Modelling Operation Process of Baltic Port, Shipping and Ship Traffic and Operation Information Critical Infrastructure Network

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ABSTRACT: The main aim of the article is modelling the operation process of the Baltic Port, Shipping and Ship Traffic and Port Operation Information Critical Infrastructure Network. To achieve this goal it is necessary to define three critical infrastructure networks for a Baltic Sea Region and their operation processes: port critical infrastructure network, shipping critical infrastructure network and ship traffic and port operation information critical infrastructure network. Thus, the concept of networks of three networks, called Baltic Port, Shipping and Ship Traffic and Port Operation Information Critical Infrastructure Network, is introduced. This way, the operation process of network of networks is proposed. To understand this approach, the basic classification and description of interdependencies and interconnections in this network are presented.

1 INTRODUCTION

The maritime transport is the most effective and relatively inexpensive transportation mode. Mandatory elements of this complex system are: ports, ships and ICT supporting and management systems. It is well-known fact, that ports are the connectors between the seas, oceans, and land, and specifically between water transport and land. Thus, logistics and distribution of goods are one of the main tasks of the port centres. Thus, at the macroeconomic level, the ports provide contacts with distant countries, continents, through easier access to them. In the case of the microeconomic scale, it is doing the business activities, services by the operators at the port area. These economic activities can include cargo handling and stowage, repair, parts production, and many other services performed for the port or the ships being in the port. The connections between particular ports are carried out using the ships, which are very important components of the maritime transportation system. Their technical condition, crew training, traffic safety are influential factors for the whole safety of transportation system. Complement of these elements of maritime transport are: vessel traffic and monitoring systems, telecommunication systems and port management and information systems. They are very important factor for safety of ports and shipping. They are subjected to the EU law regulations and implementations to Member States law [26]. Their technological development also gives the opportunity to improve safety of navigation, commercial efficiency and security which is manifested in the e-Navigation concept [31], [36].

According to [30], [35], the national airspace, maritime and land transportation systems, and the vessels operating thereon, pipelines and other delivery services are the physical distribution systems critical to supporting the national security and economic well-being of this nation.

Thus, the European Commission defines the Critical Infrastructure (CI) as an asset or system which is essential for the maintenance of vital societal

functions. The damage to a critical infrastructure, its destruction or disruption by natural disasters or other threats (terrorism, criminal activity or malicious behaviour), may have a significant negative impact on the security of the EU and the well-being of its citizens [9]. Nowadays, the main goal of the EU is reducing the vulnerabilities of critical infrastructure and increasing their resilience [19], [25], particularly for the weather-climate changes [18]. Thus, the European Programme for Critical Infrastructure Protection (EPCIP) has been started [5], [10]. The EPCIP has proposed a list of European critical infrastructures based upon inputs by its Member States. According to the European Commission's "Green Paper" on the EPCIP the following 8 main critical infrastructure networks operating in the Baltic Sea Region are distinguished ([1], [5]):
- port critical infrastructure network;
- shipping critical infrastructure network;
- oil rig critical infrastructure network;
- wind farm critical infrastructure network;
- electric cable critical infrastructure network;
- gas pipeline critical infrastructure network;
- oil pipeline critical infrastructure network;
- ship traffic and port operation information critical infrastructure network.

All of these networks should be considered as the complex system that is defined as a set or group of interacting, interrelated or interdependent elements or parts, that are organized and integrated to form a collective unity or an unified whole, to achieve a common objective [1]. According to above, the critical infrastructure is defined as a complex system in its operating environment that significant features are inside-system dependencies and outside-system dependencies, that in the case of its degradation have significant destructive influence on the health, safety and security, economics and social conditions of large human communities and territory areas [1]. According to this definition, the key features of CIs are internal dependencies and connections between their components.

To answer for the globalization of life and economy, it should be considering not a single CI but the networks of CIs. Thus, the critical infrastructure network, as the more general notion, is introduced in literature ([1] – [3], [15] –[17]). It is defined as a set of interconnected and interdependent critical infrastructures interacting directly and indirectly at various levels of their complexity and operating activity [1]. This way of defining allow us to use the well-known methods for reliability and safety analysis of large complex systems [7], [20], [24] – [25]. Furthermore, the approach to modelling operation process can be done by methods described in [7], [21] – [23]. It also takes into account the environmental and infrastructural influence on reliability and operation process [21].

The paper is devoted modelling operation process of the Baltic Port, Shipping and Ship Traffic and Port Operation Critical Infrastructure Network (BPSSTPOCIN) and presenting the main interdependencies and interconnections [27].

2 DEFINITION OF THE BALTIC PORT, SHIPPING AND SHIP TRAFFIC AND PORT OPERATION INFORMATION CRITICAL INFRASTRUCTURE NETWORK

According to the current approach, the ports and their supported infrastructure (i.e. roads, railways, piers, breakwaters, power lines, ICT networks, etc.) are considered as the maritime critical infrastructure [25], [35]. The aspects of maritime critical infrastructures protection take into account only the ensuring the security and defence of ports. But the complexity of the port activities causes that such a description is no longer sufficient. Thus, the concept of Baltic Port, Shipping and Ship Traffic and Port Operation Information CI Network is introduced as the network of three networks in [16]. It consists of port critical infrastructure network [2], shipping critical infrastructure network [3] and ship traffic and port operation information critical infrastructure network [17]. As we know, there are strong inner and outer dependencies between these three networks.

The description of the above networks is contained in Subsections 2.1 – 2.3.

2.1 *Baltic Port Critical Infrastructure Network*

In the paper [2], the Baltic Port Critical Infrastructure Network (BPCIN) is defined and composed of 18 following core ports placed at the Baltic seaside:
1. The Port of Aarhus (P_1);
2. The Copenhagen – Malmö Port (P_2);
3. The Lübecker Hafen-Gesellschaft (P_3);
4. The Port of Rostock (P_4);
5. The Port of Tallinn (P_5);
6. The Freeport of Riga (P_6);
7. The Freeport of Ventspils (P_7);
8. The Klaipeda State Seaport (P_8);
9. The Port of Gdańsk (P_9);
10. The Port of Gdynia (P_{10});
11. The Szczecin-Swinoujście Port (P_{11});
12. The Port of Helsinki (P_{12});
13. The Port of Turku (P_{13});
14. The Port of Hamina-Kotka(P_{14});
15. The Port of Gothenburg (P_{15});
16. The Port of Luleå (P_{16});
17. The Port of Stockholm (P_{17});
18. The Port of Trelleborg (P_{18}).

The distribution of ports form the BPCIN is presented in Figure 1.

Figure 1. The Baltic core ports forming BPCIN [2]

More details are provided in paper [2].

2.2 *Baltic Shipping Critical Infrastructure Network*

According to the paper [3] the set of ships operating at the Baltic Sea waters at the fixed moment of time (or at the fixed time interval) is called the dynamic Baltic Shipping Critical Infrastructure Network (BSCIN).

2.3 *Baltic Ship Traffic and Port Operation Information Critical Infrastructure Network*

The paper [17] defines the Baltic Ship Traffic and Port Operation Information Critical Infrastructure Network (BSTPOICIN) composed of 121 AIS base stations and 25 DGPS stations and 21 port/terminal operation systems listed in [17].

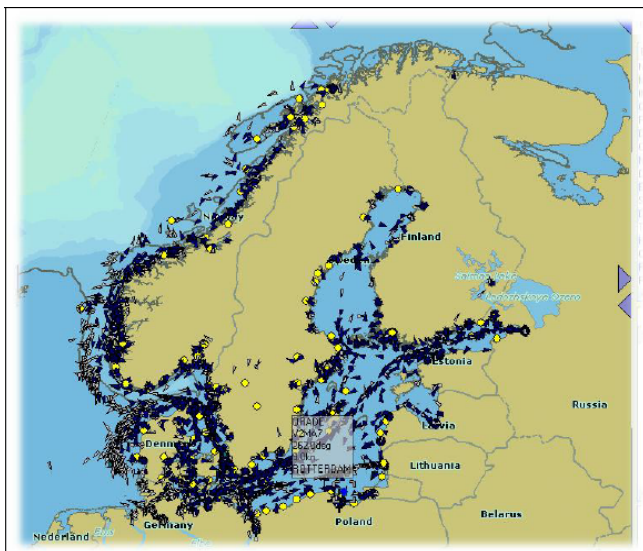The distribution of AIS base station is presented on Figure 2.

Figure 2. The map of Baltic Sea Region area – the yellow points represents the AIS base stations [3]

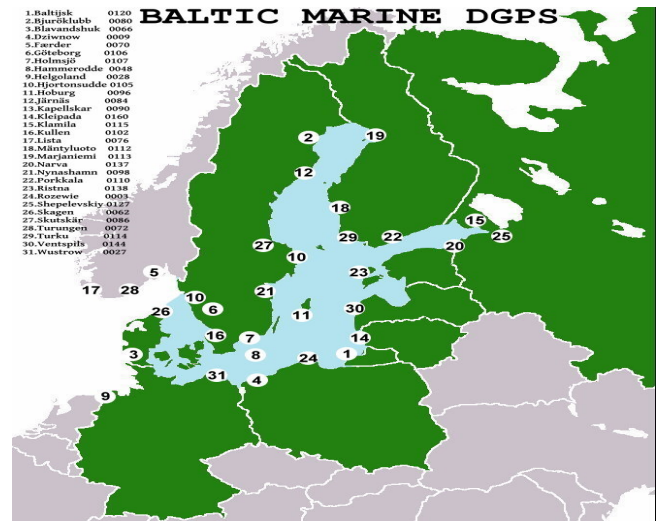Besides, the Baltic Marine DGPS network is presented on Figure 3.

Figure 3. Baltic Marine DGPS Stations [17]

The detailed information about this critical infrastructure network is presented in [15] - [17].

3 INTERDEPENDENCIES AND INTERCONNECTIONS

In earlier Sections the strong internal connections and dependencies between the elements of CI network are distinguished. Therefore, this section is devoted to the classification and description of these internal relationships ([27], [30], [32]).

According to the [32] we take into account four types of interdependency:
– Physical – the state of one is dependent on the material output of the other;
– Systems – the state of the one depends on the properties of the system transmitted through another asset;
– Geographic – an incident in an asset may impact the state of assets in a defined spatial proximity;
– Logical – a mechanism that does not fall into any of the above.

As it is presented in Figure 4, infrastructures are interconnected not only across national and continental boundaries. There exist the interconnections and interdependencies between infrastructure sectors (see Fig. 4).
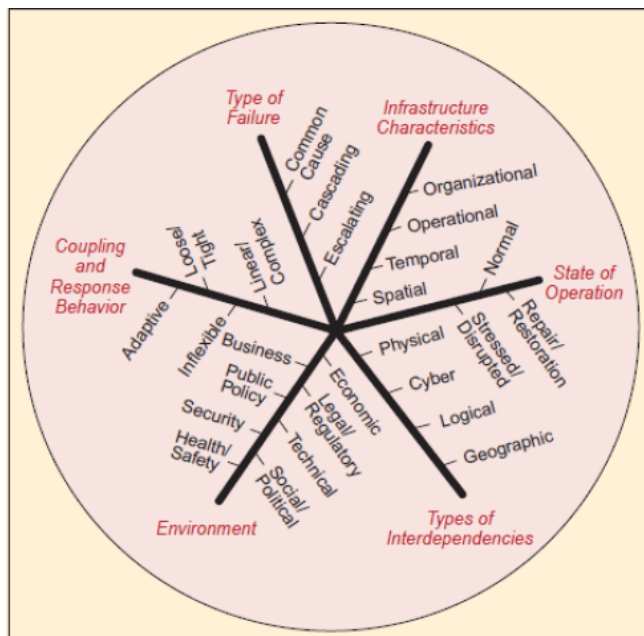
Figure 4. Critical infrastructure interdependencies [32]

In this way, the chain dependencies is created. It provides to the unforeseen cascading effect or domino effects. This means that disruption of one CI network or one CI in this network may become a source of disturbance to other CI or CI networks [4]. It seems the big problem, because interconnectedness and interdependence make these infrastructures more vulnerable to disruption or destruction ([19]). Moreover, in the era of the advanced ICT technologies CI networks have become more dependent on common information technologies, including the internet and space-based radio-navigation and communication [4].

A clear understanding of the extent of the interdependence is crucially important for dealing with such cascading effects, along with the application of effective emergency preparedness measures [4].

3.1 Port CI network's interconnections and interdependencies

The ports are the place, where the interaction between the private sector (which owns and operates most infrastructures) and the public sector occurs. Thus, seaports cannot be analysed as infrastructures that merely handle ships. A modern port interconnects and offers a choice between various modes of transport. Goods can be transferred from sea to rail, road or inland navigation. They constitute a vital interconnection in the world logistics, including several trade activities. This interconnection allows citizens to buy cheap products from all over the world.

On the other side are the interdependence of maritime activities and policies. These justify the need for a comprehensive system of spatial planning. Such system would prevent unintended and contradictory effects of legislation, developed according to the needs and objectives of policy, on other maritime goals in

the context of sustainable development. The example of this approach is the TEN-T infrastructure.

The another way of the interconnection is a trade (direct connections) between the ports from BPCIN. It represents the country's interconnection and interdependence with the maritime element and with the exterior (port to port). In this way, we also take into account, the geographic interconnections and independence port to port and port to the city, where it is located. Mainly, it corresponds to the trade market and workplaces. Besides, the important thing is transportation environment of ports, what are constituted the connections and dependencies with other types of transport (i.e. railway and road).

As it was mentioned before, the set of ships operating in the Baltic Sea waters at the fixed moment of time (or at the fixed time interval) we call the Baltic Shipping Critical Infrastructure Network (BSCIN) that is particularly described in [1] and [3]. The operation process and safety of the shipping critical infrastructure network depends strongly on the individual ships it is composed of operating area within the Baltic Sea region [3].

Because of the high density of the ship traffic in the Baltic Sea Region, there are strong interconnections between the different types of vessels. These relationships are especially visible at the transhipment type ship-to-ship or ship-port-ship (combined route using, at least, two ships).

As with the traditional aspects of the transportation network, interdependencies also exist between the assets, people, and the facilities in which they reside. The frequency of departures mostly depends on the port of ship destination.

3.2 Ship traffic and port operation information CI network's interconnections and interdependencies

Modern life is increasingly dependent on a multitude of interconnected and interdependent infrastructures. While sectors such as food, water, health and transportation and the infrastructure that supports them have always been critical, their ability to deliver is increasingly enmeshed with the ICT technologies that have become essential components of daily life. The maritime transportation system operates using information and communication systems. They play an important role in each of these links as a core platform for an information exchange and supporting the safety monitoring of people, vessels, equipment and cargo in ports and during the ship passage on the waterways. We can distinguish two types of ICT systems:
− ship traffic information systems;
− ship port operation information systems.

The first group consists of the following systems: AIS, LRIT, DGPS, GNSS. They are used by MSSiS, SafeSeaNet, THETIS. In the second group, we can highlight the Electronic Data Interchange (EDI)

systems and Port Management Information Systems (PMIS).

The above ICT systems are forming the maritime information system represented by the maritime information network. Thus the maritime information system consists of the LRIT, the AIS and VHF ship equipment, base stations and data centers, vessel and overland computer systems and other computing hardware devices (in ports, terminals, Maritime Offices, etc.) that are linked together through communication and information channels to facilitate communication, information and resource-sharing among a wide range of users. It is represented by interconnected and interdependent maritime information network. The maritime information network consists of the maritime information system with its structure and flow. The nodes of this network can be base stations, satellites, VTS Centres, ports, terminals, Maritime Offices, data centres, vessels, goods storages and destination places. The routes of this network are single links between the nodes.

Thus, the sum these components create the cyberspace. It is sometimes categorized as a discrete sector, in practice it is so deeply embedded into sectors such as energy and transport as to make any separation meaningless. Cyberspace can be visualized instead as a thin layer or nervous system running through all other sectors, enabling them to communicate and function.

3.3 *Port, shipping and ship traffic and port operation information CI network's interconnections and interdependencies*

We can take into account more general approach. The set of assets consists of the ports, ships and ICT systems described as the large, complex systems. Besides, as it was mentioned in Sections 2 - 3, the port, shipping and ship traffic and port operation critical infrastructure network represents the system interconnection and interdependency. It is the fact, because, the state of the one component depends on the properties of the system transmitted through another asset. Exemplary, the port, and the ships are connected, first of all, by ICT systems: VTS, LRIT, DGPS, and PMIS. It seems that the ICT systems are needed for safe and secure ship traffic and port operations in every area of Baltic Sea Region.

4 BPSSTPOICIN OPERATION PROCESS

An approach to the BPSSTPOICIN operation process has been introduced in [15]. This paper extends results to the complete elements necessary to modelling the operation process.

As it was mentioned in Section 2, we consider the network composed of the following three critical infrastructure networks which operates in Baltic Sea Region area:
- $CIN^{(1)}$ - the Baltic Port Critical Infrastructure Network (BPCIN),
- $CIN^{(2)}$ - the Baltic Shipping Critical Infrastructure Network (BSCIN),

- $CIN^{(3)}$ - the Baltic Ship Traffic and Port Operation Information Critical Infrastructure Network (BSTPOICIN).

This network of networks is characterized by strong interacting, interconnections and interdependencies, which are presented in Section 3. Moreover, we suppose that the operation processes of these critical infrastructure networks have an influence on their safety and depend on their operating area within the Baltic Sea Region.

As it is mentioned in [15], we can divide the Baltic Sea area D into a grid of rectangles D_{ab}, i.e.

$$D = \bigcup_{a=1}^{m} \bigcup_{b=1}^{n} D_{ab} \text{ , where } a = 1,2,...,m, \quad b = 1,2,...,n,$$

$m, n \in N$. The grid dimension ($m \times n$) depends on the assumed accuracy of geographical coordinates (see Fig. 5).
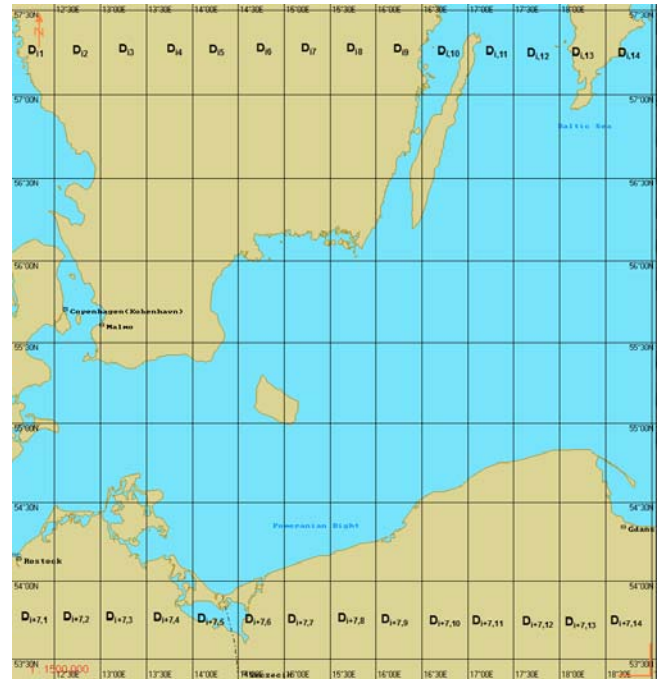

Figure 5. An exemplary grid of the Baltic Sea region according to the geographical coordinates [15]

We assume that the critical infrastructure networks $CIN^{(i)}, i = 1,2,3$ during its operation process are taking numbers of different operation states, described in Sections 4.1 – 4.3.

4.1 *Operation Process of Port Critical Infrastructure Network*

We assume that the critical infrastructure network $CIN^{(1)}$ during its operation process are taking numbers of different operation states defined as follows ([15])

$$\left[Z^{(2)} \right]_{1 \times \nu^{(2)}} = \left[z_1^{(2)}, z_2^{(2)}, ..., z_{\nu^{(2)}}^{(2)} \right], \tag{1}$$

where $z_a^{(2)}$ are the numbers of ships in the port P_a, $a = 1,2,...,\nu^{(2)}$, $\nu^{(2)} \in N$, is the number of ports under the consideration in the the Baltic Sea Region D ($\nu^{(2)} = 18$ for whole Baltic Sea Region);

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Further, we define the critical infrastructure networks $CIN^{(i)}, i = 1,2,3$, operation processes $Z^{(i)}(t)$, $t \in \langle 0, +\infty)$, as follows ([15]):

$$Z^{(2)}(t) = [Z^{(2)}(t)]_{1 \times v^{(2)}} = [z_1^{(2)}(t), z_2^{(2)}(t), ..., z_{v^{(2)}}^{(2)}(t)] \quad (2)$$

with discrete operation states from the set defined by (1), where the operation subprocesses $z_a^{(2)}(t)$ assume the values equal to the numbers $z_a^{(2)}$ of ships in the ports P_a, $a = 1,2,..., v^{(2)}$, at the moment $t \in \langle 0, +\infty)$;

In detailed definitions of the states and the operation process $Z^{(2)}(t)$ of the Baltic Port Critical Infrastructure Network $CIN^{(2)}$, consisted of all ports with their facilities, where the operation states are defined by the numbers of vessels in ports P_a, $a = 1,2,..., v^{(2)}$, either waiting for port services or being under port services, the impacts of those numbers of ships and their port operations interactions should be include.

Taking into account the above assumption to describe the operation process of the port critical infrastructure network we consider the $n^p = 18$ main Southern Baltic Sea ports. In the port we consider the number of ships (15]):
– entering to the port,
– outgoing into the port,
– waiting,
– handled (loaded/unloaded).

According to (1) – (2), we assume that the operation process for a single port P_a, $a = 1,2,..., ,18$, is given by the following vector with dimension 4 ([15]):

$$[Z^{(1)}(t)]_{1 \times 4} = [z_1^{(1)}(t), z_2^{(1)}(t), z_3^{(1)}(t), z_4^{(1)}(t)]$$
$$= [n_1^{(1)}(t), n_2^{(1)}(t), n_3^{(1)}(t), n_4^{(1)}(t)], \quad (3)$$

where

$n_1^{(2)}(t)$ - number of the entering ships in the port P_a, $a = 1,2,..., ,18$, at the moment $t \in \langle 0, +\infty)$,

$n_2^{(2)}(t)$ - number of the outgoing ships in the port P_a, $a = 1,2,..., ,18$, at the moment $t \in \langle 0, +\infty)$,

$n_3^{(2)}(t)$ - number of the waiting ships in the port P_a, $a = 1,2,..., ,18$, at the moment $t \in \langle 0, +\infty)$,

$n_4^{(2)}(t)$ - number of the handled(loaded/unloaded) ships in the port P_a, $a = 1,2,..., ,18$, at the moment $t \in \langle 0, +\infty)$.

Thus, the operation states are defined as follows([15]):

$$z_0^{(2)} = [0,0,0,0], \; z_1^{(2)} = [1,0,0,0], \; ...,$$
$$z_{n_1}^{(2)} = [n_1,0,0,0], \; z_{n_1+1}^{(2)} = [0,1,0,0], \; z_{n_1+2}^{(2)} = [0,2,0,0], ...,$$
$$z_{n_1+n_2}^{(2)} = [0,n_2,0,0], \; ..., \; z_{n_1 n_2}^{(2)} = [n_1,n_2,0,0],$$
$$z_{n_1 n_2+1}^{(2)} = [0,0,1,0], \; z_{n_1 n_2+2}^{(2)} = [0,0,2,0], ...,$$
$$z_{n_1 n_2+n_3}^{(2)} = [0,0,n_3,0], \; ..., \; z_{n_1 \cdot n_2 \cdot n_3}^{(2)} = [n_1,n_2,n_3,0],$$
$$z_{n_1 \cdot n_2 \cdot n_3+1}^{(2)} = [0,0,0,1], \; z_{n_1 \cdot n_2 \cdot n_3+2}^{(2)} = [0,0,0,2],$$
$$z_{n_1 \cdot n_2 \cdot n_3+n_4}^{(2)} = [0,0,0,n_4], \; ..., \; z_{n_1 \cdot n_2 \cdot n_3 \cdot n_4}^{(2)} = [n_1,n_2,n_3,n_4].$$

It means, we consider the $n_1 \cdot n_2 \cdot n_3 \cdot n_4$ operation states for every ports P_a, $a = 1,2,..., ,18$.

4.2 Operation Process of Shipping Critical Infrastructure Network

Critical infrastructure network $CIN^{(2)}$ during its operation process are taking numbers of different operation states defined as follows ([15])

$$[Z^{(2)}]_{m \times n} = \begin{bmatrix} z_{11}^{(2)} & z_{12}^{(2)} & \cdots & z_{1n}^{(2)} \\ z_{21}^{(2)} & z_{22}^{(2)} & \cdots & z_{2n}^{(2)} \\ \cdots & & & \\ z_{m1}^{(2)} & z_{m2}^{(2)} & \cdots & z_{mn}^{(2)} \end{bmatrix}, \quad (4)$$

where $z_{ab}^{(1)}$ are the numbers of ships in the regions D_{ab}, $a = 1,2,...,m$, $b = 1,2,...,n$, $m, n \in N$;

Further, we define the critical infrastructure networks $CIN^{(i)}, i = 1,2,3$, operation processes $Z^{(i)}(t)$, $t \in \langle 0, +\infty)$, as follows ([15]):

$$Z^{(2)}(t) = [Z^{(2)}(t)]_{m \times n} = \begin{bmatrix} z_{11}^{(2)}(t) & z_{12}^{(2)}(t) & \cdots & z_{1n}^{(2)}(t) \\ z_{21}^{(2)}(t) & z_{22}^{(2)}(t) & \cdots & z_{2n}^{(2)}(t) \\ \cdots & & & \\ z_{m1}^{(2)}(t) & z_{m2}^{(2)}(t) & \cdots & z_{mn}^{(2)}(t) \end{bmatrix}, \quad (5)$$

with discrete operation states from the set defined by (4) where the operation subprocesses $z_{ab}^{(1)}(t)$ is assumed as equal to the numbers $z_{ab}^{(1)}$ of ships in the rectangles D_{ab} $a = 1,2,...,m$, $b = 1,2,...,n$, $m, n \in N$, at the moment $t \in \langle 0, +\infty)$;

Considering interactions between ships creating the Baltic Shipping Critical Infrastructure Network $CIN^{(1)}$, we assume that there are strong inner and outer dependencies between the ships operating in a single fixed rectangle D_{ab}, $a = 1,2,...,m$, $b = 1,2,...,n$, $m, n \in N$, and that ships in each two adjacent rectangles influence each other as well. These influences that should be included in detailed definitions of this network operation process $Z^{(1)}(t)$ and its states strongly depend on the operation states of this network defined by the numbers of ships in these rectangles and those ships technical operations.

To describe the operation process of the shipping critical infrastructure network we exemplary divide the Southern Baltic Sea area on the square matrix with dimension m=5, n=14. (see Fig. 6).

Figure 6. The division of the Southern Baltic Sea region according to the geographical coordinates

Further, we assume that the operation process is given by the rectangular matrix with accordance to (4) – (5), [15],

$$[Z^{(2)}(t)]_{5\times14} = \begin{bmatrix} z_{11}^{(2)}(t) & z_{12}^{(2)}(t) & \cdots & z_{1,14}^{(2)}(t) \\ z_{21}^{(2)}(t) & z_{22}^{(2)}(t) & \cdots & z_{2,14}^{(2)}(t) \\ \cdots & & & \\ z_{51}^{(2)}(t) & z_{52}^{(2)}(t) & \cdots & z_{5,14}^{(2)}(t) \end{bmatrix}, \quad (6)$$

where the operation subprocesses $z_{ab}^{(2)}(t)$ is assumed as equal to the numbers $z_{ab}^{(2)}$ of ships in the rectangles D_{ab}, $a = 1,2,...,5$, $b = 1,2,...,14$, at the moment $t \in <0,+\infty)$;

The operation states are defined as follows ([15]):

$$[z_0^{(1)}]_{5\times14} = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \cdots & & & \\ 0 & 0 & \cdots & 0 \end{bmatrix}, ...,$$

$$[z_{n_{11}^{(1)}}^{(1)}]_{5\times14} = \begin{bmatrix} n_{11}^{(1)} & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \cdots & & & \\ 0 & 0 & \cdots & 0 \end{bmatrix}, ...,$$

$$[z_{n_{11}^{(1)}+1}^{(1)}]_{5\times14} = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \cdots & & & \\ 0 & 0 & \cdots & 0 \end{bmatrix}, ...,$$

$$[z_{n_{11}^{(1)}+n_{12}^{(1)}}^{(1)}]_{5\times14} = \begin{bmatrix} 0 & n_{12}^{(1)} & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \cdots & & & \\ 0 & 0 & \cdots & 0 \end{bmatrix}, ...,$$

$$[z_{n_{11}^{(1)}+n_{12}^{(1)}+...+n_{1,13}^{(1)}+1}^{(1)}]_{5\times14} = \begin{bmatrix} 0 & 0 & \cdots & 1 \\ 0 & 0 & \cdots & 0 \\ \cdots & & & \\ 0 & 0 & \cdots & 0 \end{bmatrix}, ...,$$

$$[z_{n_{11}^{(1)}+n_{12}^{(1)}+n_{13}^{(1)}+...+n_{1,14}^{(1)}}^{(1)}]_{5\times14} = \begin{bmatrix} 0 & 0 & \cdots & n_{1,14}^{(1)} \\ 0 & 0 & \cdots & 0 \\ \cdots & & & \\ 0 & 0 & \cdots & 0 \end{bmatrix}, ...,$$

$$[z_{n_{11}^{(1)}\cdot n_{12}^{(1)}\cdot n_{13}^{(1)}\cdot...\cdot n_{1,14}^{(1)}}^{(1)}]_{5\times14} = \begin{bmatrix} n_{11}^{(1)} & n_{12}^{(1)} & \cdots & n_{1,14}^{(1)} \\ 0 & 0 & \cdots & 0 \\ \cdots & & & \\ 0 & 0 & \cdots & 0 \end{bmatrix}, ...,$$

$$[z_{n_{11}^{(1)}\cdot n_{12}^{(1)}\cdot n_{13}^{(1)}\cdot...\cdot n_{1,14}^{(1)}+1}^{(1)}]_{5\times14} = \begin{bmatrix} n_{11}^{(1)} & n_{12}^{(1)} & \cdots & n_{1,14}^{(1)} \\ 1 & 0 & \cdots & 0 \\ \cdots & & & \\ 0 & 0 & \cdots & 0 \end{bmatrix}, ...,$$

$$[z_{n_{11}^{(1)}\cdot n_{12}^{(1)}\cdot n_{13}^{(1)}\cdot...\cdot n_{1,14}^{(1)}+n_{21}^{(1)}}^{(1)}]_{5\times14} = \begin{bmatrix} n_{11}^{(1)} & n_{12}^{(1)} & \cdots & n_{1,14}^{(1)} \\ n_{21}^{(1)} & 0 & \cdots & 0 \\ \cdots & & & \\ 0 & 0 & \cdots & 0 \end{bmatrix}, ...,$$

$$[z_{n_{11}^{(1)}\cdot...\cdot n_{1,14}^{(1)}\cdot n_{21}^{(1)}\cdot...\cdot n_{2,14}^{(1)}}^{(1)}]_{5\times14} = \begin{bmatrix} n_{11}^{(1)} & n_{12}^{(1)} & \cdots & n_{1,14}^{(1)} \\ n_{21}^{(1)} & n_{22}^{(1)} & \cdots & n_{2,14}^{(1)} \\ \cdots & & & \\ 0 & 0 & \cdots & 0 \end{bmatrix}, ...,$$

$$[z_{n_{11}^{(1)}\cdot...\cdot n_{1,14}^{(1)}\cdot n_{21}^{(1)}\cdot...\cdot n_{2,14}^{(1)}\cdot n_{31}^{(1)}\cdot...\cdot n_{3,14}^{(1)}\cdot n_{41}^{(1)}\cdot...\cdot n_{4,14}^{(1)}\cdot n_{51}^{(1)}\cdot...\cdot n_{5,14}^{(1)}}^{(1)}]_{5\times14}$$

$$= \begin{bmatrix} n_{11}^{(1)} & n_{12}^{(1)} & \cdots & n_{1,14}^{(1)} \\ n_{21}^{(1)} & n_{22}^{(1)} & \cdots & n_{2,14}^{(1)} \\ \cdots & & & \\ n_{51}^{(1)} & n_{52}^{(1)} & \cdots & n_{5,14}^{(1)} \end{bmatrix}.$$

Thus, we consider the $n_{11}^{(1)}\cdot...\cdot n_{1,14}^{(1)}\cdot n_{21}^{(1)}\cdot...\cdot n_{2,14}^{(1)}\cdot n_{31}^{(1)}\cdot...\cdot n_{3,14}^{(1)}\cdot n_{41}^{(1)}\cdot...\cdot n_{4,14}^{(1)}\cdot n_{51}^{(1)}\cdot...\cdot n_{5,14}^{(1)}$ operation states.

4.3 Operation Process of Ship Traffic and Port Operation Information Critical Infrastructure Network

We assume that the critical infrastructure network $CIN^{(3)}$ during its operation states process are taking numbers of different operation states defined as follows ([15])

$$[Z^{(3)}]_{1\times \nu^{(3)}} = [z_1^{(3)}, z_2^{(3)}, ..., z_{\nu^{(3)}}^{(3)}], \quad (7)$$

where $z_a^{(3)}$ are the numbers of ships in the range of the information systems I_a, $a = 1,2,...,\nu^{(3)}$, $\nu^{(3)} \in N$, is the number of information systems under the consideration in the Baltic Sea Region D (for general case $\nu^{(3)} = 146$).

Further, we define the critical infrastructure networks $CIN^{(i)}, i = 1,2,3$, operation processes $Z^{(i)}(t)$, $t \in <0,+\infty)$, as follows ([15]):

$$Z^{(3)}(t) = [Z^{(3)}(t)]_{1\times \nu^{(3)}} = [z_1^{(3)}(t), z_2^{(3)}(t), ..., z_{\nu^{(3)}}^{(3)}(t)]. \quad (8)$$

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with discrete operation states from the set defined by (7), where the operation subprocesses $z_a^{(3)}(t)$ assume the values equal to the numbers $z_a^{(3)}$ of ships in the range of the information systems I_a, $a = 1,2,...,v^{(3)}$, at the moment $t \in <0,+\infty)$.

The Shipping, Ship Traffic and Operation Information Critical Infrastructure Network $CIN^{(3)}$ is a platform to exchange the information about ships' operations and their cargo. Due to the fact that all information are given mainly in electronic form, this network is very sensitive for any disruption, especially cyber-attacks [8], but also for natural hazards [18]. Thus, in detailed defining this network operation process and its states those features should be taken into account.

According to Section 4.3 and formulae (7) – (8), the operation process of BSTPOICIN is given by the vector ([15])

$$[Z^{(3)}(t)]_{1 \times 146} = [z_1^{(3)}(t), z_2^{(3)}(t),...,z_{146}^{(3)}(t)], \qquad (9)$$

where the operation subprocesses $z_a^{(3)}(t)$ assume the values equal to the numbers $z_a^{(3)}$ of ships in the range of the information systems $TPOIS_a$, $a = 1,2,...,146$, at the moment $t \in <0,+\infty)$.

The following operation states are defined ([15]):

$z_0^{(2)} = [0,0,0,...,0]$, $z_1^{(2)} = [1,0,0,...,0]$, ...,
$z_{n_1}^{(2)} = [n_1,0,0,...,0]$,

$z_{n_1+1}^{(2)} = [0,1,0,...,0]$, $z_{n_1+2}^{(2)} = [0,2,0,...,0]$, ...,
$z_{n_1+n_2}^{(2)} = [0,n_2,0,...,0]$,

$z_{n_1+n_2+1}^{(2)} = [0,0,1,...,0]$, $z_{n_1+n_2+2}^{(2)} = [0,0,2,...,0]$, ...,
$z_{n_1+n_2+n_3}^{(2)} = [0,0,n_3,...,0]$, ..., $z_{n_1+...+n_{146}}^{(2)} = [0,0,0,...,n_{146}]$,

$z_{n_1+...+n_{146}+1}^{(2)} = [1,1,...,0]$, $z_{n_1+...+n_{146}+2}^{(2)} = [1,2,...,0]$, ...,
$z_{n_1+2n_2+...+146}^{(2)} = [1,n_2,...,0]$, ...,

$z_{n_1 n_2}^{(2)} = [n_1,n_2,...,0]$, ..., $z_{n_1 \cdot n_2 \cdot n_3 \cdot n_4}^{(2)} = [n_1,n_2,...,n_{146}]$.

It means, we consider the $n_1 \cdot n_2 \cdot ... \cdot n_{146}$ operation states for Baltic Ship Traffic and Port Operation Information Critical Infrastructure Network.

4.4 Semi-Markov approach to operation process of the BPSSTPOICIN

We assume that the critical infrastructure operation processes $Z^{(i)}(t)$, $i = 1,2,3$, is a semi-Markov process [11] – [15], [20] - [25], [28] – [29] with the conditional sojourn times $\theta_{bl}^{(i)}$ at the operation states $z_b^{(i)}$ when its next operation state is $z_l^{(i)}$, $b,l = 1,2,...,v^{(i)}$, $i = 1,2,3$, $b \neq l$. Under these

assumptions, the critical infrastructure network operation process may be described by:

– the vector of the initial probabilities $p_b^{(i)}(0) = P(Z^{(i)}(0) = z_b^{(i)})$, $b = 1,2,...,v^{(i)}$, $i = 1,2,3$, of the critical infrastructure networks $CIN^{(i)}, i = 1,2,.3$ operation processes $Z^{(i)}(t)$ staying at particular operation states at the moment $t = 0$

$$[p_b^{(i)}(0)]_{1 \times v^{(i)}} = [p_1^{(i)}(0), p_2^{(i)}(0),...,p_{v^{(i)}}^{(i)}(0)], \qquad (10)$$

– the matrix of probabilities $p_{bl}^{(i)}$, $b,l = 1,2,...,v^{(i)}$, $b \neq l$, $i = 1,2,3$, of the critical infrastructure networks $CIN^{(i)}, i = 1,2,.3$, operation processes $Z^{(i)}(t)$ transitions between the operation states $z_b^{(i)}$ and $z_l^{(i)}$

$$[p_{bl}^{(i)}(t)]_{v^{(i)} \times v^{(i)}} = \begin{bmatrix} p_{11}^{(i)}(t) & p_{12}^{(i)}(t) & \cdots & p_{1v^{(i)}}^{(i)}(t) \\ p_{21}^{(i)}(t) & p_{22}^{(i)}(t) & \cdots & p_{2v^{(i)}}^{(i)}(t) \\ \cdots & & & \\ p_{v^{(i)}1}^{(i)}(t) & p_{v^{(i)}2}^{(i)}(t) & \cdots & p_{v^{(i)}v^{(i)}}^{(i)}(t) \end{bmatrix}, \quad (11)$$

where by formal agreement $p_{bb}^{(i)} = 0$ for $b = 1,2,...,v^{(i)}$;

– the matrix of conditional distribution functions $H_{bl}^{(i)}(t) = P(\theta_{bl}^{(i)} < t)$, $b,l = 1,2,...,v^{(i)}$, $b \neq l$, $i = 1,2,3$, of the critical infrastructure networks $CIN^{(i)}, i = 1,2,.3$, operation processes $Z^{(i)}(t)$ conditional sojourn times $\theta_{bl}^{(i)}$ at the operation states

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

where by formal agreement $H_{bb}^{(i)}(t) = 0$ for $b = 1,2,...,v^{(i)}$;

We introduce the matrix of the conditional density functions of the critical infrastructure networks $CIN^{(i)}, i = 1,2,.3$, operation processes $Z^{(i)}(t)$ conditional sojourn times θ_{bl} at the operation states corresponding to the conditional distribution functions $H_{bl}^{(i)}(t)$

$$[h_{bl}^{(i)}(t)]_{v^{(i)} \times v^{(i)}} = \begin{bmatrix} h_{11}^{(i)}(t) & h_{12}^{(i)}(t) & \cdots & h_{1v^{(i)}}^{(i)}(t) \\ h_{21}^{(i)}(t) & h_{22}^{(i)}(t) & \cdots & h_{2v^{(i)}}^{(i)}(t) \\ \cdots & & & \\ h_{v^{(i)}1}^{(i)}(t) & h_{v^{(i)}2}^{(i)}(t) & \cdots & h_{v^{(i)}v^{(i)}}^{(i)}(t) \end{bmatrix}, \quad (13)$$

where

$$h_{bl}^{(i)}(t) = \frac{d}{dt}[H_{bl}^{(i)}(t)] \text{ for } b,l = 1,2,...,v^{(i)}, b \neq l,$$

and by formal agreement

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

The next steps in modelling the BNPSSTPOICIN operation process, considering taking into account just defined processes $Z^{(1)}(t)$, $Z^{(2)}(t)$ and $Z^{(3)}(t)$ interactions and interdependences, the joint operation process of this network of critical infrastructure networks can be defined in the form of the vector ([15])

$$Z(t) = [Z^{(1)}(t), Z^{(2)}(t), Z^{(3)}(t)], \qquad (14)$$

where $t \in <0, +\infty)$.

Under above definition, the critical infrastructure network joint operation process may be described by:

– the vector of the vectors of the initial probabilities $p_b^{(i)}(0) = P(Z^{(i)}(0) = z_b^{(i)})$, $b = 1,2,...,v^{(i)}$, $i = 1,2,3$, of the joint critical infrastructure network operation processes $Z(t)$ staying at particular operation states at the moment $t = 0$

$$[p_b(0)]_{1\times3} = \left[[p_b^{(1)}(0)]_{1\times v^{(1)}}, [p_b^{(2)}(0)]_{1\times v^{(2)}}, [p_b^{(3)}(0)]_{1\times v^{(3)}} \right] \quad (15)$$

where $[p_b^{(i)}(0)]_{1\times v^{(i)}}$ is given by (10);
– the vector of the matrices of probabilities $p_{bl}^{(i)}$, $b,l = 1,2,...,v^{(i)}$, $b \neq l$, $i = 1,2,3$, of the joint critical infrastructure network operation process $Z(t)$ transitions between the operation states $z_b^{(i)}$ and $z_l^{(i)}$

$$[p_{bl}]_{1\times3} = \left[[p_{bl}^{(1)}]_{v^{(1)}\times v^{(1)}}, [p_{bl}^{(2)}]_{v^{(2)}\times v^{(2)}}, [p_{bl}^{(3)}]_{v^{(3)}\times v^{(3)}} \right], \qquad (16)$$

where $[p_{bl}^{(i)}]_{v^{(i)}\times v^{(i)}}$ is given by (11) and by formal agreement $p_{bb}^{(i)} = 0$ for $b = 1,2,...,v^{(i)}$;
– the vector of the matrices of conditional distribution functions $H_{bl}^{(i)}(t) = P(\theta_{bl}^{(i)} < t)$, $b,l = 1,2,...,v^{(i)}$, $b \neq l$, $i = 1,2,3$, of the joint critical infrastructure network operation process $Z(t)$ conditional sojourn times $\theta_{bl}^{(i)}$ at the operation states

$$[H_{bl}(t)]_{1\times3} = \left[[H_{bl}^{(1)}(t)]_{v^{(1)}\times v^{(1)}}, [H_{bl}^{(2)}(t)]_{v^{(2)}\times v^{(2)}}, [H_{bl}^{(3)}(t)]_{v^{(3)}\times v^{(3)}} \right] \qquad (17)$$

where $[H_{bl}^{(i)}(t)]_{v^{(i)}\times v^{(i)}}$ is described by (12) and by formal agreement $H_{bb}^{(i)}(t) = 0$ for $b = 1,2,...,v^{(i)}$.

We introduce the vector of the matrices of the conditional density functions of the joint critical infrastructure network operation process $Z(t)$ conditional sojourn times θ_{bl} at the operation states corresponding to the conditional distribution functions $H_{bl}^{(i)}(t)$

$$[h_{bl}(t)]_{1\times3} = \left[[h_{bl}^{(1)}(t)]_{v^{(1)}\times v^{(1)}}, [h_{bl}^{(2)}(t)]_{v^{(2)}\times v^{(2)}}, [h_{bl}^{(3)}(t)]_{v^{(3)}\times v^{(3)}} \right], \quad (18)$$

where $[h_{bl}^{(i)}(t)]_{v^{(i)}\times v^{(i)}}$ is described by (13) and

$$h_{bl}^{(i)}(t) = \frac{d}{dt}[H_{bl}^{(i)}(t)] \text{ for } b,l = 1,2,...,v^{(i)}, b \neq l,$$

and by formal agreement

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

5 CONCLUSIONS

The definitions of the Critical Infrastructure and Critical Infrastructure Network has been introduced. Based on these, the three critical infrastructure networks are defined: the Baltic Shipping Critical Infrastructure Network (BSCIN), the Baltic Port Critical Infrastructure Network (BPCIN) and the Baltic Ship Traffic and Operation Information Critical Infrastructure Network (BSTPOICIN). Furthermore, the Baltic Port, Shipping and Ship Traffic and Port Operation Information Critical Infrastructure Network has been defined as the network of three networks.

The basic description of the interconnections and interdependencies for CI networks in Baltic Sea Region have been introduced.

The semi-Markov approach to modelling the operation process of the BPSSTPOICIN has been proposed.

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