_i^{'},\ i = vw+1, vw+2,..., vw+vw(w-1)/2; \qquad (9)$$

$$- v \cdot \binom{w}{w} = v \qquad (10)$$

operation states including all w operating environment threats ut_i, $i = 1,2,...,w,$

$$z_i^{'},\ i = v2^w - v + 1, v2^w - v + 2, ..., v2^w. \quad (11)$$

Practically more comfortable numeration of the operation states of the critical infrastructure operation process including its operating environment threats is as follows:

- operation states without including operating environment threats by

$$z_i^{'} = z_1 \text{ for } i = 1,\ z_i^{'} = z_2 \text{ for } i = 2^w + 1,\ \ldots,$$
$$z_i^{'} = z_v \text{ for } i = (v-1)2^w + 1; \quad (12)$$

- operation states including state z_1 and successively 1, 2 until w operating environment threats ut_i, $i = 1,2,...,w,$ by

$$z_i^{'},\ i = 2,\ \ldots,\ 2^w, \quad (13)$$

- operation states including state z_2 and successively 1, 2 until w operating environment threats ut_i, $i = 1,2,...,w,$ by

$$z_i^{'},\ i = 2^w + 2,\ \ldots,\ 2 \cdot 2^w, \quad (14)$$

$\ldots;$

- operation states including state z_v and successively 1, 2 until w operating environment threats ut_i, $i = 1,2,...,w,$ by

$$z_i^{'},\ i = (v-1)2^w + 2,\ \ldots,\ v \cdot 2^w. \quad (15)$$

In our further considerations, we assume that, the critical infrastructure during its operation process can take $v',\ v' \in N,$ defined above by (12)-(15) different operation states

$$z_1^{'}, z_2^{'}, \ldots, z_v^{'}, z_{v+1}^{'}, \ldots, z_{v'}^{'}. \quad (16)$$

Further, we define the critical infrastructure new operation process $Z'(t)$, $t \in < 0,+\infty),$ related to the critical infrastructure operating environment threats with discrete operation states from the set $\{z'_1, z'_2, \ldots, z'_{v'}\}$. Moreover, we assume that the critical infrastructure operation process $Z'(t)$ related to its operating environment threats is a semi-Markov process similar to that one considered in Section 2 with the conditional sojourn times θ'_{bl} at the operation states z'_b when its next operation state is z'_l, $b, l = 1,2,...,v'$, $b \neq l.$ Under these assumptions, the critical infrastructure operation process may be described by:

- the vector of the initial probabilities $p'_b(0) = P(Z'(0) = z'_b),\ b = 1,2,...,v',$ of the critical infrastructure operation process $Z'(t)$ staying at particular operation states at the moment $t = 0$

$$[p'_b(0)]_{1xv'} = [p'_1(0), p'_2(0), ..., p'_v(0)]; \quad (17)$$

- the matrix of probabilities p'_{bl}, $b, l = 1,2,...,v',$ of the critical infrastructure operation process $Z'(t)$ transitions between the operation states z'_b and z'_l

$$[p'_{bl}]_{v'xv'} = \begin{bmatrix} p'_{11}\ p'_{12} \cdots p'_{1v'} \\ p'_{21}\ p'_{22} \cdots p'_{2v'} \\ \cdots \\ p'_{v'1}\ p'_{v'2} \cdots p_{v'v'} \end{bmatrix}; \quad (18)$$

- the matrix of conditional distribution functions $H'_{bl}(t) = P(\theta'_{bl} < t)$, $b, l = 1,2,...,v',$ of the critical infrastructure operation process $Z'(t)$ conditional sojourn times θ'_{bl} at the operation states

$$[H'_{bl}(t)]_{v'xv'} = \begin{bmatrix} H'_{11}(t)\ H'_{12}(t) \ldots H'_{1v'}(t) \\ H'_{21}(t)\ H'_{22}(t) \ldots H'_{2v'}(t) \\ \cdots \\ H'_{v'1}(t)\ H'_{v'2}(t) \ldots H'_{v'v'}(t) \end{bmatrix} \quad (19)$$

We assume that the suitable and typical distributions suitable to describe the critical infrastructure operation process $Z'(t)$ conditional sojourn times θ'_{bl}, $b, l = 1,2,...,v',\ b \neq l,$ in the particular operation states are of the same kind as that listed in Section 2.2 [22] for the critical infrastructure operation process $Z(t)$ conditional sojourn times θ_{bl}, eventually with different parameters they are dependent on.

3.2. Various cases of critical infrastructure operation process including operating environment threats

In practice, to make the model from Section 3.1 the next step is to identify the unknown parameters of the critical infrastructure operation process $Z'(t)$, i.e. to identify the vector of the initial probabilities $[p'_b(0)]_{1xv'}$, the matrix of probabilities of transtions

$[p'_{bl}]_{v' \times v'}$ and the matrix of conditional distribution functions $[H'_{bl}(t)]_{v' \times v'}$.

The sufficiently accurate evaluation of these parameters can be performed according to the methods and procedures prezented in [22] under the conditions that there is the possibilty of the statistical data collection coming from empirical realizations of the operation process with the separated operation states including the operating environment threats. In the case these operation process realizations are not available, the less accurate evaluations of the uknown parameters can be performed in the analogous way either applying the procedures included in [22] and using approximate necesssary data coming from experts or to ask them for direct approximate evaluation of the unknown parameters of the vector $[p'_b(0)]_{1 \times v'}$, the matrix $[p'_{bl}]_{v' \times v'}$ and the matrix of the mean values $[M'_{bl}]_{v' \times v'}$ of the critical infrastructure operation process $Z'(t)$ conditional sojourn times θ'_{bl}, $b, l = 1,2,...,v', b \neq l,$ at the operation states instead of the matrix of their distributions $[H'_{bl}(t)]_{v' \times v'}$.

Another case that can be met in practice is that we have in disposal the statistical evaluations of the parameters including operating environment threats $[p_b(0)]_{1 \times v}$, the matrix $[p_{bl}]_{v \times v}$ and either the matrix of the mean values $[M_{bl}]_{v \times v}$ of the critical infrastructure operation process $Z(t)$ conditional sojourn times θ_{bl}, $b, l = 1,2,...,v', b \neq l,$ at the operation states or the the matrix of their distributions $[H_{bl}(t)]_{v \times v}$ without of separation the operation states including the operating environment threats. In this case, to get the evaluations of the unknown parameters of the vector $[p'_b(0)]_{1 \times v'}$, the matrix $[p'_{bl}]_{v' \times v'}$ and the matrix of the mean values $[M'_{bl}]_{v' \times v'}$ of the conditional sojourn times θ'_{bl}, $b, l = 1,2,...,v', b \neq l,$ at the operation states (instead of the matrix of their distributions $[H'_{bl}(t)]_{v' \times v'}$) of the critical infrastructure operation process $Z'(t)$ with included and separated operating threats), we proceed as follows.

Since according to Section 3.1, the critical infrastructure operation process can be affected by a number $w, w \in N,$ of unnatural threats ut_i, $i = 1,2,...,w,$ coming from the critical infrastructure operating environment, we assume that they are random and we mark the probability of the operating environment threat ut_i, $i = 1,2,...,w,$ appearance by

$$P_b(ut_i),\ i = 1,2,...,w,\ b = 1,2,...,v.$$

Moreover, in this approach, we consider 2 variants:

variant 1 - the probabilities of the operating environment threats ut_i, $i = 1,2,...,w,$ appearance $P_b(ut_i)$, $i = 1,2,...,w,$ $b = 1,2,...,v,$ are conditional and concerned with each of the critical infrastructure particular states (they can be different for various operation states);

variant 2 - the probabilities of the operating environment threats ut_i, $i = 1,2,...,w,$ appearance $P_b(ut_i)$, $i = 1,2,...,w,$ $b = 1,2,...,v,$ are unconditional and concerned with the critical infrastructure operation proces independently of its particular states.

Further, to get the initial probabilities of the vector $[p'_b(0)]$ of the operation process $Z'(t)$ with separated operation states including the operating environment threats, we distribute the initial probabilities of the vector $[p_b(0)]$ in the following way:

i) variant 1

- if

$$p_b(0) \neq 0,\ b = 1,2,...,v,$$

we replace it by

$$p'_{(w+1)(b-1)+1}(0) = p_b(0) - [P_b(ut_1) + P_b(ut_2) + \ldots + P_b(ut_w)], \quad (20)$$

$$p'_{(w+1)(b-1)+1+i}(0) = P(ut_i),\ i = 1,2,...,w, \quad (21)$$

for

$$b = 1,2,...,v;$$

- if

$$p_b(0) = 0,\ b = 1,2,...,v,$$

we replace it by

$$p'_{(w+1)(b-1)+1}(0) = 0, \quad (22)$$

$$p'_{(w+1)(b-1)+1+i}(0) = 0,\ i = 1,2,...,w, \quad (23)$$

for $b = 1,2,...,v.$

ii) variant 2

- if

$$p_b(0) \neq 0,\ b = 1,2,...,v,$$

we replace it by

$p'_{(w+1)(b-1)+1}(0) = p_b(0) - p_b(0)[P_b(ut_1) + P_b(ut_2)$

$+ \ldots + P_b(ut_w)],$ (24)

$p'_{(w+1)(b-1)+1+i}(0) = p_b(0)P_b(ut_i), \ i = 1,2,...,w,$ (25)

for $b = 1,2,...,v$;

- if

$p_b(0) = 0, \ b = 1,2,...,v,$

we replace it by

$p'_{(w+1)(b-1)+1}(0)_b(0) = 0,$ (26)

$p'_{(w+1)(b-1)+1+i}(0) = 0, \ i = 1,2,...,w,$ (27)

for $b = 1,2,...,v$.

To get the probabilities of transitions between the operation states of the matrix $[p'_{bl}(0)]$ of the operation process $Z'(t)$ with separated operation states including the operating environment threats, we distribute the probabilities of transitions between the operation states of the matrix $[p_{bl}]$ in the following way:

i) variant 1:

- if

$p_{bl} \neq 0, \ b,l = 1,2,...,v,$

we replace it by

$p'_{(w+1)(b-1)+1\ (w+1)(l-1)+1} = p_{bl} - [P_b(ut_1) + P_b(ut_2)$

$+ \ldots + P_b(ut_w)],$ (28)

$p'_{(w+1)(b-1)+1\ (w+1)(l-1)+1+i} = P_b(ut_i), \ i = 1,2,...,w,$ (29)

for $b,l = 1,2,...,v$;
and we additionally assume that

$p'_{(w+1)(b-1)+1+i\ (w+1)(b-1)+1} = 1, \ i = 1,2,...,w,$ (30)

$p'_{(w+1)(b-1)+1+i\, j} = 0, \ i = 1,2,...,w, \ j = 1,2,...,v2^w,$ (31)

and $j \neq (w+1)(b-1)+1$;

- if

$p_{bl} = 0, \ b,l = 1,2,...,v,$

we replace it by

$p'_{(w+1)(b-1)+1\ (w+1)(l-1)+1} = 0,$ (32)

$p'_{(w+1)(b-1)+1\ (w+1)(l-1)+1+i} = 0, \ i = 1,2,...,w,$ (33)

for $b,l = 1,2,...,v$.

ii) variant 2:

- if

$p_{bl}(0) \neq 0, \ b,l = 1,2,...,v,$

we replace it by

$p'_{(w+1)(b-1)+1\ (w+1)(l-1)+1} = p_{bl} - p_{bl}[P_b(ut_1) + P_b(ut_2)$

$+ \ldots + P_b(ut_w)],$ (34)

$p'_{(w+1)(b-1)+1\ (w+1)(l-1)+1+i} = p_{bl}P_b(ut_i), \ i = 1,2,...,w,$ (35)

for $b,l = 1,2,...,v$,
and we additionally assume that

$p'_{(w+1)(b-1)+1+i\ (w+1)(b-1)+1} = 1, \ i = 1,2,...,w,$ (36)

$p'_{(w+1)(b-1)+1+i\, j} = 0, \ i = 1,2,...,w, \ j = 1,2,...,v2^w,$ (37)

and $j \neq (w+1)(b-1)+1$;

- if

$p_{bl} = 0, \ b,l = 1,2,...,v, \ b \neq l,$

we replace it by

$p'_{(w+1)(b-1)+1\ (w+1)(l-1)+1} = 0,$ (38)

$p'_{(w+1)(b-1)+1\ (w+1)(l-1)+1+i} = 0, \ i = 1,2,...,w,$ (39)

for $b,l = 1,2,...,v$.
The conditions (30)-(31) and (36)-(37) mean that the transitions from the operation states including the operating environment threats is possible only to the corresponding operation states without the operating envitonment threats.
Finally, as the transformation of the matrix $[H_{bl}(t)]_{v \times v}$ of the critical infrastructure operation process $Z(t)$ conditional sojourn times θ_{bl}, $b,l = 1,2,...,v$, at the operation states without of separation the operation states including the operating environment threats into the matrix $[H'_{bl}(t)]_{v' \times v'}$ of the distributions of the conditional

sojourn times θ'_{bl}, $b,l = 1,2,...,v'$, at the operation states of the critical infrastructure operation process $Z'(t)$ with included and separated operating threats on the basis of expert opnions is practically not possible, we transform the corresponding matrix $[M_{bl}]_{v\times v}$ of the mean values of the conditional sojourn times θ_{bl}, $b,l = 1,2,...,v$, at the operation states into the matrix $[M'_{bl}]_{v'\times v'}$ of the mean values of the conditional sojourn times θ'_{bl}, $b,l = 1,2,...,v'$. We proceed, for both variants (variant 1 and variant 2), in the following way:

- if $M_{bl}(0) \neq 0$, $b,l = 1,2,...,v$,

we fix the mean values

$$M'_{(w+1)(b-1)+1+i\;(w+1)(b-1)+1} \quad i = 1,2,...,w,\; b = 1,2,...,v, \tag{40}$$

on the basis of expert opinions and assume

$$M'_{(w+1)(b-1)+1+i\;j} = 0,\; i = 1,2,...,w,\; j = 1,2,...,v2^w, \tag{41}$$

and $j \neq (w+1)(b-1)+1$, and

$$M'_{(w+1)(b-1)+1\;(w+1)(l-1)+1} = M_{bl} - \sum_{i=1}^{w} M'_{(w+1)(b-1)+1+i\;(w+1)(b-1)+1}, \tag{42}$$

for $b,l = 1,2,...,v$;

- if $M_{bl}(0) = 0$, $b,l = 1,2,...,v$,

we replace it by

$$M'_{(w+1)(b-1)+1\;(w+1)(l-1)+1} = 0, \tag{43}$$

$$M'_{(w+1)(b-1)+1\;(w+1)(l-1)+1+i} = 0,\; i = 1,2,...,w, \tag{44}$$

for $b,l = 1,2,...,v$.

4. Conclusion

In the paper there is presented the probabilistic model of the critical infrastructure operation process. Presented model is the basis for further considerations in particular tasks of the EU-CIRCLE project. Next this model will be used to construct the integrated general safety probabilistic model of the critical infrastructure related to its operation process and climate-weather process [3]. The model will be applied to real critical infrastructures such as the port oil piping transportation system and the maritime ferry technical system. The model further development will be done in the following EU-CIRCLE project reports: [4]-[6], [9]-[12].

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