TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 13
Number 4
December 2019
DOI: 10.12716/1001.13.04.10

# Safety Analysis of Interdependent Critical Infrastructure Networks

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ABSTRACT: Certain critical infrastructure networks show some interconnections, relations and interactions with other ones, most frequently when located and operating within particular areas. Failures arising within one critical infrastructure network, can then negatively impact not only on associated systems, societies and natural environment, but also on mutual critical infrastructure networks. Therefore, interdependent critical infrastructure networks can be determined as network of critical infrastructure networks (network of networks approach).
The paper presents safety analysis of the network of critical infrastructure networks, taking into account interconnections, relations and interactions between particular ones. Critical infrastructures networks as multistate systems are considered, by distinguishing subsets of no-hazards safety states, and crisis situation states, and by analysing transitions between particular ones.
Issues introduced in the article are based on the assumption that one key critical infrastructure network impacts on functioning of other critical infrastructure networks - can reduce their functionality and change level of their safety and inoperability, furthermore, other networks can impact each other, too.
Safety characteristics of network of critical infrastructure networks: safety function, mean values and standard deviations of lifetimes in particular safety state subsets, are determined, taking into account interdependencies between particular networks. The results are related to various values of coefficients defining the significance of influence of interdependencies among networks.

## 1 INTRODUCTION

Critical Infrastructure (CI) systems protection against accidents, natural disasters, and acts of terrorism, has become key point of many public institutions and entrepreneurs activities (Dziula et al. 2015). The need for ensuring high security and resilience of CI assets and services appears as strategic and critical for running vital activities, and ensuring proper functioning of industries, populations, natural environment and national security (Lazari 2014). Thus, works on critical infrastructure systems protection are concentrated mainly on formulating procedures and building resources, able to monitor level of threats, capable of lowering their negative impact if needed, and restoring their full functionality, in case of disruptions caused by internal or external hazards (Blokus-Roszkowska & Dziula 2015).

Remarkable number of works concerning CIs protection, show that many of them feature some interactions and interconnections. Disruptions, affecting one infrastructure can directly and indirectly influence other infrastructures, impact large geographic regions, and send ripples throughout the national and global economy. The degree to which the infrastructures are coupled or linked, strongly influences their functionality (Rinaldi et al. 2001). That makes, interacted and interconnected CIs are often classified as critical infrastructure networks (Yusta et al. 2011, Utne et al. 2011, Huang et al. 2014).

Consequently, CI networks, operating within certain area, interacting, and being also interconnected, can be classified as a Network of Critical Infrastructure Networks (Network of CI Networks).

As the example, the result of analysis of specifics related to the Baltic Sea region, its location and geographic conditions, concentration of various installations qualified as critical infrastructure, distinguishing following CI Networks within the area, can be shown (Dziula & Kołowrocki 2017a):

– Baltic IT CI Network;
– Baltic Port CI Network;
– Baltic Shipping CI Network;
– Baltic Oil Rig CI Network;
– Baltic Wind Farm CI Network;
– Baltic Electric Cable CI Network;
– Baltic Gas Pipeline CI Network;
– Baltic Oil Pipeline CI Network.

Interconnections and interactions among above mentioned networks, have then led to formulate the concept of Global Baltic Network of Critical Infrastructure Networks (*GBNCIN*), that is used in this paper for safety analysis of network of interdependent critical infrastructure networks.

## 2 INTERDEPENDENCIES AMONG CRITICAL INFRASTRUCTURES AND CRITICAL INFRASTRUCTURE NETWORKS

CIs and CI networks can be related in multiple ways. Most widely, literature concerning this issue, indicates dependencies and interdependencies as framework characterisation of their relations. Dependencies usually concern unidirectional relationships, while interdependencies in general indicate bidirectional interactions (Rinaldi et al. 2001). However it can be noted, dependencies usually are regarded as interdependencies, unless specially referred (Ouyang 2014).

There are several approaches to classification of interdependencies among critical infrastructures and critical infrastructure networks. One of frequently cited proposals (Rinaldi et al. 2001), specifies four types of interdependencies: physical (concerns material flows between CIs), cyber (refers to information flows), geographic (related to physical proximity), and logical (mechanisms other than physical, cyber or geographic). Another one, proposed by Zimmermann (2001) divides relations into functional (operation of one infrastructure is necessary for the operation of another infrastructure) and spatial (proximity between infrastructures). Dudenhoeffer (2006), indicates physical (direct linkages between infrastructure systems), geospatial (co-location of infrastructure components within the same footprint), policy (binding of infrastructure components due to policy or high level decisions), and informational (binding or reliance on information flow between infrastructure systems) interactions. Interdependencies distinguished by Wallace et al. (2003), and Lee et al. (2007), are: input (infrastructure systems require as input one or more services from another infrastructure), mutual (activities of each infrastructure system is dependent upon each of the other infrastructure systems), shared (physical components or activities of the infrastructure systems are shared with one or more other infrastructure systems), exclusive (only one of two or more services can be provided by an infrastructure system), and co-located (components of two or more systems are situated within a prescribed geographical region). Zhang & Peeta (2011), suggested relations like functional (functioning of one system requires inputs from another system, or can be substituted, to a certain extent, by the other system), physical (systems are coupled through shared physical attributes), budgetary (infrastructure systems involve some level of public financing), plus market and economic (infrastructure systems interact with each other in the same economic system).

As it can be read out of above, there are quite many different proposals of classification. Adoption of particular one depends mainly on character of interdependencies existing among analysed CIs or CI networks (Ouyang 2014).

## 3 MODELLING OF INTERDEPENDENCIES IN CRITICAL INFRASTRUCTURES

As described in the above chapter, relations among critical infrastructures and critical infrastructure networks, can be identified and described according to different approaches. Numerous modelling methods, that can be found in the literature related to that subject, are introduced in this chapter.

Usually, the first stage is identification of possible interconnections among particular entities forming critical infrastructure, and determining their mutual impact in case of their failure. The impact can be defined by specifying potential initiating events, and behaviour of particular CI objects before, during and after each initiating event (Bloomfield et al. 2017, Huang et al. 2014, Utne et al. 2011).

Identification of critical infrastructure objects interconnections, and their mutual impacts, leads to build a model, representing specified interdependencies. Nagurney & Qiang (2008), for critical network efficiency measure, use model shown in Fig. 1.

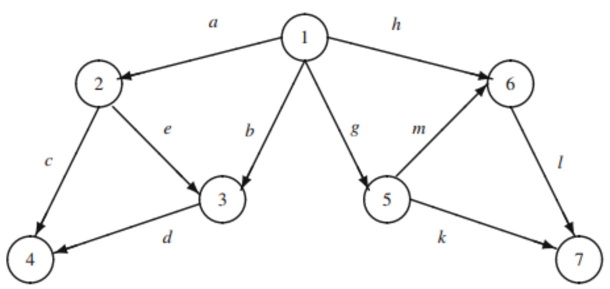


Figure. 1. Critical infrastructure network structure model used for efficiency measure (Nagurney & Qiang 2008).

They identify network nodes (1,2,…,7), and links (*a*,*b*,…,*k*). Then, by specifying link cost functions, the importance and the rankings of particular links and the nodes, can be determined. The approach allows to find the significance of particular network components, and determine the most and least important links.

Another approach is a multilayer infrastructure network model showing infrastructure interdependencies (Fig. 2), proposed by Zhang & Peeta (2011). Individual infrastructure systems are represented as network layers I(1), I(2) and I(3). All infrastructure networks have the same set of nodes. A node represents a geographical region at a spatial scale, which can range from a city zone to a city, county, state, or country. The (horizontal) links within each network layer represent the flow connectivity in that infrastructure system, manifesting primarily through the physical facilities enabling the flow. As different infrastructure systems have different physical network configurations, flow characteristics, and institutional organization, the set of links may vary across infrastructure systems, as indicated in Fig. 1 by the different sets of links connecting the nodes in the various infrastructure network layers.

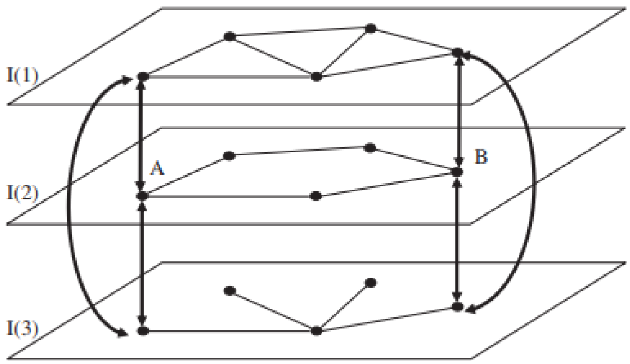


Figure. 2. Multilayer infrastructure network framework (Zhang & Peeta 2011).

Vertical links denote the infrastructure interdependencies in the same geographical region, as nodes are common to the various MIN network layers. The interdependencies between one infrastructure system in a region and another infrastructure system in another region are captured through a combination of horizontal and vertical links. Example of such an interdependency, involving systems I(1) and I(2), is represented by nodes A and B. It manifests first as being transmitted from node B in infrastructure I(2) to node A in I(2) through the horizontal links, and then to node A in I(1) through the vertical links.

Rueda & Calle (2017), introduce interdependency matrices to analyse interdependencies between interconnected critical infrastructures. They consider two undirected networks $G_1$ and $G_2$ (Fig. 3), each with sets of nodes and links, respectively. When $G_1$ and $G_2$ interact, a set of bidirectional interlinks, joining the two networks, appears.

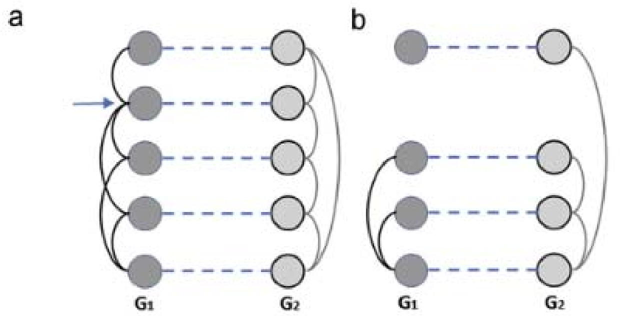


Figure. 3. Mutual interactions of interdependent networks in case of nodes failures (Rueda and Calle 2017).

By generating interdependency matrices: High Centrality Interdependency Matrix (correspondence between high centrality nodes in $G_1$ and high centrality nodes in $G_2$), Low Centrality Interdependency Matrix (correspondence between low centrality nodes in $G_1$ and low centrality nodes in $G_2$), and Random Interdependency Matrix (correspondence between nodes in $G_1$ and nodes in $G_2$ without their centrality measures), the impact of failure of one network element on another network can be determined, as shown in Fig. 3(a) and Fig. 3(b).

Methodology submitted by Reed et al. (2009), is delivering network model illustrated in Fig. 4., derived from the eleven-system interdependent infrastructure.

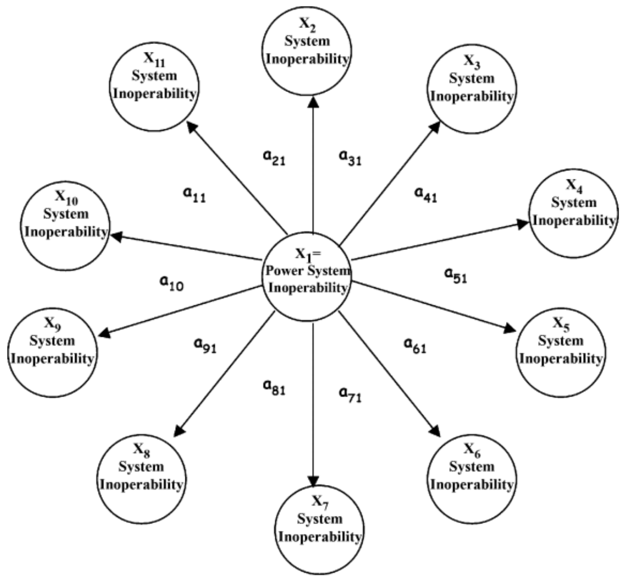


Figure. 4. Interdependencies coefficients between selected subsystems (Reed et al. 2009).

One central node ($X_1$ – Power System), has been determined, and the other ($X_2$ – $X_{11}$) interdependent ones such as telecommunications, transportation, etc., have been pointed. Interdependencies ($a_{ij}$), between various subsystems are related to probability of inoperability that one subsystem contributes to other one. The approach lets to evaluate engineering resilience and interdependency for subsystems of a multi-system networked infrastructure for extreme natural hazard events.

The approaches introduced above, show slight differences, concerning modelling of interdependencies within CI network, or among CI networks. They all let however to specify the approach for the purpose of this article, that is introduced in the next chapter.

## 4 ASSUMPTIONS FOR MODELLING SAFETY RELATED TO INTERDEPENDENCIES

For the analysis of Global Baltic Network of Critical Infrastructure Networks, we adopt model proposed by Reed et al. (2009), enhanced however with interdependencies among particular networks, besides relations related to central one only (Fig. 5).

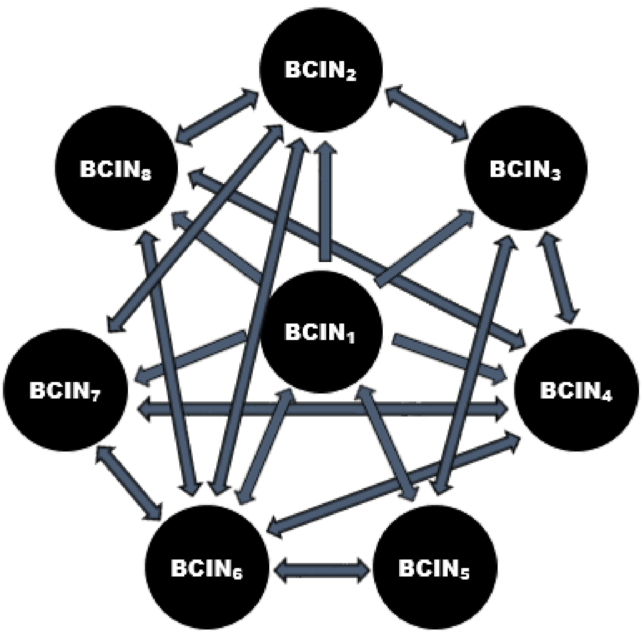


Figure. 5. Interdependencies among particular networks within GBNCIN.

The Baltic IT CI Network, is assumed as one, that most significantly impacts on other networks. Baltic CI networks specified in Chapter 1 are denoted as follows:
- Baltic IT CI Network – BCIN1;
- Baltic Port CI Network – BCIN2;
- Baltic Shipping CI Network – BCIN3;
- Baltic Oil Rig CI Network – BCIN4;
- Baltic Wind Farm CI Network – BCIN5;
- Baltic Electric Cable CI Network – BCIN6;
- Baltic Gas Pipeline CI Network – BCIN7;
- Baltic Oil Pipeline CI Network – BCIN8.

The interdependencies among particular networks can be both unidirectional and bidirectional, as also indicated in the Fig. 5. The impact of malfunctions within $BCIN_j$, $j \in \{1,2,...,8\}$ network, on $BCIN_i$, $i \in \{1,2,...,8\}$ network, related to their safety states, is denoted by coefficient $q_{ij}$, where $i \in \{1,2,...,8\}$ and $j \in \{1,2,...,8\}$. The $q_{ij}$ coefficients can take values from the range [0;1). If there is no influence of $BCIN_j$ network on $BCIN_i$ network, the coefficient equals to zero.

For the paper purposes, the multistate approach is adopted for the safety analysis of the *GBNCIN* (Blokus-Roszkowska et al. 2018, Dziula & Kołowrocki 2017b). Following four safety states, of the *GBNCIN* and $BCIN_i$, $i \in \{1,2,...,8\}$ networks, have been distinguished:
- GBNCIN/ BCIN network state of full ability – z3 = 3;
- GBNCIN/ BCIN network impendency over safety state – z2 = 2;
- state of GBNCIN/ BCIN network unreliability – z1 = 1;
- state of full inability of GBNCIN/ BCIN network – z0 = 0.

The safety function of $BCIN_i$, $i = \{1,2,...,8\}$ network is defined by the vector (Blokus-Roszkowska et al. 2018, Dziula & Kołowrocki 2017b):

$$S_i(t,\cdot) = [S_i(t,0), S_i(t,1), S_i(t,2), \ldots, S_i(t,z_3)], \quad (1)$$

$t \in <0,\infty)$, $i = 1,2,...,8$.

By the assumption the coordinates of the above safety function are exponential, they take following forms:

$$S_i(t,u) = \exp[-\lambda_i(u)t],\ u = 1,2,\ldots,z_3,\ i = 1,2,...,8, \quad (2)$$

where $\lambda_i(u)$, $u = 1,2,...z_3$, are the intensities of departure from the safety state subset $\{u, u+1,...,z_3\}$ – subset of safety states not worse than the state $u$, $u = 1,2...,z_3$, and $S_i(t,0) = 1$.

We assume that the *GBNCIN* is a multistate series network. That means that the *GBNCIN* is in the safety states subset $\{u, u+1,...,z_3\}$, $u = 1,2,...z_3$, if and only if all $BCIN_i$, $i = 1,2,\ldots,8$, networks are in this subset of safety states.

## 5 SAFETY ANALYSIS OF GLOBAL BALTIC NETWORK OF CRITICAL INFRASTRUCTURE NETWORKS

For the purposes of the *GBNCIN* safety analysis, taking into account interdependencies among particular $BCIN_i$, $i = 1,2,\ldots,8$, networks, the multistate approach (Blokus-Roszkowska et al. 2018, Kołowrocki 2014) is applied. The approach states, that impact of $BCIN_j$, $j = 1,2,\ldots,8$ network, on functioning of the $BCIN_i$, $i = 1,2,\ldots,8$ network, means that transition of the $BCIN_j$ safety state from better to worse one (i.e. from $z_3 = 3$, to $z_2 = 2$ or $z_1 = 1$), results with transition of the $BCIN_i$ safety state also from better to worse. It is coming out of fact that lifetimes of $BCIN_i$, $i \in \{1,2,...,8\}$ network, within subset of safety states, shorten, and its safety characteristics get worse. In more details, if the $BCIN_j$, $j \in 1,2,\ldots,8$, network exceeds subset $\{u,u+1,...,z_3\}$, $u = 1,2,...,z_3$, of safety states, it results the $BCIN_i$, $i = 1,2,\ldots,8$ network lifetimes and their mean values in the subset $\{\upsilon, \upsilon+1,...,z_3\}$, where $\upsilon = 1,2,\ldots,u$, and $u = 1,2,...,z_3-1$, decrease according to the formulas given by Blokus-Roszkowska et al. (2018):

$$T_{i/j}(\upsilon) = [1 - q(\upsilon, BCIN_j, BCIN_i)] \cdot T_i(\upsilon), \quad (3)$$

$$E[T_{i/j}(\upsilon)] = [1 - q(\upsilon, BCIN_j, BCIN_i)] \cdot E[T_i(\upsilon)],$$

$$i = 1,2,\ldots,8,\ j = 1,2,\ldots,8, \quad (4)$$

where $q(\upsilon, BCIN_j, BCIN_i)$, $i,j = 1,2,\ldots,8$, $i \neq j$, are the coefficients of $BCIN_j$ network impact on functioning of $BCIN_i$ network,

$$q(\upsilon, BCIN_i, BCIN_i) = 0,\ i = 1,2,...,8, \tag{5}$$

and

$$0 \le q(\upsilon, BCIN_j, BCIN_i) < 1 \tag{6}$$

for $i,j = 1,2,\ldots,8$, $\upsilon = u,u\text{-}1,...,1$, and $u = 1,2,...,z_3\text{-}1$.

$T_i(\upsilon)$ and $T_{i/j}(\upsilon)$, given by formulae (3) and (4) are independent random variables representing lifetimes of $BCIN_i$, $i \in \{1,2,...,8\}$ network in the safety state subset $\{\upsilon, \upsilon+1,...,z_3\}$, respectively before and after $BCIN_j$, $j \in \{1,2,...,8\}$ network departures states subset $\{u,u+1,...,z_3\}$, $u = 1,2,...,z_3$. Similarly, $E[T_i(\upsilon)]$ and $E[T_{i/j}(\upsilon)]$ are respectively mean values of lifetimes $T_i(\upsilon)$ and $T_{i/j}(\upsilon)$.

Due to fact it has been assumed, that the *GBNCIN* is a series network, we do not consider impact on time of stay of $BCIN_i$ network in the best state ($z_3$). That is because series network is in the best state $z_3$ only if its all $BCIN_i$, $i = 1,2,...,8$, networks, are in the state $z_3$. Thus, departure of one of $BCIN_j$, $j \in \{1,2,...,8\}$ networks from subset $\{z_3\}$, automatically results with the *GBNCIN* departure from the state $z_3$. We analyse only influence on other networks $BCIN_i$, $i \in 1,2,...,8$, time of stay within subsets $\{1,2,..., z_3\}$, $\{2,..., z_3\}$, ..., $\{z_3\text{-}1, z_3\}$.

In further safety analysis, we replace $z_3$ by 3, as assumed before. Under the assumption about the exponential distribution, the conditional intensities of the network $BCIN_i$ departure from the subset $\{\upsilon,\upsilon+1,\ldots,3\}$, after the departure of the network $BCIN_j$, by (4), are:

$$\lambda_{i/j}(\upsilon) = \frac{\lambda_i(\upsilon)}{1 - q(\upsilon, BCIN_j, BCIN_i)}, \tag{7}$$

for $i,j = 1,2,\ldots,8$, $\upsilon = u,u\text{-}1,...,1$, and $u = 1,2$.

Assuming the *GBNCIN* is a multistate series network and interdependences among *BCIN* networks, expressed in (3)-(4), in case the *BCIN* networks have exponential safety functions (1)-(2), and considering (7), the safety function of the *GBNCIN* is given by the vector (Blokus-Roszkowska & Kołowrocki 2017):

$$\boldsymbol{S}(t,\cdot) = [1, \boldsymbol{S}(t,1), \boldsymbol{S}(t,2), \boldsymbol{S}(t,3)], \tag{8}$$

where

$$\boldsymbol{S}(t,1) = \exp[-\sum_{i=1}^{8}\lambda_i(2)t] + \sum_{j=1}^{8}\frac{\lambda_j(2)-\lambda_j(1)}{\sum_{i=1}^{8}\lambda_i(2)-\sum_{i=1}^{8}\lambda_i(1)}$$
$$\cdot[\exp[-\sum_{i=1}^{8}\frac{\lambda_i(1)}{1-q(1,BCIN_j,BCIN_i)}t]$$
$$-\exp[-(\sum_{i=1}^{8}\lambda_i(2)-\sum_{i=1}^{8}\lambda_i(1)$$
$$+\sum_{i=1}^{8}\frac{\lambda_i(1)}{1-q(1,BCIN_j,BCIN_i)})t]], \tag{9}$$

$$\boldsymbol{S}(t,2) = \exp[-\sum_{i=1}^{8}\lambda_i(3)t] + \sum_{j=1}^{8}\frac{\lambda_j(3)-\lambda_j(2)}{\sum_{i=1}^{8}\lambda_i(3)-\sum_{i=1}^{8}\lambda_i(2)}$$
$$\cdot[\exp[-\sum_{i=1}^{8}\frac{\lambda_i(2)}{1-q(2,BCIN_j,BCIN_i)}t]$$
$$-\exp[-(\sum_{i=1}^{8}\lambda_i(3)-\sum_{i=1}^{8}\lambda_i(2)$$
$$+\sum_{i=1}^{8}\frac{\lambda_i(2)}{1-q(2,BCIN_j,BCIN_i)})t]], \tag{10}$$

$$\boldsymbol{S}(t,3) = \exp[-\sum_{i=1}^{8}\lambda_i(3)t], \tag{11}$$

for $t \ge 0$.

Table 1. Coefficients $q(\upsilon, BCIN_j, BCIN_i)$, $i,j = 1,2,\ldots,8$, $\upsilon = 1,2$, of the $BCIN_j$ network impact on lifetimes and their mean values in the subsets {1,2,3} and {2,3} of the $BCIN_i$ network.

| $j \mid I$ | $BCIN_1$ | $BCIN_2$ | $BCIN_3$ | $BCIN_4$ | $BCIN_5$ | $BCIN_6$ | $BCIN_7$ | $BCIN_8$ |
|---|---|---|---|---|---|---|---|---|
| $BCIN_1$ | 0 | 0 | 0 | 0 | q | q | 0 | 0 |
| $BCIN_2$ | q | 0 | q | 0 | 0 | q | q | q |
| $BCIN_3$ | q | q | 0 | q | q | 0 | 0 | 0 |
| $BCIN_4$ | q | 0 | q | 0 | 0 | q | q | q |
| $BCIN_5$ | q | 0 | q | 0 | 0 | q | 0 | 0 |
| $BCIN_6$ | q | q | 0 | q | q | 0 | q | q |
| $BCIN_7$ | q | q | 0 | q | 0 | q | 0 | 0 |
| $BCIN_8$ | q | q | 0 | q | 0 | q | 0 | 0 |

Coefficients of impact of particular *BCIN* networks on the *GBNCIN* network, formulated according to model introduced in Fig. 5, are shown in Table 1. Table 2 presents intensities of particular $BCIN_i$, $i = 1,2,...,8$, networks departures from the safety states subsets {1,2,3}, {2,3}, and {3}. The *BCINs* lifetimes in the safety states are expressed in years.

Table 2. Intensities $\lambda_i(1)$, $\lambda_i(2)$ and $\lambda_i(3)$ of the $BCIN_i$, $i = 1,2,\ldots,8$, networks departure from the safety states subsets {1,2,3}, {2,3}, and {3}, respectively [year$^{-1}$].

| $BCIN_i$ | $\lambda_i(1)$ | $\lambda_i(2)$ | $\lambda_i(3)$ |
|---|---|---|---|
| $BCIN_1$ | 0.2 | 0.5 | 1 |
| $BCIN_2$ | 0.1 | 0.2 | 0.5 |
| $BCIN_3$ | 0.1 | 0.2 | 0.5 |
| $BCIN_4$ | 0.1 | 0.2 | 0.5 |
| $BCIN_5$ | 0.2 | 0.5 | 1 |
| $BCIN_6$ | 0.067 | 0.1 | 0.2 |
| $BCIN_7$ | 0.067 | 0.1 | 0.2 |
| $BCIN_8$ | 0.067 | 0.1 | 0.2 |

By entering intensity values given in Table 2, into the formulas (8)-(11), and assuming that coefficients of impact of particular *BCIN* networks $q(1, BCIN_j, BCIN_i) = q(2, BCIN_j, BCIN_i)$, $i,j = 1,2,\ldots,8$, indicated in Table 1, take the values 0 and $q = 0.50$ (exemplary value), we obtain safety function of the *GBNCIN*.

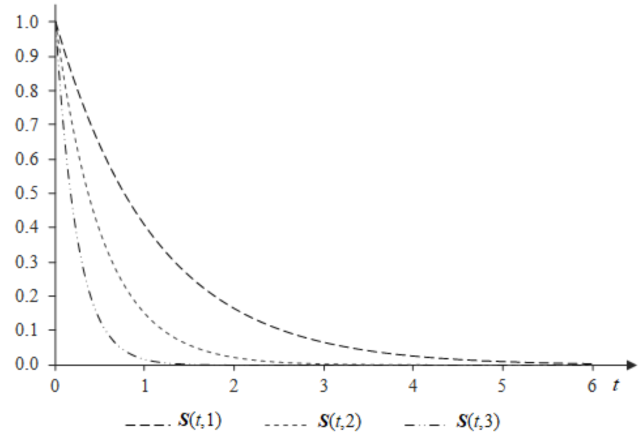


Figure. 6. Safety function coordinates of the *GBNCIN* for $q = 0$.

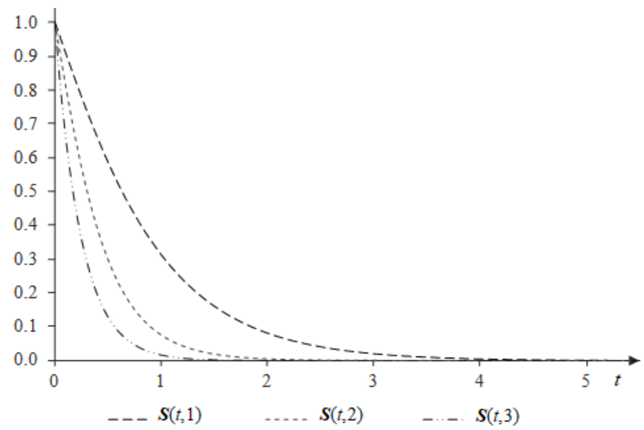


Figure. 7. Safety function coordinates of the *GBNCIN* for exemplary value $q = 0.50$.

The graph of safety function coordinates of the *GBNCIN* for $q = 0$ is shown in Fig. 6, and for $q = 0.50$ in Fig. 7. In case the coefficients $q(\upsilon, BCIN_j, BCIN_i)$, $i,j \in \{1,2,\ldots,8\}$, $\upsilon = 1,2$, equal to zero, the results are identical to the results for *GBNCIN* assuming independence of *BCIN* networks.

Table 3 shows mean values and standard deviations of the *GBNCIN* lifetimes in safety states subsets {1,2,3}, {2,3}, and {3}, obtained for $q(\upsilon, BCIN_j, BCIN_i) = q$, $i,j \in \{1,2,\ldots,8\}$, $\upsilon = 1,2$, coefficients varying from zero to 0.99, demonstrating how relations level influences on the whole *GBNCIN* network. The results are calculated in years by applying *GBNCIN* safety function (8)-(11), for intensities $\lambda_i(1)$, $\lambda_i(2)$ and $\lambda_i(3)$, given in Table 2.

Table 3. Mean values and standard deviations of the *GBNCIN* lifetimes in safety states subsets {1,2,3}, {2,3}, and {3}, for coefficients $q(\upsilon, BCIN_j, BCIN_i) = q$, $i,j \in \{1,2,\ldots,8\}$, $\upsilon = 1,2$, ranging from zero to 0.99.

| $q$ | $\mu(1)$ | $\sigma(1)$ | $\mu(2)$ | $\sigma(2)$ | $\mu(3)$ | $\sigma(3)$ |
|---|---|---|---|---|---|---|
| 0 | 1.110 | 1.110 | 0.526 | 0.526 | 0.244 | 0.244 |
| 0.1 | 1.064 | 1.049 | 0.507 | 0.500 | 0.244 | 0.244 |
| 0.2 | 1.015 | 0.987 | 0.485 | 0.473 | 0.244 | 0.244 |
| 0.3 | 0.963 | 0.920 | 0.462 | 0.443 | 0.244 | 0.244 |
| 0.4 | 0.907 | 0.849 | 0.437 | 0.411 | 0.244 | 0.244 |
| 0.5 | 0.846 | 0.774 | 0.409 | 0.377 | 0.244 | 0.244 |
| 0.6 | 0.780 | 0.696 | 0.378 | 0.340 | 0.244 | 0.244 |
| 0.7 | 0.710 | 0.619 | 0.344 | 0.301 | 0.244 | 0.244 |
| 0.8 | 0.636 | 0.552 | 0.306 | 0.265 | 0.244 | 0.244 |
| 0.9 | 0.567 | 0.517 | 0.269 | 0.240 | 0.244 | 0.244 |
| 0.99 | 0.527 | 0.525 | 0.245 | 0.242 | 0.244 | 0.244 |

The impact of interdependencies among *BCIN* networks, expressed by (3)-(4), on mean values $\mu(1)$, $\mu(2)$, $\mu(3)$ of the *GBNCIN* lifetimes in safety states subsets {1,2,3}, {2,3}, and {3} respectively, is also illustrated in Fig. 8.

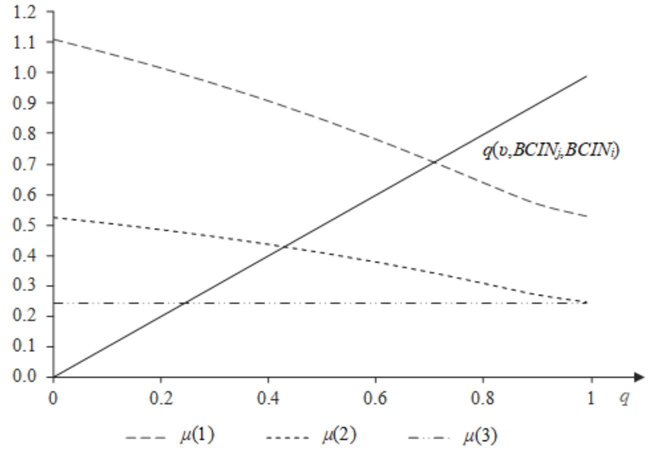


Figure. 8. Mean values of the *GBNCIN* lifetimes in safety states subsets {1,2,3}, {2,3}, and {3}, given in years for coefficients $q(\upsilon, BCIN_j, BCIN_i) = q$, $i,j \in \{1,2,\ldots,8\}$, $\upsilon = 1,2$, ranging from zero to 0.99.

It can be noticed that values of coefficients $q(\upsilon, BCIN_j, BCIN_i)$, $i,j \in \{1,2,\ldots,8\}$, $\upsilon = 1,2$, have no influence on the *GBNCIN* lifetime in safety state 3. This is due to the fact that in case of a series network structure, as previously pointed out, the safety function coordinate $\boldsymbol{S}(t,3)$ does not depend on the value of these coefficients and is the same as for independent series network.

## 6 CONCLUSIONS

The paper presents multistate approach to modelling safety of network of CI networks related to interdependencies. Proposed model of safety analysis for series network is applied to determine safety function of the *GBNCIN*, taking into account interdependencies among particular *BCIN* networks, forming the *GBNCIN*. By use of the safety function, mean values and standard deviations of the *GBNCIN* lifetimes in safety states subsets, are determined. The results are compared for different values of coefficient expressing interdependencies among particular networks within *GBNCIN*. The proposed method allows to assess the influence level of interdependencies among CI networks on the whole *GBNCIN* network lifetimes in safety states subsets.

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