**Safety and Reliability of Systems and Processes**

ESREL 2024
Training Course Abstract

# General Approach To Critical Infrastructure Safety Modelling

Krzysztof Kołowrocki

*Polish Safety and Reliability Association, Gdynia, Poland*

**Organiser use only:** Received date; revised date; accepted date

---

**Abstract**

General approach is proposed to the System of Critical Infrastructure Training Courses (SCISTC) that is composed of a number of Training Courses on selected safety and reliability topics. Each of the courses is developed in the form of easy to understand guide including theoretical backgrounds and examples of procedures based on them applications. The integrated part of each course is the power point presentation grounded on the guide. Considering that the SCISTC is devoted to critical infrastructure safety and reliability mathematical modelling and prediction, the critical infrastructure is understood as a complex multistate ageing system composed of multistate ageing components / assets in its operating environment. In practical usage, the critical infrastructure significant features are its inside dependencies and its outside impacts, that in the case of its degradation or failure have a significant destructive influence on the health, safety and security, economics and social conditions of large human communities and territory areas.

*Keywords*: complex system, critical infrastructure, safety, safety structure, safety indicator, inside dependences, outside impacts, operation impact, climate-weather impact, resilience indicator, operation cost, accident consequences, optimization, mitigation, maintenance, business continuity

---

## 1. Introduction

Many of the terms and notions needed for the critical infrastructure safety analysis are used in different and sometimes conflicting ways across various disciplines and approaches (Berg & Petrek, 2018; Bogalecka, 2020; Kjølle et al., 2012; Kołowrocki, 2021, 2022b, 2023b; Lauge et al., 2015; Magryta, 2020; Ouyang, 2014; Rinaldi et al., 2001; Svedsen & Wolthunsen, 2007). Some of them are incorrect. Thus, a standard set of definitions should be fixed to support a shared understanding of the SCISTC and be applied by all its users. Therefore, the definitions concerned with the methodology including the notions and the meanings of the critical infrastructure and its safety, the operation conditions, the climate and weather change and the resilience should be convergent with those used in available literature. The spectrum of the terms concerned with those main notions should be sufficiently wide and exhaustive in depth. The main fault in defining some of the terms is mixing the meaning of the defined notion with the values of its parameters it is characterized by. Having in mind this terminology state of the art and considering its imperfection and faults, the main principles in preparation of this set of Training Courses are:

- to differ between the notion and the values of the parameters it is defined by;
- to illustrate shortly the notion and its parameters together with short illustrations/interpretations of their meanings and their expected practical usage in order to provide a better understanding.

The first and most important term for the SCISTC is the notion of the critical infrastructure. To follow the European Commission approach, the critical infrastructure is an asset or a system which is essential for the maintenance of vital societal functions. The damage of a critical infrastructure, its destruction or disruption by natural disasters, terrorism, criminal activity or malicious behavior, may have a significant negative impact for the safety and security of the European Union and the well-being of its citizens.

The critical infrastructure is a term used by governments to describe assets that are essential for the functioning of a society and economy. Most commonly associated with the term of critical infrastructure are facilities for:

- electricity generation, transmission and distribution;
- gas production, transport and distribution;
- oil and oil products production, transport and distribution;
- telecommunication;
- water supply;
- agriculture, food production and distribution;
- heating;
- public health;
- transportation systems;
- financial services;
- security services.

Critical infrastructures are usually interconnected and mutually dependent in various and complex ways (De Porcellinis et al., 2009; Kjølle et al., 2012; Kołowrocki, 2020b, 2022a; Nieuwenhuijs et al., 2008; Svedsen & Wolthunsen, 2007; Wang & Pham 2012), creating critical infrastructure networks. They are interacting directly and indirectly at various levels of their complexity and operating activity. Identifying and modeling dependencies depend on the level of analysis. The selected level of analysis can vary from micro to macro level. A holistic approach can be considered or a reductionist approach in which elementary components are identified and their behavior is described. For example, the focus on the components of critical infrastructure networks and they demonstrate several types of multi-dependency structures.

Considering that this set of training courses is devoted to critical infrastructure safety mathematical modelling and prediction the critical infrastructure is defined as a complex multistate ageing system in its operating environment that significant features are its inside dependencies and its outside impacts (Bogalecka, 2020; De Porcellinis et al., 2009; Kjølle et al., 2012; Kołowrocki, 2020b, 2021, 2022ab, 2023b; Magryta, 2020; Nieuwenhuijs et al., 2008; Ouyang, 2014; Svedsen & Wolthunsen, 2007; Wang & Pham 2012), that in the case of its degradation have a significant destructive influence on the health, safety and security, economics and social conditions of large human communities and territory areas.

In this Training Course 1, the methodology and general approach to critical infrastructure safety and resilience analysis is proposed. The principles of multistate approach to critical infrastructure safety analysis (Abouammoh & Al-Kadi, 1991; Amari & Misra, 1997; Aven, 1985, 1993; Barlow & Wu, 1978; Brausch, 1987; Brunelle & Kapur, 1999; Butler, 1982; Dąbrowska, 2020; Ebrahimi, 1984; El-Neweihi et al., 1978; Fardis & Cornell, 1981; Griffith, 1980; Hudson & Kapur, 1982, 1983; Kołowrocki, 2000, 2003ab, 2005, 2008b, 2011, 2014, 2020ab, 2022ab, 2023ac; Kossow & Preuss, 1995; Kvassay et al., 2020; Li & Pham, 2005; Murchland, 1975; Natvig, 2007; Natvig & Morch, 2003; Natvig & Streller, ….; Ohio & Nishida, 1984; Ramirez-Marqueza & Coit, 2007; Ross, 1979; Xue, 1985; Xue & Yang, 1995ab; Yingkui & Jing, 2012; Yu et.al., 1994; Zaitseva & Levashenko, 2017) are introduced. There are introduced the notions of critical infrastructure basic safety indicators like, the critical infrastructure safety function, the critical infrastructure risk function and the critical infrastructure fragility curve. Basic critical infrastructure safety structures are defined and the general formulae for their safety functions and their particular forms when the critical infrastructure assets have piecewise exponential safety functions are given. The critical infrastructure safety and resilience indicators are proposed to be obtained using probabilistic approach to modelling of operation threats and extreme weather hazard impacts on its assets safety (Kołowrocki, 2021. The critical infrastructure safety and operation cost optimization to improve its safety and resilience and operation effectiveness and its accident consequences optimization and mitigation (Klabjan & Adelman, 2016; Kołowrocki & Magryta-Mut, 2021, 2023ab; Kosmowski, 2021; Magryta-Mut, 2020, 2023ab) are proposed as well. The general scheme of this approach is presented together with the description of its boxes' contains. There are proposed safety and resilience indicators, crucial for operators and users of the critical infrastructure, defined as a complex system in its operating environment (Kołowrocki, 2023a).

## 2. Multistate approach to critical infrastructure safety analysis

Considering the above performed analysis, similarly as in the case of multistate approach to critical infrastructure reliability in Training Course 3 (Kołowrocki, 2023c), in the multistate safety analysis to define the critical infrastructure with degrading/ageing components/assets (Kołowrocki, 2008b, 2020b, 2023a; Kołowrocki & Magryta, 2020a; Kołowrocki & Magryta-Mut, 2023; Szymkowiak, 2018ab, 2019), we assume that:

- $n$ is the number of the critical infrastructure assets;
- $A_i$, $i = 1,2,...,n$, are the critical infrastructure assets;
- all assets and the critical infrastructure have the safety state set $\{0,1,...,z\}$, $z \geq 1$;
- the safety states are ordered, the safety state 0 is the worst and the safety state $z$ is the best;
- $r$, $r \in \{1,2,...,z\}$, is the critical safety state;

- $T_i(u)$, $u = 1,2,...,z$, $i = 1,2,...,n$, are independent random variables representing the lifetimes of assets $A_i$ in the safety state subset $\{u,u+1,...,z\}$, $u = 1,2,...,z$, while they were in the safety state $z$ at the moment $t = 0$;
- $T(u)$, $u = 1,2,...,z$, is a random variable representing the lifetime of the critical infrastructure in the safety state subset $\{u,u+1,...,z\}$, $u = 1,2,...,z$, while it was in the safety state $z$ at the moment $t = 0$;
- the assets and the critical infrastructure safety states degrade with time;
- $s_i(t)$, $t \in < 0,\infty)$, $i = 1,2,...,n$, is the asset $A_i$, safety state at the moment $t$, $t \in < 0,\infty)$, given that it was in the safety state $z$ at the moment $t = 0$;
- $s(t)$, $t \in < 0,\infty)$, is the critical infrastructure safety state at the moment $t$, $t \in < 0,\infty)$, given that it was in the safety state $z$ at the moment $t = 0$.

The critical safety state $r$ means that the critical infrastructure and its assets staying in the safety states less than this safety state is highly dangerous for them and for their operating environment.

The above assumptions mean that the safety states of the critical infrastructure with degrading assets may be changed in time only from better to worse.

## 3. Critical infrastructure safety structures

On the basis of the approach to critical infrastructure safety analysis proposed in Section 2, considering definitions of reliability functions of two-state systems (Aven & Jensen, 1999; Barlow& Proschan, 1975; Bautista et al., 2020; Cepin, 2020; Gouldby, et al., 2010; Kołowrocki, 1998, 2005, 2008a, 2011, 2014, 2023bd; Kołowrocki & Magryta, 2020a; Lauge et al., 2015; Melchers & Beck, 2018; Misra, 1992; Rinaldi et al., 2001; Samaniego, 2007; Wang at al., 2011) introduced in Training Course 2 (Kołowrocki, 2023b) and multistate ageing systems (Abouammoh & Al-Kadi, 1991; Amari & Misra, 1997; Aven, 1985, 1993; Barlow & Wu, 1978; Brausch, 1987; Brunelle & Kapur, 1999; Butler, 1982; Dąbrowska, 2020; Ebrahimi, 1984; El-Neweihi et al., 1978; Fardis & Cornell, 1981; Griffith, 1980; Hudson & Kapur, 1982, 1983; Kołowrocki, 2000, 2003ab, 2005, 2008b, 2011, 2014, 2020ab, 2022ab, 2023ac; Kossow & Preuss, 1995; Kvassay et al., 2020; Li & Pham, 2005; Murchland, 1975; Natvig, 2007; Natvig & Morch, 2003; Natvig & Streller, 2008; Ohio & Nishida, 1984; Ramirez-Marqueza & Coit, 2007; Ross, 1979; Xue, 1985; Xue & Yang, 1995ab; Yingkui & Jing, 2012; Yu et.al., 1994; Zaitseva & Levashenko, 2017) introduced in Training Course 3 (Kołowrocki, 2023c), we may similarly define basic critical infrastructure safety structures (Kołowrocki, 2021).

For instance a critical infrastructure composed of $n$ assets $A_i$, $i = 1,2,..,n$, is called series if its lifetime T(u), $u = 1,2,...,z$, in the safety state subset $\{u, u+1, \dots, z\}$, $u = 1,2,...,z$, is given by

$$T(u) = \min_{1 \le i \le n}\{T_i(u)\},\ u = 1,2,...,z, \tag{1}$$

where $T_i(u)$, $u = 1,2,...,z$, $i = 1,2,\dots,n$, are the lifetimes of the assets $A_i$, $i = 1,2,..,n$, in the safety state subset $\{u, u+1, \dots, z\}$, $u = 1,2,...,z$. The number $n$ is called the series critical infrastructure safety structure shape parameter.

The above definition means that the series critical infrastructure is in the safety state subset $\{u, u+1, \dots, z\}$, $u = 1,2,...,z$, if and only if all its n assets are in this subset of safety states. That meaning is very close to the definition of a two-state critical infrastructure considered in a classical reliability analysis that is not failed if all its assets are not failed (see: Training Course 2). This fact can justify the safety structure scheme for a series critical infrastructure presented in Figure 1.

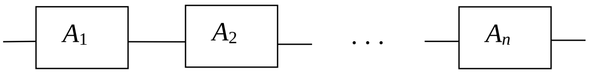

Fig. 1. The scheme of a series critical infrastructure safety structure.

It is easy to work out that the safety function of the series critical infrastructure is given by the vector

$$\boldsymbol{S}(t,\cdot) = [\boldsymbol{S}(t,1), \boldsymbol{S}(t,2), \dots, \boldsymbol{S}(t,z)]\ ,\ t \in < 0,\infty), \tag{2}$$

with the coordinates

$$\boldsymbol{S}(t,u) = \prod_{i=1}^{n} S_i(t,u),\ t \in < 0,\infty),\ u = 1,2,...,z. \tag{3}$$

Other basic critical infrastructure safety structures with assets degrading in time can be defined in an analogous way (Kołowrocki, 2021).

## 4. General scheme of approach to critical infrastructure safety modelling through training courses

Most real complex technical systems are strongly influenced by their, changing in time, operation conditions and the climate-weather conditions at their operating areas (Kołowrocki, 2021). The time dependent interactions between the operation process, related to varying states of the climate-weather change process at the system operating area, and the system safety structure and its changing components/assets safety states, are evident features of most real technical systems including critical infrastructures. The critical infrastructure is defined as a complex system in its operating environment that significant features are inside-system dependencies and outside-system impacts. In case of system degradation these dependencies have a significant destructive influence on the health, safety, security, economics and social conditions of large human communities and territories.

The critical infrastructure may be affected by outside processes which have negative influence on its safety. By outside processes we understand critical infrastructure operation process and the process of weather change in the area of operation. Therefore critical infrastructure safety analysis related to its operation process and the climate-weather change process at its operating area (Kołowrocki, 2021) has a great value in the industrial practice due to often negative impacts of these processes on the critical infrastructure safety and resilience.

As a rule the safety analysis of the critical infrastructure impacted by those processes is very complex. This problem can be solved by the multistate critical infrastructures safety modelling performed similarly to reliability modelling of multistate complex systems (Kołowrocki, 2023c)commonly used with the semi-Markov modelling (Klabjan & Adelman, 2016; Kołowrocki & Magryta-Mut, 2021, 2023ab; Kosmowski, 2021; Magryta-Mut, 2020, 2023ab) of the joint operation process and climate-weather change process (Kołowrocki, 2021). This approach leads to the construction of the joint general safety model of the critical infrastructure impacted by the operation process and changing weather at its operating area, significantly developed by the selected authors cited in (Kołowrocki, 2021) and collected in the SCISTC.

This original and innovative general approach to common influence of operation process and climate-weather change process on critical infrastructure safety and resilience modelling and analysis consists in combining of the critical infrastructure operation process model and the climate-weather change process model and constructing one general joint safety model of the critical infrastructure impacted by its operation process and climate-weather process at its operating area (Kołowrocki, 2021). This approach can be basis for the formulation and development of the new solutions, which consist of the improvement and optimization of the safety of the critical infrastructure related to their operation

processes and outside climate-weather change processes (Klabjan & Adelman, 2016; Kołowrocki & Magryta, 2020ab; Kołowrocki & Magryta-Mut, 2021, 2023ab; Kosmowski, 2021; Magryta-Mut, 2020, 2023ab) and the mitigation the consequences of accidents caused by their degradation (Bogalecka, 2020). A novel concept, which would induce further complexity to the approach, is an introduction of impacts of climate pressures in the interconnection between critical infrastructures. New and innovative part of this approach lies in inclusion of linkages and dependencies, both internal and external (De Porcellinis et al., 2009; Kjølle et al., 2012; Kołowrocki, 2020b, 2022a; Nieuwenhuijs et al., 2008; Svedsen & Wolthunsen, 2007; Wang & Pham 2012), to critical infrastructures that are impacted by climate-weather hazards.

In order to organize the efforts at finding solutions of formulated problems, the scheme of a general approach to safety and resilience analysis of critical infrastructure through Training Courses, including subsequent steps in the research activity, can be created. The content in the approaches of the this scheme items is concerned in:

- General approach to critical infrastructure safety modelling through training courses in Training Course TC1, with the scheme of general approach to critical infrastructure safety modelling through Preliminary Training Courses TC2-TC3 and Advanced Training Courses TC4-TC22 and its description;
- Preliminary Training Courses TC2-TC3, with modelling reliability of two-state and multistate critical infrastructure being the introduction to Advanced Training Courses TC4-TC22;
- Critical Infrastructure Free of Outside Impact Safety Modelling (CIS Model 0) in Training Course TC6, with constructing of critical infrastructure multistate safety model independent of outside operation and climate-weather impacts and introducing of practically useful critical infrastructure safety characteristics, called safety indicators;
- Critical Infrastructure Operation Process (CIOP) in Training Course TC7 and Climate-Weather Change Process (C-WCOP) in Training Course TC9, with modelling of critical infrastructure operation process and climate-weather change process in its operation area through defining parameters of these processes and giving the ways of their characteristics determination;
- Integration of CIOP and C-WCP in Training Course TC11, with creating of a joint model of critical infrastructure operation process and climate-weather change process at its operating area through defining the critical infrastructure operation process impacted by climate-weather change at its operating area, defining its parameters and giving the procedures of its characteristics determinations;
- Integration of CIOP, C-WCP and CIOP&C-WCP with CIS Model 0 (CIS Models 1-3) in Training Courses TC8, TC10, TC12, with constructing critical infrastructure safety models, separately and jointly dependent

on outside operation and climate-weather impacts and introducing of practically useful safety characteristics of critical infrastructure impacted separately and jointly by outside operation and climate-weather conditions, called safety indicators and resilience indicators;

- Inventory of Critical Infrastructure Safety and Resilience Indicators in Training Course TC13, with creating of detailed list of all safety indicators of critical infrastructure free of outside impacts and safety indicators and resilience indicators of critical infrastructure under outside impacts;
- Models Application and Validation in Training Course TC14, with all proposed models and creating safety and resilience indicators application and validation in practice to exemplary critical infrastructure, car wheel system, truck wheel system, port oil terminal critical infrastructure and maritime ferry technical safety examination;
- Research on Critical Infrastructure Safety Examination in Training Courses TC15-TC21, with research and development of proposed models in creating practically important tools for critical infrastructure safety strengthening and operation cost optimization, examination and mitigation of critical infrastructure accident consequences and critical infrastructure business continuity analysis.
- Research on Critical Infrastructure with Dependent Assets Safety Examination in Training Course TC22, with principles of selected Training Courses TC1-21 modification for critical infrastructure with dependent assets and subsystems.

Thus, starting from the simplest, pure safety CIS Model 0, defined as a multistate ageing system without considering outside impacts, several safety parameters and indicators are defined. Namely, the critical infrastructure and its assets' safety functions, the critical infrastructure mean values and standard deviations of lifetimes in the safety state subsets and in the particular safety states, the critical infrastructure risk function, its fragility curve, the moment of exceeding by the critical infrastructure critical safety state and its intensities of ageing/degrading, are introduced.

Next, the CIS Model 0 is combined with the critical infrastructure operation process CIOP Model to create the integrated CIS Model 1, which is intended to safety modelling and prediction of critical infrastructure impacted by its operation process. In CIS Model 1 we define the critical infrastructure as a complex system in its operating environment that significant features are its operation impacts. That safety model of a critical infrastructure related to its operation process links its multistate safety model and its operation process model, to create the critical infrastructure operation impact safety model. Moreover, CIS Model 1 considers also critical infrastructure variable safety structure and its asseys/components' safety parameters at different operation states. In this model, we introduce additional safety indicators, which are typical for the critical infrastructure and are related to its varying in time safety structures and its components' safety parameters. Namely, CIS Model 1 extends the set of safety indicators of CIS Model 0 by the components and critical infrastructure conditional intensities of ageing at particular operation states and conditional and unconditional coefficients of the operation process impact on the critical infrastructure intensities of ageing and the critical infrastructure coefficient of resilience to its operation process.

Further, an integrated safety CIS Model 2 of critical infrastructure safety is proposed. This critical infrastructure safety model is related to influence of the climate-weather change process in the critical infrastructure operating area on its safety. It is the integrated model of critical infrastructure safety, linking its multistate safety CIS Model 0 and the C-WCP Model of the climate-weather change process at its operating area, to create the critical infrastructure climate-weather impact safety model. The CIS Model 2 considers variable system components safety parameters impacted by different climate-weather states. The conditional safety functions at the particular climate-weather states, the unconditional safety function and the risk function of the critical infrastructure at changing in time climate-weather conditions are defined. Other, practically significant, critical infrastructure safety indicators introduced in the CIS Model 2 are, its mean lifetime to the moment of exceeding a critical safety state, the moment when its risk function value exceeds the acceptable safety level, the intensities of ageing of the critical infrastructure related to the climate-weather change process at its operating area and coefficients of the impact of the climate-weather change process on the critical infrastructure and its components intensities of ageing and the critical infrastructure coefficient of resilience to climate-weather change process at its operating area.

Next, the general critical infrastructure safety CIS Model 3 is proposed that simultaneously considers the operation process and the climate-weather change process influence on the safety of a critical infrastructure. It is a safety model of a critical infrastructure under the influence of the operation process related to climate-weather change at its operating area. It is an integrated model of a critical infrastructure safety, linking its multistate safety CIS Model 0 and the joint CIOP&C-WCP Model of its operation process related to climate-weather change process at its operating area, to create the critical infrastructure joint operation and climate-weather impact safety model. Thus, CIS Model 3 considers variable system safety structures and its components safety parameters, impacted by climate-weather states, at different operation states. The conditional safety functions at the operation and climate-weather states of the operation process related the climate-weather change, the unconditional safety function and the risk function of a critical infrastructure at changing in time operation and climate-weather conditions are defined. Other useful critical infrastructure safety indicators introduced in CIS Model 3 are, its mean lifetime up to the moment of exceeding a critical safety state and the moment when its risk function value exceeds the acceptable safety level, the intensities of ageing of the critical infrastructure and its components impacted by the operation process related to the climate-weather change process, coefficients of the operation process related to climate-weather change impact on the critical infrastructure and its components intensities of ageing and the critical infrastructure coefficient of resilience to operation process related to climate-weather change process at its operating area.

These all, above mentioned, safety indicators, proposed in CIS Models 0-3, are defined in general for any critical infrastructures with varying in time their safety structures and components/assets safety parameters, which are influenced by, changing in time, operation and climate-weather conditions at their operating areas.

The next step in SCISTC that is done to perform the tasks formulated in scheme items is these models application and validation, what is practically realized in the particular Training Courses through the validation in practice to exemplary critical infrastructure, car wheel system, truck wheel system, port oil terminal critical infrastructure and maritime ferry technical safety examination examination.

The path we should follow in our further research activity in SCISTC is to investigate and solve problems of safety and resilience strengthening of critical infrastructure impacted by operation and climate-weather change. This activity, in Training Courses TC15-TC21, leads to establishing of elaborate models of maintenance and business continuity for critical infrastructure under operation and climate pressures, as well as to solving the critical infrastructure safety optimization and its degradation and accident consequences identification and mitigation.

All presented models are the basis for preparation of procedures, which are very easy to use by the practitioners and operators of the critical infrastructures in their operation and safety analysis. The use of these procedures for real critical infrastructure is presented in details in all Training Courses of SCISTC.

All created in SCISTC models, and procedures based on them, can be modified and developed for other problems of safety features of critical infrastructure analysis. In this context, modelling and prediction of critical infrastructure safety presented in this SCISTC, in Training Course TC22, developed by considering inside dependences between the critical infrastructure assets is very important broadening to real practice in critical infrastructure safety examination to build the model considering commonly the critical infrastructure ageing its inside dependences and outside impacts as an innovative general approach significant and breakthrough real applications of these new theoretical and educational results.

## 5. Critical infrastructure safety and resilience indicators

In the SCISTC Preliminary Training Courses TC2-TC3, we introduce respectively the following parameters and characteristics (indicators) of critical infrastructure reliability.

In Training Course TC2, there are defined two-state critical infrastructure reliability indicators (RelIs):

- the critical infrastructure reliability function (RelI1);
- the critical infrastructure risk function / the critical infrastructure unreliability function (RelI2);
- the graph of the critical infrastructure risk function / the fragility curve (RelI3);
- the mean value of the critical infrastructure lifetime (RelI4);
- the standard deviation of the critical infrastructure lifetime (RelI5);
- the moment of exceeding acceptable value of critical infrastructure risk function level (RelI6);
- the intensity of failure of the critical infrastructure / the failure rate of critical infrastructure (RelI7).

In the Training Course TC3, there are defined the multistate critical infrastructure reliability indicators (RelIs):

- the critical infrastructure reliability function (RelI1);
- the critical infrastructure risk function (RelI2);
- the graph of the critical infrastructure risk function / the fragility curve (RelI3);
- the mean value of the critical infrastructure lifetime up to exceeding critical reliability state (RelI4);
- the standard deviation of the critical infrastructure lifetime up to the exceeding the critical reliability state (RelI5);
- the moment of exceeding acceptable value of critical infrastructure risk function level (RelI6);
- the mean values of the critical infrastructure lifetimes in the reliability state subsets (RelI7);
- the standard deviations of the critical infrastructure lifetimes in the reliability state subsets (RelI8);
- the mean values of the critical infrastructure lifetimes in particular reliability states (RelI9);
- the intensities of degradation (ageing) of the critical infrastructure / the intensities of critical infrastructure departure from the reliability state subsets (RelI10).

In the first of the approach proposed in SCISTC Advanced Training Courses TC4-TC5, we introduce respectively the following parameters and characteristics (indicators) of critical infrastructure safety.

In Training Course TC4, there are defined two-state critical infrastructure safety indicators (SafIs):

- the critical infrastructure safety function (SafI1);

- the critical infrastructure risk function / the critical infrastructure unsafety function (SafI2);
- the graph of the critical infrastructure risk function / the fragility curve (SafI3);
- the mean value of the critical infrastructure lifetime (SafI4);
- the standard deviation of the critical infrastructure lifetime (SafI5);
- the moment of exceeding acceptable value of critical infrastructure risk function level (SafI6);
- the intensity of failure of the critical infrastructure / the failure rate of critical infrastructure (SafI7).

In the Training Course TC5, there are defined the multistate critical infrastructure safety indicators (SafIs):

- the critical infrastructure safety function (SafI1);
- the critical infrastructure risk function (SafI2);
- the critical infrastructure fragility curve (SafI3);
- the mean value of the critical infrastructure lifetime up to the exceeding the critical safety state (SafI4);
- the standard deviation of the critical infrastructure lifetime up to the exceeding the critical safety state (SafI5);
- the moment of exceeding acceptable value of critical infrastructure risk function level (SafI6);
- the mean values of the critical infrastructure lifetimes in the safety state subsets (SafI7);
- the standard deviations of the critical infrastructure lifetimes in the safety state subsets (SafI8);
- the mean value of the critical infrastructure lifetimes in particular safety states (SafI9);
- the intensities of degradation (ageing) of the critical infrastructure / the intensities of critical infrastructure departure from the safety state subsets (SafI10).

In the second step of the approach proposed in SCISTC Advanced Training Courses, in Training Course 6, we start with the simplest pure safety model CIS Model 0, without considering outside impacts. For the critical infrastructure (and its assets) following useful safety indicators are defined:

- the critical infrastructure safety function (SafI1);
- the critical infrastructure risk function (SafI2);
- the critical infrastructure fragility curve (SafI3);
- the mean value of the critical infrastructure lifetime up to the exceeding the critical safety state (SafI4);
- the standard deviation of the critical infrastructure lifetime up to the exceeding the critical safety state (SafI5);
- the moment of exceeding acceptable value of critical infrastructure risk function level (SafI6);
- the mean values of the critical infrastructure lifetimes in the safety state subsets (SafI7);
- the standard deviations of the critical infrastructure lifetimes in the safety state subsets (SafI8);
- the mean value of the critical infrastructure lifetimes in particular safety states (SafI9);
- the intensities of degradation (ageing) of the critical infrastructure / the intensities of critical infrastructure departure from the safety state subsets (SafI10).

In the next step of the proposed approach in SCISTC Advanced Training Courses, in Training Course 8, the simplest safety model CIS Model 0 is combined with the critical infrastructure operation process model CIOP Model, in order to create a safety model CIS Model 1of critical infrastructure related to its operating environment.

Further, in training Course 10, an impact model on critical infrastructure safety CIS Model 2 related to the climate-weather change process in its operating area is proposed.

The most general safety impact model CIS Model 3 which consider jointly the operation process and climate-weather change process influence on the safety of a critical infrastructure is presented SCISTC Advanced Training Courses, in Training Course 12. It is the integrated model of a critical infrastructure safety, linking its multistate safety model CIS Model 0 and the joint model CIOP&C-WCP of its operation process and the climate-weather change process in its operating area. These model consider variable safety structures of the critical infrastructure at different operation and climate-weather states, as well as safety parameters of critical infrastructure assets. For those models, the following safety indicators are respectively defined:

- the critical infrastructure safety function (SafI1);
- the critical infrastructure risk function (SafI2);
- the critical infrastructure fragility curve (SafI3);
- the mean value of the critical infrastructure lifetime up to the exceeding the critical safety state (SafI4);
- the standard deviation of the critical infrastructure lifetime up to the exceeding the critical safety state (SafI5);
- the moment of exceeding acceptable value of critical infrastructure risk function level (SafI6);
- the mean values of the critical infrastructure lifetimes in the safety state subsets (SafI7);
- the standard deviations of the critical infrastructure lifetimes in the safety state subsets (SafI8);
- the mean value of the critical infrastructure lifetimes in particular safety states (SafI9);
- the intensities of degradation (ageing) of the critical infrastructure / the intensities of critical infrastructure departure from the safety state subsets (SafI10).

These all safety indicators are defined, in general, for any critical infrastructures with varying in time their safety structures and their assets safety parameters influenced by changing in time operation conditions and climate-weather conditions at their operating areas.

We make in the SCISTC, in Training Courses 8, 10 and 12, a next step in order to terminate methodological framework, for critical infrastructures with outside impacts to define the following critical infrastructure resilience indicators:

- the coefficients of operation process impact on the critical infrastructure intensities of degradation / the coefficients of operation process impact on critical infrastructure intensities of departure from the safety state subset (ResI1);
- the indicator of critical infrastructure resilience to operation process impact (ResI2);
- the coefficients of climate-weather change process impact on the critical infrastructure intensities of degradation / the coefficients of climate-weather change process impact on critical infrastructure intensities of departure from the safety state subset (ResI1);
- the indicator of critical infrastructure resilience to climate-weather change process impact (ResI2);
- the coefficients of operation process and climate-weather change process impact on the critical infrastructure intensities of degradation / the coefficients of operation process and climate-weather change process impact on critical infrastructure intensities of departure from the safety state subset (ResI1);
- the indicator of critical infrastructure resilience to operation process and climate-weather change process impact (ResI2).

All the proposed in SCISTC indicators and other safety and resilience tools are validated through their practical application to the real critical infrastructures.

Further research activities of SCISTC are concentrated on investigating and solving of optimization problems for critical infrastructure safety in Training Course 15. These research includes finding of optimal values of safety and resilience indictors, as well as analysis of resilience and strengthening of critical infrastructure to operation and climate-weather change. This activity results in elaboration of cost-effectiveness analysis and modelling in Training Courses TC16-TC17, critical infrastructure degradation and accident consequences analysis and mitigation in Training Courses TC18-TC19 and maintenance and business continuity models for critical infrastructure under the operation and climate-weather pressures in Training Courses TC20-TC21.

## Summary

Selected Training Courses TC2-21 Modification for Critical Infrastructure with Dependent Assets will be done in Training Courses TC22-TC22+.

## Acknowledgement

The paper presents the results of the work granted by Polish Safety and Reliability Association.

## References

Abouammoh, A., Al-Kadi, M. 1991. Component relevancy in multi-state reliability models. IEEE Trans on Reliability 40, 370-375.

Amari, S.V., Misra, R.B. 1997. Comment on: Dynamic reliability analysis of coherent multistate systems. IEEE Transactions on Reliability 46, 460–461.

Ancione, G., Paltrinieri, N. & Milazzo, M.F. 2020. Integrating real-time monitoring data in risk assessment for crane related offshore operations. Journal of Marine Science and Engineering, 8(7), 1–28, 532.

Aven, T. 1985. Reliability evaluation of multistate systems with multistate components. IEEE Transactions on Reliability 34, 473-479.

Aven, T. 1993. On performance measures for multistate monotone systems. Reliabilitty Engineering and System Safety 41, 259-266.

Aven, T. & Jensen, U. 1999. Stochastic models in reliability. Springer-Verlag, New York.

Barlow, R. E. & Proschan, F. 1975. Statistical Theory of Reliability and Life Testing. Probability Models. Holt Rinehart and Winston, Inc., New York.

Barlow, R. E. & Wu, A. S. 1978. Coherent systems with multi-state components. Math Oper Res 3(11), 275–81

Bautista, B.L., Torres, C.I. & Landesa, P.L. 2020. A condition-based maintenance for complex systems consisting of two different types of components. In K. Kołowrocki et al. (Eds.), Safety and Reliability of Systems and Processes, Summer Safety and Reliability Seminar 2020. Gdynia Maritime University, Gdynia, 7-16.

Berg, H. P. & Petrek, N. 2018. Threats and possible approaches of vulnerability of natural hazards on road infrastructure. Journal of Polish Safety and Reliability Association Summer Safety and Reliability Seminars, Volume 9, Number 3, 1-10.

Bogalecka, M. 2020. Consequences of Maritime Critical Infrastructure Accidents – Environmental Impacts. Elsevier.

Brausch, A. 1987. Calculation of critical importance for multi-state components. IEEE Transactions on Reliability 36, 247-249.

Brunelle, R.D. & Kapur, K.C. 1999. Review and classification of reliability measures for multistate and continuum models. IEEE Transactions 31, 1117–1180.

Butler, D. 1982. Bounding the reliability of multi-state systems. Opertion Research 30, 530-544.

Cepin, M. 2020. The extended living probabilistic safety assessment. Proceedings of the Institution of Mechanical Engineers. Pt. O, Journal of risk and reliability, vol. 234, iss. 1, 183-192.

Dąbrowska, E. 2020. Safety analysis of car wheel system impacted by operation process, Chapter 5 in Safety and Reliability of Systems and Processes, Summer Safety and Reliability Seminar, 61–75.

De Porcellinis, S., Oliva, G., Panzieri, S. & Setola, R. 2009. A holistic-reductionistic approach for modeling interdependencies. Critical Infrastructure Protection III. Springer, USA, 215–227.

Ebrahimi, N. 1984. Multistate reliability models. Naval Res Logistics 31, 671-680.

El-Neweihi, E., Proschan, F. & Sethuraman, J. 1978. Multistate coherent systems. Journal of Applied Probability 15(12), 675–88.

Fardis, M. N. & Cornell, C. A. 1981. Analysis of coherent multistate systems. IEEE Transactions on Reliability 30, 117-122.

Ferreira, F. & Pacheco, A. 2007. Comparison of level-crossing times for Markov and semi-Markov processes. Statistics & Probability Letters 77(2), 151–157.

Glynn, P.W. & Haas, P.J. 2006. Laws of large numbers and functional central limit theorems for generalized semi-Markov processes. Stochastic Models 22(2), 201–231.

Gouldby, B.P., Schultz, M.T., Simm, J.D. & Wibowo, J.L. 2010. Beyond the Factor of Safety: Developing Fragility Curves to Characterize System Reliability, Report in Water Resources Infrastructure Program ERDC SR-10-1, Prepared for Headquarters. U.S. Army Corps of Engineers, Washington.

Grabski, F. 2002. Semi-Markov Models of Systems Reliability and Operations Analysis. System Research Institute, Polish Academy of Science, (in Polish).

Grabski, F. 2014. Semi-Markov Processes: Application in System Reliability and Maintenance. Elsevier.

Griffith, W. 1980. Multistate reliability models. J Applied Probability 17, 735-744.

Holden, R., Val, D.V., Burkhard, R. & Nodwell, S. 2013. A network flow model for interdependent infrastructures at the local scale. Safety Science 53(3), 51–60.

Hudson, J. C. & Kapur, K. C. 1982. Reliability theory for multistate systems with multistate components. Microelectronic Reliability 22, 1-7.

Hudson, J. C. & Kapur, K. C. 1983. Reliability analysis of multistate systems with multistate components. Trans Inst Ind Eng 15, 127-135.

Kjølle, G. H., Utne, I. B. & Gjerde, O. 2012. Risk analysis of critical infrastructures emphasizing electricity supply and interdependencies. Reliability Engineering and System Safety 105. 80-89.

Klabjan, D. & Adelman, D. 2016. Existence of optimal policies for semi-Markov decision processes using duality for infinite linear programming. Society for Industrial and Applied Mathematics Control and Optimization 44(6), 2104–212.

Kołowrocki, K. 1998. On applications of asymptotic reliability functions to the reliability and risk evaluation of pipelines. International Journal of Pressure Vessels and Piping 75, 545–558.

Kołowrocki, K. 2000. On asymptotic approach to multi-state systems reliability evaluation. Chapter 11, in Recent Advances in Reliability Theory: Methodology, Practice and Inference. Birkhauser, Boston, 163–180.

Kołowrocki, K. 2003a. An asymptotic approach to reliability evaluation of large multi-state systems with applications to piping transportation systems. International Journal of Pressure Vessels and Piping 80, 59–73

Kołowrocki, K. 2003b. Asymptotic approach to reliability analysis of large systems with degrading components. International Journal of Reliability, Quality and Safety Engineering 10(3), 249–288.

Kołowrocki, K. 2005. Reliability of Large Systems. Elsevier, Amsterdam – Boston – Heidelberg – London – New York – Oxford – Paris – San Diego – San Francisco – Singapore – Sydney – Tokyo.

Kołowrocki, K. 2008a. Reliability of large systems. In Encyclopedia of quantitative risk analysis and assessment, Vol. 4, John Wiley & Sons.

Kołowrocki, K. 2008b. Reliability and risk analysis of multi-state systems with degrading components. International Journal of Reliability, Quality and Safety Engineering 6(2), 213–228.

Kołowrocki, K. 2011. Reliability modelling of complex systems. In H. Pham (Eds.), Safety and Risk Modelling and Its Applications. Chapter 1, 3-54, Springer.

Kołowrocki, K. 2014. Reliability of Large and Complex Systems. 2nd Edition. Elsevier, Amsterdam – Boston –Heidelberg – London – New York – Oxford – Paris – San Diego – San Francisco – Singapore – Sydney – Tokyo.

Kołowrocki, K. 2020a. Port Oil Terminal Safety Examination. Scientific Journals of the Maritime University of Szczecin 61(133), 143–151.

Kołowrocki, K. 2020b. Safety analysis of multistate ageing car wheel system with dependent components. Chapter 8 in Safety and Reliability of Systems and Processes, Summer Safety and Reliability Seminar, 101–116.

Kołowrocki, K. 2021. Safety analysis of critical infrastructure impacted by operation and climate-weather changes – theoretical backgrounds, Chapter 9 in Safety and Reliability of System and Processes, 139-180.

Kołowrocki, K. 2022a. Safety analysis of multistate ageing system with inside dependences and outside impacts. Current Research in Mathematical and Computer Sciences III. A. Lecko (Ed.). University of Warmia and Mazury Press, 175-214.

Kołowrocki, K. 2022b. European Union Global Critical Infrastructure Safety Management System - Research Project Proposition. Chapter 6 in Safety and Reliability of System and Processes, 79-92.

Kołowrocki, K. 2023a. Safety analysis of complex multistate ageing system**.** In Safety and Reliability of Systems and Processes, Summer Safety and Reliability Seminar.

Kołowrocki, K. 2023b. Two-state approach to critical infrastructure reliability analysis. In Safety and Reliability of Systems and Processes, Summer Safety and Reliability Seminar.

Kołowrocki, K. 2023c. Multistate approach to critical infrastructure reliability analysis. In Safety and Reliability of Systems and Processes, Summer Safety and Reliability Seminar.

Kołowrocki, K. 2023d. Two-state approach to critical infrastructure safety analysis. In Safety and Reliability of Systems and Processes, Summer Safety and Reliability Seminar.

Kołowrocki, K. & Kuligowska, E. 2018. Operation and climate-weather change impact on maritime ferry safety. Safety and Reliability – Safe Societies in a Changing World. Taylor and Francis, 849–854.

Kołowrocki, K. & Magryta, B. 2020a. Port oil terminal reliability optimization. Scientific Journals Maritime University of Szczecin.

Kołowrocki, K. & Magryta, B. 2020b. Changing system operation states influence on its total operation cost. DepCoS-RELCOMEX 2020: Theory and Applications of Dependable Computer Systems, 355–365.

Kołowrocki, K. & Magryta-Mut, B. 2020c. Safety of maritime ferry technical system impacted by operation process, Chapter 9 in Safety and Reliability of Systems and Processes, Summer Safety and Reliability Seminar, 117–134.

Kołowrocki, K. & Magryta-Mut, B. 2021. Operation cost and safety optimization of maritime transportation system. Current Research in Mathematical and Computer Sciences III". A. Lecko (Ed.). University of Warmia and Mazury Press.

Kołowrocki, K. & Magryta-Mut, B. 2023. Safety and operation cost optimization of complex multistate ageing systems. Chapter in Advances in Reliability and Maintainability Methods and Engineering Applications: Essays in Honor of Professor Hong-Zhong Huang on his 60th Birthday, Springer.

Kosmowski, K.T. 2021. Functional Safety and Cybersecurity Analysis and Management in Smart Manufacturing Systems. In: Handbook of Advanced Performability Engineering (Ed. K.B. Misra), Chapter 3. Springer Nature Switzerland AG.

Kossow, A. & Preuss, W. 1995. Reliability of linear consecutively-connected systems with multistate components. IEEE Transactions on Reliability 44, 518–522.

Kvassay, M., Rusnak, P., Zaitseva, E. & Kostolny, J. 2020. Minimal cut vectors of multi-state systems identified using logic differential calculus and multi-valued decision diagrams, 30th European Safety and Reliability Conference, ESREL 2020 and 15th Probabilistic Safety Assessment and Management Conference, PSAM 2020, 3053–3060.

Lauge, A., Hernantes, J. & Sarriegi, J.M. 2015. Critical infrastructure dependencies: a holistic, dynamic and quantitative approach. International Journal of Critical Infrastructure Protection 8, 16–23.

Li, W. & Pham, H. 2005. Reliability modeling of multi-state degraded systems with multi-competing failures and random shocks. IEEE Transactions on Reliability 54(2), 297–303.

Limnios, N. & Oprisan, G. 2005. Semi-Markov Processes and Reliability. Birkhauser. Boston.

Magryta, B. 2020. Reliability approach to resilience of critical infrastructure impacted by operation process. Journal of KONBiN 50(1).

Magryta-Mut, B. 2020. Safety optimization of maritime ferry technical system, Chapter 12 in Safety and Reliability of Systems and Processes, Summer Safety and Reliability Seminar, 175–182.

Magryta-Mut, B. 2023a. Safety and operation cost optimization of complex multistate ageing systems. In Safety and Reliability of Systems and Processes, Summer Safety and Reliability Seminar.

Magryta-Mut, B. 2023b. Safety and operation cost optimization of port and maritime transportation systems, PhD Thesis (under completion). Szczecin Maritime Technical University.

Melchers, R. E. & Beck, A. T. 2018. Structural Reliability Analysis and Prediction, 3rd ed. John Wiley & Sons.

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

Misra, K. B. 1992. Reliability Analysis and Prediction, Elsevier.

Murchland, J. 1975. Fundamental concepts and relations for reliability analysis of multistate systems. Reliability and Fault Tree Analysis, in: Theoretical and Applied Aspects of System Reliability, SIAM, 581-618.

Natvig, B. 2007. Multi-state reliability theory, Chapter in Encyclopedia of Statistics in Quality and Reliability. Wiley, New York, 1160–1164.

Natvig, B. & Morch, H. 2003. An application of multistate reliability theory to an offshore gas pipeline network. International Journal of Reliability, Quality and Safety Engineering 10(4), 361–381.

Natvig, B. & Streller, A. 2008. The steady-state behaviour of multistate monotone systems. Journal of Applied Probability 21, 826-835.

Nieuwenhuijs, A., Luiijf, E. & Klaver, M. 2008. Modeling dependencies in critical infrastructures. Critical Infrastructure Protection II, IFIP International Federation for Information Processing, Series 253. Springer, Boston, Massachusetts, 205–213.

Ohio, F. & Nishida, T. 1984. On multistate coherent systems. IEEE Transactions on Reliability 33, 284-287.

Ouyang, M. 2014. Review on modelling and simulation of interdependent critical infrastructure systems. Reliability Engineering & System Safety 121, 43–60.

Ramirez-Marqueza, J.E. & Coit, D.W. 2007. Multi-state component criticality analysis for reliability improvement in multi-state systems. Reliability Engineering & System Safety 92, 1608–1619.

Rinaldi, S., Peerenboom, J. & Kelly, T. 2001. Identifying, understanding and analyzing critical infrastructure interdependencies, IEEE Control Systems Magazine 21(6), 11–25.

Ross, S. 1979. Multivalued state component systems. Annals of Probability 7. 379-383.

Samaniego, F. J. 2007. System Signtures and their Applications in Engineering Reliability (Internat. Ser. Operat. Res. Manag. Sci. 110). Springer, New York.

Svedsen, N. & Wolthunsen, S. 2007. Connectivity models of interdependency in mixed-type critical infrastructure networks. Information Security Technical Report 12(1), 44–55.

Szymkowiak, M. 2018a. Characterizations of Distributions Through Aging Intensity, IEEE Transactions on Reliability 67.

Szymkowiak, M. 2018b. Generalized aging intensity functions, Reliability Engineering and System Safety 178.

Szymkowiak, M. 2019. Lifetime Analysis by Aging Intensity Functions. Monograph in series: Studies in Systems, Decision and Control (196). Springer International Publishing.

Tang, H., Yin, B.Q. & Xi, H.S. 2007. Error bounds of optimization algorithms for semi-Markov decision processes. International Journal of Systems Science 38(9).

Wang, Y. & Pham, H. 2012. Modeling the dependent competing risks with multiple degradation processes and random shock using time-varying copulas. IEEE Transactions on Reliability 64(1), 13-22.

Wang, Z., Huang, H.Z., Li, Y. & Xiao, N.C. 2011. An approach to reliability assessment under degradation and shock process. Reliability, IEEE Transactions on Reliability 60(4), 852–863.

Xue, J. 1985. On multi-state system analysis. IEEE Transactions on Reliability 34, 329–337.

Xue, J. & Yang, K. 1995a. Dynamic reliability analysis of coherent multi-state systems. IEEE Transactions on Reliability 4(44), 683–688.

Xue, J. & Yang, K. 1995b. Symmetric relations in multi-state systems. IEEE Transactions on Reliability 4(44), 689–693.

Yingkui, G. & Jing, L. 2012. Multi-state system reliability: a new and systematic review. Procedia Engineering 29, 531–536.

Yu, K., Koren, I. & Guo, Y. 1994. Generalised multistate monotone coherent systems. IEEE Transactions on Reliability 43, 242-250.

Zaitseva, E. & Levashenko, V. 2017. Reliability analysis of Multi-State System and Multiple-Valued Logic, International Journal of Quality & Reliability Management, 34(6), 862-878.