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On safety of critical infrastructures

Keywords

critical infrastructure, safety, hazards, accident consequences, modeling, identification, prediction, optimization

Abstract

The paper presents a general approach to safety analysis of critical infrastructures that aims to suggest new and to develop existing methods and tools capable of supporting intelligent modeling and decision making in controlling and optimizing the safety of those systems and their accidents consequences risk. Its main focus is on the suggestions of the creation and usage of new techniques, procedures and strategies to improve and to optimize safety of real complex infrastructure systems related to the inside dependencies - among their subsystems and components and the outside dependencies - coming from their operation environment and from other dangerous events and natural hazards. The approach tries to create an original and coherent methodology of safety of critical infrastructures useful in ensuring and improving safety of those systems in various industrial sectors by providing an integrated package of solutions consisting of various packages of theoretical and practical tools ready for direct use by safety theoreticians and practitioners dealing with safety of real critical infrastructures.

1. Introduction

Many technical systems belong to the class of complex critical infrastructure systems as a result of the large number of interacting components and subsystems they are built of and their complicated operating processes having significant influence on their safety. This complexity and the inside-infrastructure and outside-infrastructure dependencies and hazards cause that there is a need to develop a new and comprehensive approach and general methods of safety analysis, identification, prediction, improvement and optimization for these complex systems. We meet such complex critical infrastructure systems, for instance, in piping transportation of water, gas, oil and various chemical substances, in port and maritime transportation.

From the point of view of more precise analysis of the safety and effectiveness of critical infrastructures, the developed methods should be based on a multistate approach to those complex systems safety analysis instead of normally used two-state approach. This would be enable different critical infrastructure inside and outside safety states to be distinguished, such that they ensure a demanded level of the infrastructure operation effectiveness with accepted for the environment consequences of its dangerous accidents. In most safety analyses, it is assumed that components of a system are independent. But in reality, especially in the case of critical infrastructures, this assumption is not true, so that the dependencies among the critical infrastructure systems components and subsystems should be assumed and considered. In the proposed approach the new results of the safety investigations of the multistate complex systems with dependent components and subsystems should be significantly developed. To tie the results of investigations of the critical infrastructures inside-dependences together with the results coming from the assumed in the critical infrastructures outside-dependencies, the semi-Markov models could be used to describe the complex systems operation processes. This linking of the inside and outside the critical infrastructures dependencies and including other outside dangerous events and hazards coming from the environment and from other dangerous processes, under the assumed their structures multi-state models, is the main idea of the proposed approach methodology. This join considering of all those elements is a main innovative aspect of this approach and the basis for the formulation and development of the new solutions concerned with the modelling, identification, prediction, improvement and optimization of the safety of the complex critical infrastructures related to their operation processes and their inside and outside interactions. Including into the considerations the risk modelling, identification, prediction and optimization of critical infrastructure accidents consequences also is of great added value fort he proposed methodology.

In this aspect, the approach is aimed on the entire elaboration of the methods of evaluation and improvement of safety of as wide as possible class of complex multistate systems composed of dependent components and related to their operation processes and other outside dependencies and on the pointing out of the possibility of those methods practical applications to real complex industrial infrastructures and to analysis and optimization of their accidents consequences with particular applications to maritime and coastal transportation infrastructure systems and to maritime accidents consequences concerned with chemical spills at sea. The analytical methods proposed should be complemented with the statistical methods for safety data processing that will include an innovative approach to the methods of safety and security evaluation and optimization on the basis of the existing rough data for the processing of safety and security data on the basis of the most important and specific distribution functions of the classical statistics. Thus, those all suggestions will fulfill a comprehensive solution of problems the approach is concerned with. The activities also performed in the approach will propose newly developed tools practical testing.

The proposed approach will deliver detailed results for safety models of complex critical infrastructure systems related to their inside and outside dependencies, their integration into a general model of inside and outside dependencies and hazards influence on safety of critical infrastructures and processes, the risk assessment models of the critical infrastructure accidents consequences and the methods of those models unknown parameters identifications and their preliminary testing in real industrial infrastructures and particularly in maritime and port transport critical infrastructures.

Further, the approach will deliver the validated general methods of prediction and optimization of the safety of critical infrastructures, their accidents consequences and risk. Practical application and testing of the results in the complex port and maritime transportation systems will be performed and all general models and methods of safety modelling, identification, prediction and optimization developed will be modified according to the practical incomes coming from these experiments.

The main theoretical results will be created in the form of the monographs [1], [10] and [26]. Practically validated safety decision support system in the form of an overall guide-book [11] will be created, the packages of practical tools in the form of new procedures and regulations assuring high safety of critical infrastructures will be provided and a set of training courses on critical infrastructures safety will be prepared as well.

The proposed approach to the problems of safety of complex critical infrastructures is an innovative and very important aspect for the safety science as there are no comprehensive and general solutions concerned with the safety of multistate complex industrial systems related to their operation processes and their inside and outside dependencies considered simultaneously. The results of testing and primary practical applications of the created methodology of safety and developed methods to the real critical infrastructures of maritime and port transport sector and to maritime critical infrastructure accident consequences risk analysis also are an important reason for the realization of this approach.

2. Safety of multistate systems

Taking into account the importance of the safety and operating process effectiveness of real technical systems it seems reasonable to expand the two-state approach to multi-state approach [16], [26] in system safety analysis. The assumption that the systems are composed of multi-state components with safety states degrading in time [16], [26] gives the possibility for more precise analysis of their safety and operational processes’ effectiveness. This assumption allows us to distinguish a system safety critical state to exceed which is either dangerous for the environment or does not assure the necessary level of its operation process effectiveness. Then, an important system safety characteristic is the time to the moment of exceeding the system safety critical state and its distribution, which is called the system risk function. This distribution is strictly related to the system multi-state safety function that are basic characteristics of the multi-state system. The safety models of the considered in [16] and [26] typical multistate system structures can be applied in the safety analysis of real complex technical systems. They may be successfully applied, for instance, to safety analysis, identification, prediction and optimization of the maritime transportation systems [16], [25], [26].

In the multistate safety analysis to define the system with degrading independent components, we assume that [16], [26]:

n is the number of the system components;

- E_i, $i = 1,2,...,n$, are independent components of a system;
- all components and a system under consideration have the safety state set $\{0,1,...,z\}$;
- the safety states are ordered, the safety state 0 is the worst and the safety state z is the best;
- $T_i(u)$, $i = 1,2,...,n$, are independent random variables representing the lifetimes of components E_i in the safety state subset $\{u,u+1,...,z\}$, while they were in the safety state z at the moment $t = 0$;
- $T(u)$ is a random variable representing the lifetime of a system in the safety state subset $\{u,u+1,...,z\}$ while it was in the safety state z at the moment $t = 0$;
- the system states degrades with time t;
- $s_i(t)$ is a component E_i safety state at the moment t, $t \in < 0, \infty)$, given that it was in the safety state z at the moment $t = 0$;
- $s(t)$ is a system S safety state at the moment t, $t \in < 0, \infty)$, given that it was in the safety state z at the moment $t = 0$.

Under the above assumptions, the following notions of the ageing multistate systems safety analysis may be introduced [16], [26]:

- the multistate system components safety functions;
- the multistate system safety function;
- the mean values and variances of the multistate system lifetimes in the safety state subsets;
- the mean values and variances of the multistate system lifetimes in the particular safety states;
- the multi-state system risk function;
- the moment of exceeding by the multistate system the critical safety state.

Further, the basic multistate safety structures of the multistate systems with ageing independent components may be defined and their safety functions determined [16], [26]. As a particular case, the safety functions of the considered multi-state systems composed of independent components having exponential safety functions may be determined.

All those aspects of multistate systems with independent components are comprehensively considered in [16], [26] and will be applied to safety analysis of those systems under the assumption that their components are dependent [9], [17], [21]-[22] in the sense that their components intensities of safety states changing are dependent on the current safety states of the remaining components.

3. Safety of critical infrastructures modeling

Currently, the newest trends in the safety investigations of complex technical systems analysis are directed to the critical infrastructures. In general, a critical infrastructure is a single complex system of large scale or a network of complex large systems (set of hard or soft structures) that function collaboratively and synergistically in order to ensure a continuous production flow of essentials goods and services. These are complex systems that significant features are inside-system dependencies and outside-system dependencies, that in the case of damage have significantly destructive influence on the health, safety and security, economics and social conditions of large human communities and territory areas. These systems are made of large number of interacting components and even small perturbations can trigger large scale consequences in critical infrastructures that may cause multiple threats in human life and activity. For the above reason, as an extended failure within one of these infrastructures may result in the critical incapacity or destruction and can significantly damage many aspects of human life and further cascading across the critical infrastructure boundaries, they have the potential for multi-infrastructural collapse with unprecedented and transnational dangerous consequences. Therefore, the optimization of the structures, operation processes and maintenance strategies of critical infrastructures with respect to their safety and operation costs is very important. Analyzing the critical infrastructures in their variable operation conditions and considering their changing in time safety structures and their among components and subsystems dependability resulting in changes of their safety characteristics becomes much complicated. Adding to this analysis, the outside of the critical infrastructures hazards coming from other systems, from natural cataclysm and from other dangerous events makes the problem essentially more difficult to become solved in order to improve and to ensure high level of these systems safety.

From the point of view of more precise analysis of the safety and effectiveness of critical infrastructures, the developed methods should be based on a multistate approach [10]-[17], [24]-[27], [28]-[31] to these complex systems safety analysis instead of normally used two-state approach. This will enable different critical infrastructure inside and outside safety states to be distinguished, such that they ensure a demanded level of the system operation effectiveness with accepted consequences of the dangerous accidents for the environment, population, etc.

In most safety analyses, it is assumed that components of a system are independent. But in reality, especially in the case of critical infrastructures, this assumption is not true, so that the dependencies among the critical infrastructure systems components and subsystems should be assumed and considered. It is a natural assumption, as after decreasing the safety state by one of components in a subsystem, the inside interactions among the remaining components may cause further components safety states decrease [9]-[10]. In reality, in the critical infrastructures, it may even cause the whole system safety state dangerous degradation.

To tie the results of investigations of the critical infrastructures inside-dependences together with the results coming from the assumed in the critical infrastructures outside-dependencies, the semi-Markov models [1]-[5], [20]-[21] can be used to describe the complex systems operation processes. This linking of the inside and outside the critical infrastructures dependencies and including other outside dangerous events and hazards coming from the environment and from other dangerous processes, under the assumed their structures multi-state models, is the main idea of the proposed critical infrastructures safety analysis methodology [9], [10], [17].

3.1. Modeling inside dependability influence on safety of complex multistate systems

In modelling the inside of infrastructure dependencies, we omit the assumption that their components are independent in the multistate safety analysis considered in Section 2 and we assume that the components E_i, $i = 1,2,\dots,n$, of a multistate system are dependent and we developed the methodology of safety of critical infrastructures starting with the following basic definitions.

Definition 1. A vector

$$S_i(t,\cdot) = [S_i(t,0), S_i(t,1), \dots, S_i(t,z)] \qquad (1)$$

for $t \in <0,\infty)$, $i = 1,2,\dots,n$, where

$$S_i(t,u) = P(s_i(t) \ge u \mid s_i(0) = z) = P(T_i(u) > t) \qquad (2)$$

for $t \in <0,\infty)$, $u = 0,1,\dots,z$, is the probability that the multistate component E_i is in the safety state subset $\{u, u+1, \dots, z\}$ at the moment t, $t \in <0,\infty)$, while it was in the safety state z at the moment $t = 0$, is called the safety function of this component.

Definition 2. A vector

$$\boldsymbol{S}(t,\cdot) = [\boldsymbol{S}(t,0), \boldsymbol{S}(t,1), \dots, \boldsymbol{S}(t,z)],\ t \in <0,\infty), \qquad (3)$$

where

$$\boldsymbol{S}(t,u) = P(s(t) \ge u \mid s(0) = z) = P(T(u) > t) \qquad (4)$$

for $t \in <0,\infty)$, $u = 0,1,\dots,z$, is the probability that the multistate system is in the safety state subset $\{u, u+1, \dots, z\}$ at the moment t, $t \in <0,\infty)$, while it was in the safety state z at the moment $t = 0$, is called the safety function of this system.

Definition 3. A probability

$$\boldsymbol{r}(t) = P(s(t) < r \mid s(0) = z) = P(T(r) \le t),$$
$$t \in <0,\infty), \qquad (5)$$

that the system is in the subset of safety states worse than the critical safety state r, $r \in \{1,\dots,z\}$ while it was in the safety state z at the moment $t = 0$ is called a risk function of the multi-state system [16].

Under this definition, from (4), we have

$$\boldsymbol{r}(t) = 1 - P(s(t) \ge r \mid s(0) = z) = 1 - \boldsymbol{S}(t,r),$$
$$t \in <0,\infty), \qquad (6)$$

and if τ is the moment when the system risk exceeds a permitted level δ, then

$$\tau = \boldsymbol{r}^{-1}(\delta), \qquad (7)$$

where $\boldsymbol{r}^{-1}(t)$ is the inverse function of the system risk function $\boldsymbol{r}(t)$.

Further, the basic notions of the critical infrastructure safety analysis may be introduced [16]. The critical infrastructure components and the critical infrastructure safety functions, the basic safety infrastructures, the mean values and variances of the critical infrastructure lifetimes in the safety state subsets and the mean values of their lifetimes in the particular safety states may be defined. The critical infrastructure risk function and the moment of exceeding by the critical infrastructure the critical safety state may be introduced.

Next, the various safety structures of the critical infrastructures with dependent components may be defined and their safety functions determined. As a particular case, the safety functions of the considered critical infrastructures composed of dependent components having exponential safety functions may be determined. To do this, the following mathematical model of the inside the infrastructure dependences between its components can be applied.

One of the suggested approaches to safety analysis of a homogeneous infrastructure with dependent components E_i that have the same safety function

$$S_i(t,\cdot) = [1, S_i(t,1), \ldots, S_i(t,z)] \tag{8}$$

for $t \in <0,\infty)$, $i = 1,2,\ldots,n,$ with the coordinates

$$S_i(t,u) = S(t,u) \tag{9}$$

for $t \in <0,\infty)$, $u = 1,\ldots,z,$ i = 1,2,...,n, is the assumption that after changing the safety state subset by one of the system components to the worse safety state subset, the lifetimes of the remaining system components in this safety state subsets decrease dependably of the number of the components which left that subset of safety states. More exactly, we assume that if $\upsilon, \upsilon = 0,1,2,\ldots,n-1,$ components of the system are out of the safety state subset $\{u, u+1, \ldots, z\}$, the mean values of the lifetimes $T_i{}'(u)$ in this safety state subset of the system remaining components are given by

$$E[T_i{}'(u)] = c(u)[E[T_i(u)] - \frac{\upsilon}{n}E[T_i(u)]$$

$$= c(u)\frac{n-\upsilon}{n}E[T_i(u)] \tag{10}$$

for $i = 1,2,\ldots,n,$ $u = 1,2,\ldots,z,$ where $c(u)$, $u = 1,2,\ldots,z,$ are the component stress proportionality correction coefficients.

Hence, for the case when components have exponential safety functions defined by (8), with the exponential coordinates of the form

$$S_i(t,u) = \begin{cases} 1, & t < 0 \\ \exp[-\lambda(u)t], & t \geq 0, \lambda(u) \geq 0, \\ i = 1,2,\ldots,l & \end{cases} \tag{11}$$

with the intensity of departure $\lambda(u)$ from the safety state subset $\{u, u+1, \ldots, z\}$, we get the following formula for the intensities of departure from this safety state subset of the remaining components

$$\lambda^{(\upsilon)}(u) = \frac{1}{c(u)}\frac{n}{n-\upsilon}\lambda(u) \tag{12}$$

for $\upsilon = 0,1,2,\ldots,n-1,$ $u = 1,2,\ldots,z.$

This simple approach to the inside critical infrastructures dependencies may be developed for the selected critical homogeneous safety infrastructures and the analytical solutions for their safety characteristics can be found. Unfortunately, in the case of non-homogeneous infrastructures the analytical solutions are generally difficult to obtain and have to be supported by Monte Carlo simulation methods.

3.2. Modeling outside dependability influence on safety of complex multistate systems

In the proposed approach, the operation process of the complex technical system is considered and its operation states are introduced. The semi-Markov process can be used to construct a general probabilistic model of the considered complex technical system operation processes. To build this model, we may assume that the system during its operation process is taking $v, v \in N,$ different operation states $z_1, z_2, \ldots, z_v$. Further, we define the system operation process $Z(t)$, $t \in <0,+\infty)$, with discrete operation states from the set $\{z_1, z_2, \ldots, z_v\}$. Moreover, we assume that the system operation process $Z(t)$ is a semi-Markov process [10]. [16] with the conditional sojourn times θ_{bl} at the operation states z_b when its next operation state is z_l, $b, l = 1,2,\ldots,v,$ $b \neq l.$

Under these assumptions, the system operation process may be described by:

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

It is practically reasonable [16] to suggest that the suitable and typical distributions suitable to describe the system operation process $Z(t)$ conditional sojourn times θ_{bl}, $b, l = 1,2,\ldots,v,$ $b \neq l,$ in the particular operation states are [10], [16]:

- the uniform distribution with a density function

$$h_{bl}(t) = \begin{cases} 0, & t < x_{bl} \\ \dfrac{1}{y_{bl} - x_{bl}}, & x_{bl} \leq t \leq y_{bl} \\ 0, & t > y_{bl}, \end{cases} \tag{13}$$

where $0 \leq x_{bl} < y_{bl} < +\infty$;

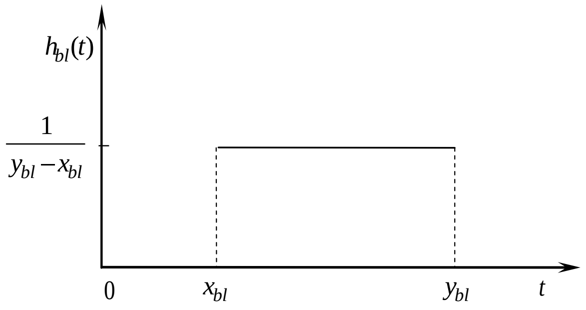


Figure 1. The graph of the uniform distribution's density function

- the triangular distribution with a density function

$$h_{bl}(t) = \begin{cases} 0, & t < x_{bl} \\ \frac{2}{y_{bl}-x_{bl}} \frac{t-x_{bl}}{z_{bl}-x_{bl}}, & x_{bl} \le t \le z_{bl} \\ \frac{2}{y_{bl}-x_{bl}} \frac{y_{bl}-t}{y_{bl}-z_{bl}}, & z_{bl} \le t \le y_{bl} \\ 0, & t > y_{bl}, \end{cases} \qquad (14)$$

where

$$0 \le x_{bl} \le z_{bl} \le y_{bl} < +\infty;$$

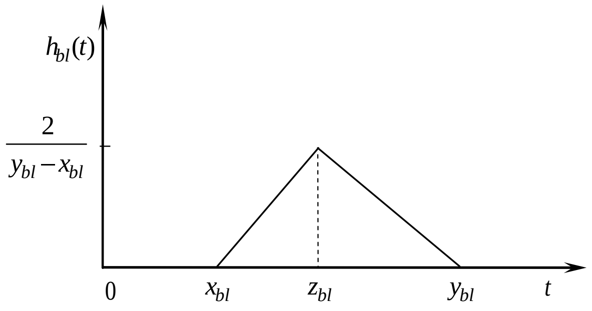


Figure 2. The graph of the triangular distribution's density function

- the double trapezium distribution with a density function

$$h_{bl}(t) = \begin{cases} 0, & t < x_{bl} \\ q_{bl} + \frac{C_{bl}-q_{bl}}{z_{bl}-x_{bl}}(t-x_{bl}), & x_{bl} \le t \le z_{bl} \\ w_{bl} + \frac{C_{bl}-w_{bl}}{y_{bl}-z_{bl}}(y_{bl}-t), & z_{bl} \le t \le y_{bl} \\ 0, & t > y_{bl}, \end{cases} \qquad (15)$$

where

$$C_{bl} = \frac{2 - q_{bl}(z_{bl}-x_{bl}) - w_{bl}(y_{bl}-z_{bl})}{y_{bl}-x_{bl}},$$

$$0 \le x_{bl} < z_{bl} < y_{bl} < +\infty, \quad 0 \le q_{bl} < +\infty,$$

$$0 \le w_{bl} < +\infty, \quad 0 \le q_{bl}(z_{bl}-x_{bl}) + w_{bl}(y_{bl}-z_{bl}) \le 2;$$

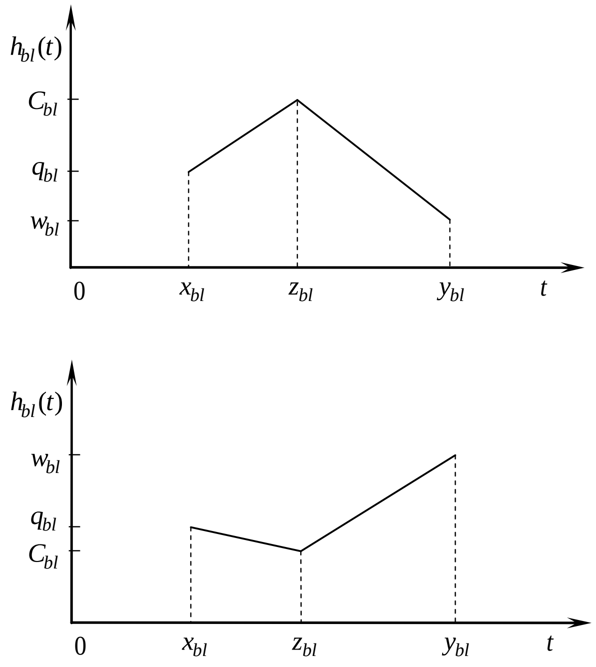


Figure 3. The graphs of the double trapezium distribution's density functions

- the quasi-trapezium distribution with a density function

$$h_{bl}(t) = \begin{cases} 0, & t < x_{bl} \\ q_{bl} + \frac{A_{bl}-q_{bl}}{z_{bl}^1-x_{bl}}(t-x_{bl}), & x_{bl} \le t \le z_{bl}^1 \\ A_{bl}, & z_{bl}^1 \le t \le z_{bl}^2 \\ w_{bl} + \frac{A_{bl}-w_{bl}}{y_{bl}-z_{bl}^2}(y_{bl}-t), & z_{bl}^2 \le t \le y_{bl} \\ 0, & t > y_{bl}, \end{cases} \qquad (16)$$

where

$$A_{bl} = \frac{2 - q_{bl}(z_{bl}^1-x_{bl}) - w_{bl}(y_{bl}-z_{bl}^2)}{z_{bl}^2 - z_{bl}^1 + y_{bl} - x_{bl}},$$

$$0 \le x_{bl} \le z_{bl}^1 \le z_{bl}^2 \le y_{bl} < +\infty,$$

$$0 \le q_{bl} < +\infty, \;\; 0 \le w_{bl} < +\infty;$$

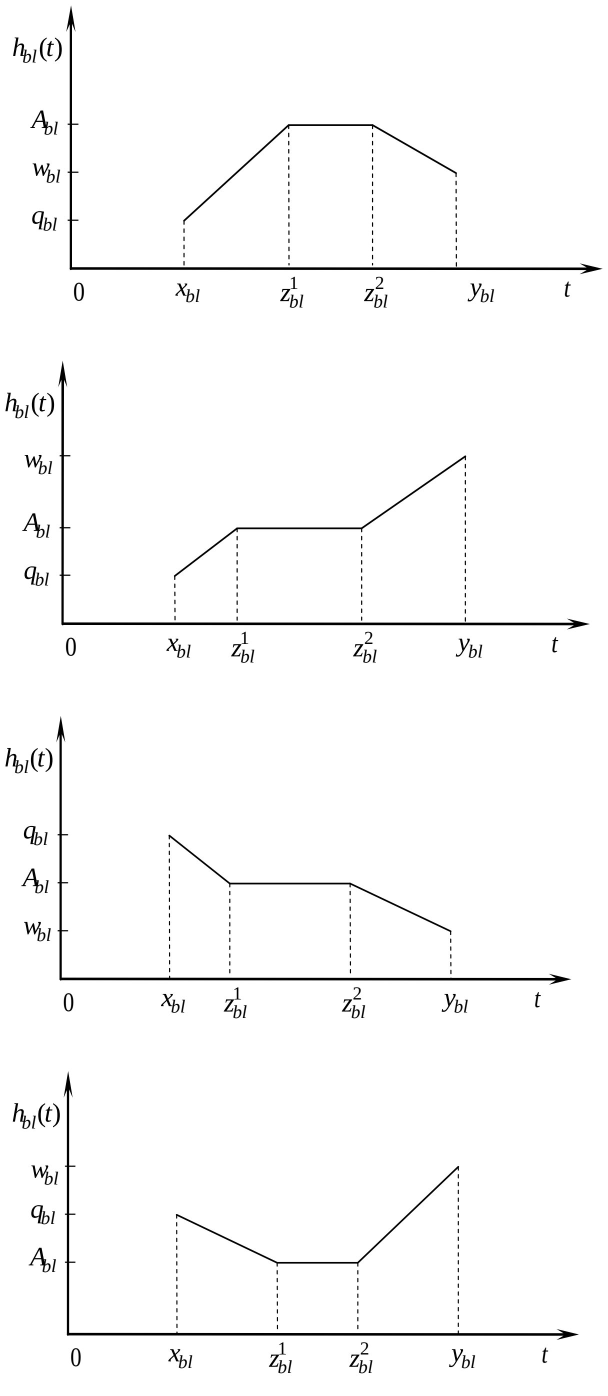


Figure 4. The graphs of the quasi-trapezium distribution's density functions

- the exponential distribution with a density function

$$h_{bl}(t) = \begin{cases} 0, & t < x_{bl} \\ \alpha_{bl} \exp[-\alpha_{bl}(t - x_{bl})], & t \ge x_{bl}, \end{cases} \tag{17}$$

where

$0 \le \alpha_{bl} < +\infty;$

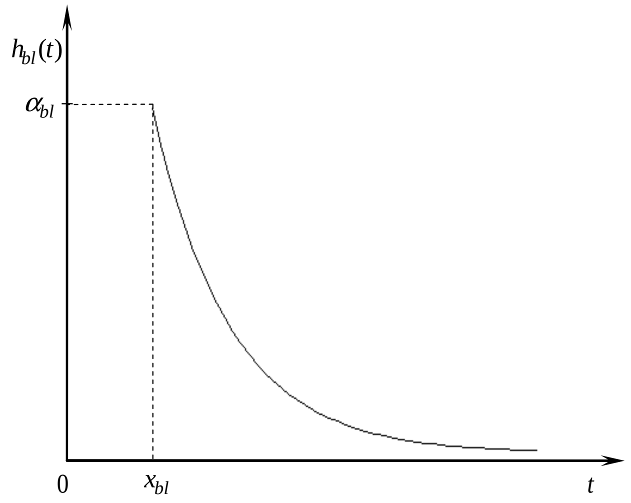


Figure 5. The graph of the exponential distribution's density function

- the Weibull distribution with a density function

$$h_{bl}(t) = \begin{cases} 0, & t < x_{bl} \\ \alpha_{bl}\beta_{bl}(t - x_{bl})^{\beta_{bl}-1} & \\ \cdot \exp[-\alpha_{bl}(t - x_{bl})^{\beta_{bl}}], & t \ge x_{bl}, \end{cases} \tag{18}$$

where $0 \le \alpha_{bl} < +\infty,\ 0 \le \beta_{bl} < +\infty;$

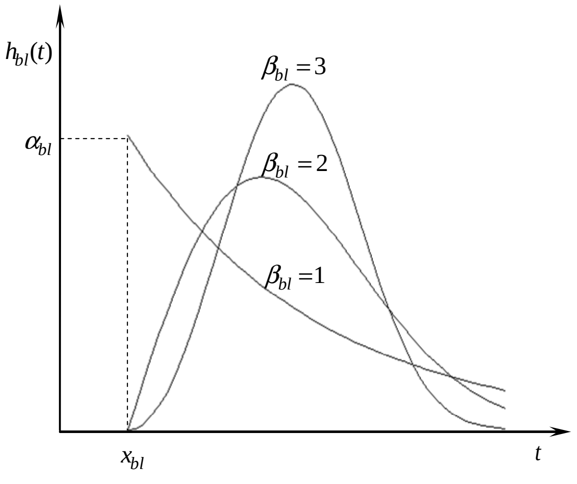
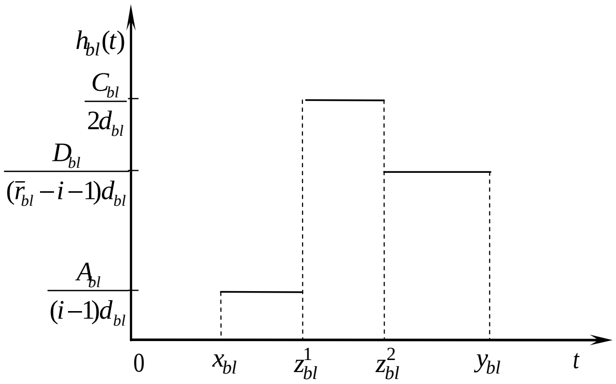


Figure 6. The graphs of the Weibull distribution's density functions

- the chimney distribution with a density function

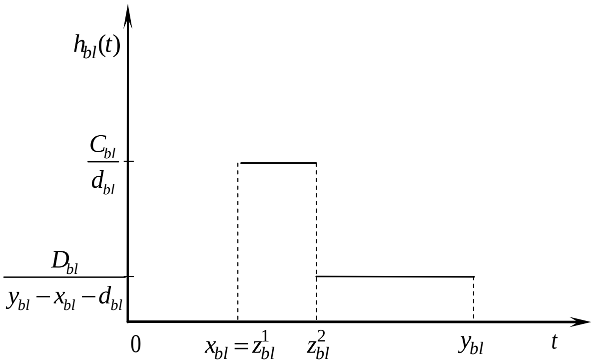
$$h_{bl}(t)=\begin{cases}0, & t<x_{bl}\\ \dfrac{A_{bl}}{z_{bl}^{1}-x_{bl}}, & x_{bl}\le t\le z_{bl}^{1}\\ \dfrac{C_{bl}}{z_{bl}^{2}-z_{bl}^{1}}, & z_{bl}^{1}\le t\le z_{bl}^{2}\\ \dfrac{D_{bl}}{y_{bl}-z_{bl}^{2}}, & z_{bl}^{2}\le t\le y_{bl}\\ 0, & t>y_{bl},\end{cases} \tag{19}$$

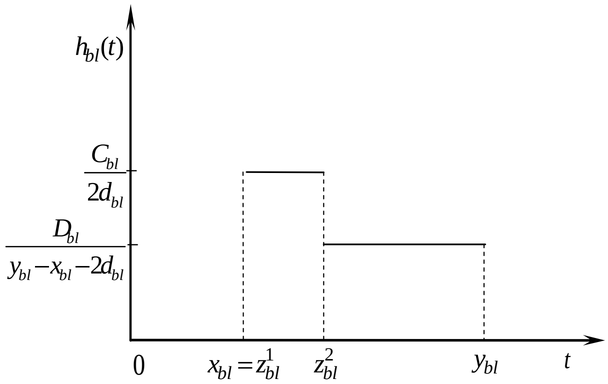


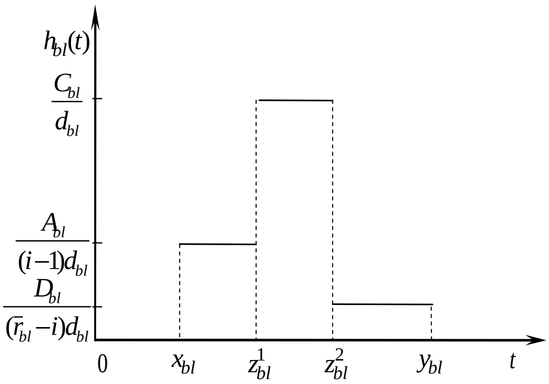
where

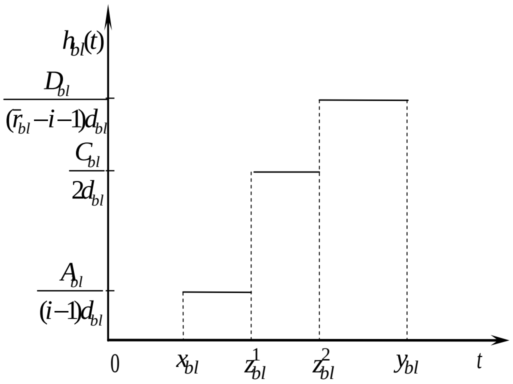
$$0\le x_{bl}\le z_{bl}^{1}\le z_{bl}^{2}\le y_{bl}<+\infty,\ \ A_{bl}\ge 0,$$

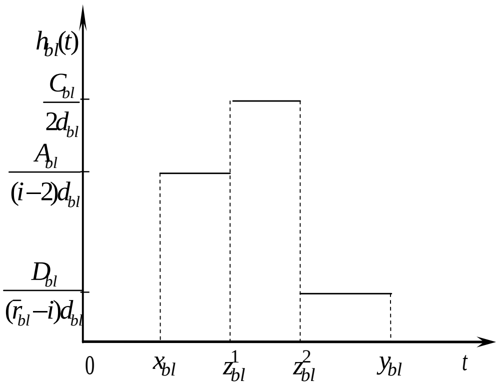
$$C_{bl}\ge 0,\ \ D_{bl}\ge 0,\ \ A_{bl}+C_{bl}+D_{bl}=1.$$

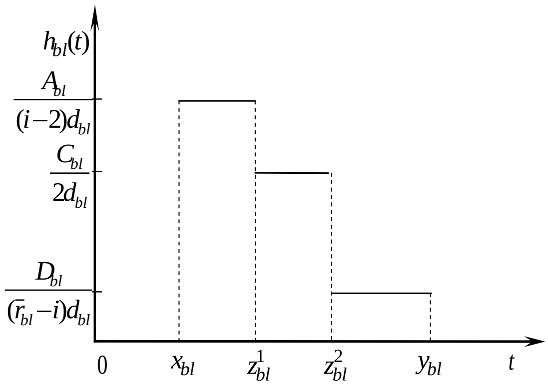












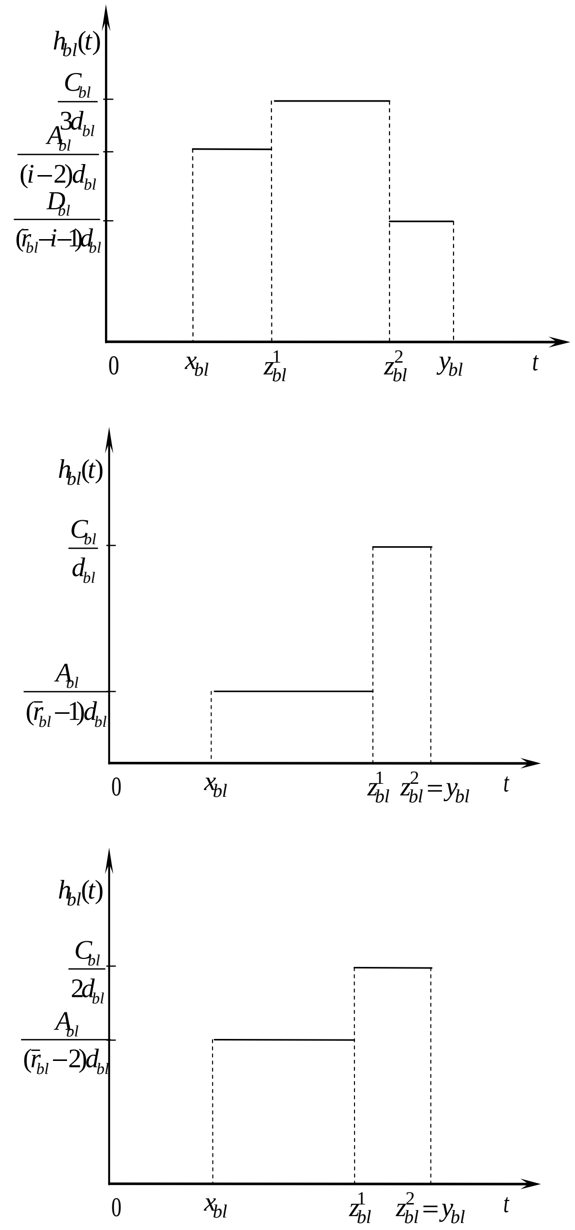


Figure 7. The graphs of the chimney distribution's density functions (the meanings of d_{bl}, i and $\bar{r}_{bl}$ are explained in Section 4.2 [16])

Under these all assumptions from the constructed model, the main characteristics of the system operation process can be found. The above distributions may be proposed as suitable for the system operation processes distributions of the conditional sojourn times at the operation states. Under this assumption, the mean values of the system operation process conditional sojourn times at the particular operation states having these distributions can be determined. Moreover, the distribution functions of the system operation process unconditional sojourn times at the particular operation states, the mean values of the system operation process unconditional sojourn times at the particular operation states, the limit values of the transient probabilities of the system operation process at the particular operation states and the approximate mean values of the system operation process total sojourn times at the particular operation states for the fixed sufficiently large system operation time can be determined as well.

4. Safety of critical infrastructures prediction

Linking of the inside and outside of the critical infrastructures dependencies and including other outside dangerous events and hazards coming from the environment and from other dangerous processes is to create new and innovative methodology for safety of critical infrastructures. Creating the main achievement of this task, the basis for the formulation and development of the new solutions concerned with the modeling and prediction of the safety of complex critical infrastructures related to their operation processes and their inside and outside interactions are introduced. Using analytical and Monte Carlo simulation methods in systems' safety prediction extend significantly the state of the art in the field of safety science by introducing new methods of investigation of the complex critical infrastructures related to their inside dependences and outside dependencies and hazards. The construction of the probabilistic general model of critical infrastructure accident consequences including the process of the accident initiating events, the process of the environment threats and the process of environment degradation models is also proposed.

4.1. Integrated model of inside and outside dependability and hazards influence on safety of critical infrastructures

The system safety models given in Section 3.1, together with the models of the system operation process presented in Section 3.2 are proposed to be used for constructing the integrated joint general safety models of complex technical systems related to their operation processes. These models are the integrated general models of complex technical systems, linking their multistate safety models and their operation processes models and considering variable at the different operation states their safety structures and their components safety parameters. The conditional safety functions at the system particular operation states and independent of the system particular operation states the unconditional safety function and the risk function of the complex technical systems can be defined.

To perform the above, we assume that the changes of the system operation process $Z(t)$ states have an influence on the system multistate components E_i, $i = 1,2,...,n,$ safety and the system safety structure as well. We mark by $T_1^{(b)}(u),\ T_2^{(b)}(u),\ ...,T_n^{(b)}(u)$ the system components $E_1, E_2, ...,\ E_n$ conditional lifetimes in the safety states subset $\{u, u+1, z\},\ u = 1,2,...,z,$ and by $T^{(b)}(u)$ the system conditional lifetimes in the safety states subset $\{u, u+1,...,z\},\ u = 1,2,...,z,$ while the system is at the operation state $z_b,\ b = 1,2,...,v.$ Further, we define the conditional safety function of the system multistate component $E_i,\ i = 1,2,...,n,$ while the system is at the operation state $z_b,\ b = 1,2,...,v,$ by the vector [10], [16]

$$[S_i(t,\cdot)]^{(b)} = [1,\ [S_i(t,1)]^{(b)},\ ...,\ [S_i(t,z)]^{(b)}\ ], \qquad (20)$$

where

$$[S_i(t,u)]^{(b)} = P(T_i^{(b)}(u) > t \,|\, Z(t) = z_b) \qquad (21)$$

for $t \in < 0,\infty),\ \ u = 1,2,...,z,\ i = 1,2,...,n,$ and the conditional safety function of the multistate system while the system is at the operation state z_b, $b = 1,2,...,v,$ by the vector [10], [16]

$$[\boldsymbol{S}(t,\cdot)]^{(b)} = [1,\ [\boldsymbol{S}(t,1)]^{(b)},\ ...,\ [\boldsymbol{S}(t,z)]^{(b)}], \qquad (22)$$

where

$$[\boldsymbol{S}(t,u)]^{(b)} = P(T^{(b)}(u) > t \,|\, Z(t) = z_b) \qquad (23)$$

for $t \in < 0,\infty),\ u = 1,2,\ldots,z,\ b = 1,2,...,v.$

The safety function $[S_i(t,1)]^{(b)}$ is the conditional probability that the component E_i lifetime $T_i^{(b)}(u)$ in the safety state subset $\{u, u+1,...,z\}$ is greater than *t*, while the process *Z*(*t*) is at the operation state z_b. Similarly, the safety function $[\boldsymbol{s}(t,u)]^{(b)}$ is the conditional probability that the system lifetime $T^{(b)}(u)$ in the safety state subset $\{u, u+1,...,z\}$ is greater than *t*, while the process *Z*(*t*) is at the operation state z_b. Consequently, we mark by $T(u)$ the system unconditional lifetime in the safety states subset $\{u, u+1,...,z\},\ u = 1,2,...,z,$ and we define the system unconditional safety function by the vector

$$\boldsymbol{S}(t,\cdot) = [1,\ \boldsymbol{S}(t,1), ...,\ \boldsymbol{S}(t,z)\ ], \qquad (24)$$

where

$$\boldsymbol{S}(t,u) = P(T(u) > t)\,, \qquad (25)$$

for $t \in < 0,\infty),\ u = 1,2,...,z.$

The joint models are applied to determining safety characteristics of these systems related to their varying in time safety structures and their components safety characteristics. Under the assumption that the considered systems are exponential, the unconditional safety functions of these systems can be determined.

Further, we may assume that the coordinates (24) of the vector of the conditional multistate safety function (23) are exponential safety functions of the form

$$[S_i(t,u)]^{(b)} = \exp[-[\lambda_i(u)]^{(b)} t] \ \text{ for } t \in < 0,\infty), \qquad (26)$$
$$u = 1,2,...,z,\ \ b = 1,2,...,v,\ \ i = 1,2,...,n.$$

Te above assumption means that the density function of the system component conditional lifetime $T^{(b)}(u)$ in the safety state subset $\{u, u+1,...,z\}$, $u = 1,2,...,z,$ at the operation state $z_b,\ b = 1,2,...,v$, is exponential of the form

$$[f_i(t,u)]^{(b)} = [\lambda_i(u)]^{(b)} \exp[-[\lambda_i(u)]^{(b)} t] \qquad (27)$$

for $t \in < 0,\infty)$, where $[\lambda_i(u)]^{(b)},\ \ [\lambda_i(u)]^{(b)} \geq 0,$ is an unknown intensity of the system component departure from this subset of the safety states.

The exemplary graph of the conditional density function $[f_i(t,u)]^{(b)}$ defined by (30) is illustrated in *Figure 8*.

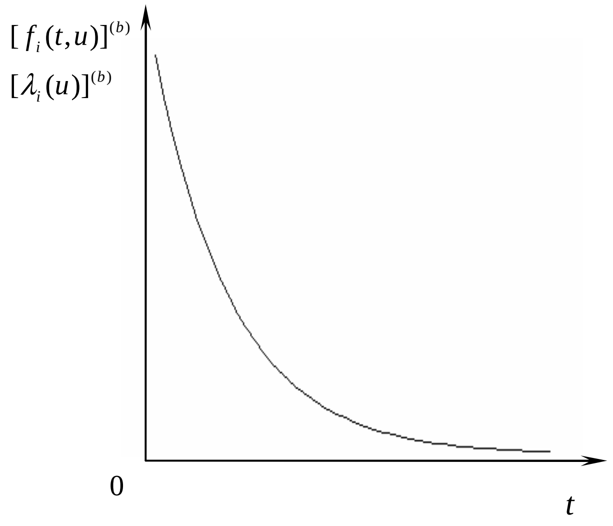


Figure 8. The graph of the conditional density function coordinate $[f_i(t,u)]^{(b)}$

In the particular case of the system operation process when the operation states are concerned either with very dangerous natural hazards or with kidnapping that almost immediately make the system seriously damaged or completely destroyed and dangerous for the environment, i.e. the system is reaching its worst safety state immediately, it is suggested to replace the exponential safety function given by the formula (27) by the uniform/chimney safety function with the density function concentrated very closely to zero of the form

$$f_i^{(b)}(t,u) = \begin{cases} 0, & t < 0 \\ \dfrac{1}{a_i^{(b)}(u)}, & 0 \le t \le a_i^{(b)}(u) \\ 0, & t > a_i^{(b)}(u), \end{cases} \qquad (28)$$

where $a_i^{(b)}(u) > 0,$ are very small numbers close to 0.

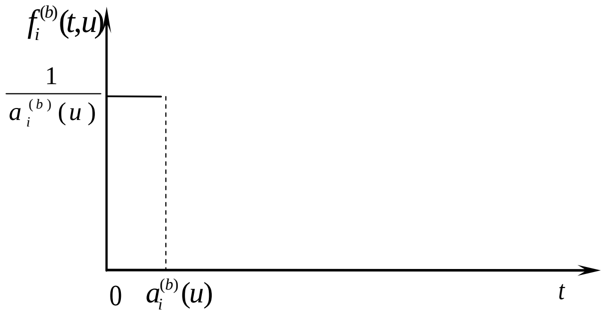


*Figure 9.*The graph of the uniform/chimney density function

Moreover, in the case of large scale systems, the possibility of combining the results coming from these joint models and the results concerning the limit safety functions [6]-[8] of the considered systems can be used. The proposed models and methods can be applied to the safety analysis, evaluation and prediction of the varios systems related to varying in time their operation processes, structures and components safety parameters.

4.2. Modelling critical infrastructure accident consequences

The risk analysis of the infrastructure accident consequences is suggested to be based on fixing and interrelating the accident initiating events, the environment threats and the environment degradation.

In the proposed approach, the basic notions concerned with the events initiating the accidents of critical infrastructures dangerous for the environment and concerned with environment threats may be introduced. The process of the accident initiating events and the process of the environment threats and their states may be defined. The vectors of initial probabilities of these processes staying at their particular states, the matrices of probabilities of those processes transitions between their particular states, the matrices of conditional distribution functions and the matrices of conditional density functions of these processes conditional sojourn times at their particular states may be defined. Under these all assumptions from the constructed models, the main characteristics of the process of the accident initiating events and the process of the environment threats can be found using methods given in [1]. The mean values of the process of these processes conditional sojourn times at their particular states having fixed distributions can also be determined. Moreover, the distribution functions of these processes unconditional sojourn times at their particular states, the mean values of these processes unconditional sojourn times at their particular states, the limit values of the transient probabilities of these processes at their particular states and the approximate mean values of these processes sojourn times at their particular states for the fixed sufficiently large time can be determined. After making the superpositions of the accident initiating events and the process of the environment threats the general model of the process of environment degradation dependent on this superposition and its states can be defined [1] and its main charakteristics can be determined. The functions of the environment losses associated with the process of environment degradation may be introduced and the critical infrastructure accident expcted value of the total environmet losses for the fixed interval of time may be determined [1].

5. Safety of critical infrastructures parameters identification

The methods and procedures for estimating unknown parameters of the integrated safety model of critical infrastructures and the general model of critical infrastructure accidents consequences should also be created in the proposed approach.

5.1. Identification of unknown parameters of integrated safety model of critical infrastructures

The methods of identification of the operation processes of critical infrastructures based on the methods given in [16] are proposed. They are the methods and procedures for estimating the unknown basic parameters of the critical infrastructure operation process semi-Markov models and identifying the distributions of the conditional critical infrastructure operation processes sojourn times at the operation states. There will be proposed the formulae estimating the probabilities of the critical infrastructure operation process staying at the operation states at the initial moment, the probabilities of the critical infrastructure operation process transitions between the operation states and the parameters of the distributions suitable and typical for the description of the critical infrastructure operation process conditional sojourn times at the operation states. The chi-square goodness-of-fit test will be described and proposed to be applied to verifying the hypotheses about the distributions choice validity. The procedure of statistical data sets uniformity analysis based on Kolmogorov-Smirnov test will be proposed to be applied to the empirical conditional sojourn times at the operation states coming from different realizations of the same critical infrastructure operation process. There will be presented procedures and formulae convergent with that given in [16], [26] estimating the unknown parameters of the critical infrastructure components safety models on the basis of statistical data coming from the components safety states changing processes. The maximum likelihood method will be applied to estimating the unknown intensities of departures from the safety state subsets of the multistate critical infrastructure components having different exponential safety functions at various critical infrastructure operation states. This method will be applied to the statistical data collected at different kinds of the empirical experiments, including the cases of small number of realizations and non-completed investigations. There will be presented the goodness-of-fit test applied to verifying the hypotheses concerned with the exponential forms of the multistate safety functions of the particular components of the critical infrastructures at the variable operations conditions. In the case of lack of data coming from the components safety states changing processes, the simplified method of estimating the unknown intensities of departures from the safety state subsets based on the expert opinions will be proposed.

5.2. Identification of unknown parameters of critical infrastructure accident consequences model

The methods of identification of the process of the accident initiating events, the process of the environment threats and the general of the process of environment degradation based on the methods given in [1] will be proposed. They will be the methods and procedures for estimating the unknown basic parameters of these processes models and identifying the distributions of their conditional sojourn times at their states. There will be given the formulae estimating the probabilities of these processes straying at the states at the initial moment, the probabilities of these processes transitions between their states and the parameters and forms of the distributions fixed for the description of these processes process conditional sojourn times at their states. There will be presented procedures and formulae estimating the unknown parameters of the functions of losses associated with the process of environment degradation and the criticl infrastructure accident expected value of the total envitonmet losses.

6. Safety of critical infrastructures optimization

The methods and procedures of optimization of safety of critical infrastructures and critical infrastructure accidents consequences based on that given in [26] and [1] respectively will be created.

6.1. Optimization of critical infrastructures safety

The methods based on the results of the joint model linking a semi-Markov modelling of the critical infrastructure operation processes with a multistate approach to critical infrastructure safety and the linear programming based on the model considered in [16], may be proposed to the critical infrastructures safety optimization. The method of the optimization of the critical infrastructures operation processes determining the optimal values of limit transient probabilities at the system operation states that maximize the critical infrastructure lifetimes in the safety state subsets may be proposed. Presented in this section tools may be useful in safety optimization of a very wide class of real critical infrastructures operating at the varying conditions that have an influence on changing their safety structures and their components safety characteristics. These tools can be tested using he methods and procedures proposed in the Section 7.1.

6.2. Optimization of critical infrastructure accidents consequences

The methods based on the results of the general model of the process of environment degradation and the linear programming based on the model considered in [1] may be proposed to the critical infrastructures accident consequences optimization. The method of the optimization of the critical infrastructures accident consequences determining the optimal values of limit transient probabilities at the process of environment degradation states that minimize the critical infrastructure accident expected value of the total environmet losses for the fixed interval of time may be proposed and practically tested using the methods and procedures proposed in the Section 7.2.

7. Applications in port and maritime industry

The improvement of the methods and procedures of safety of critical infrastructures and critical infrastructures accident consequences modeling, identification, prediction and optimization after application and testing them to complex maritime and port transportation systems and chemical spills and pollutions at sea will be performed. Applications of the proposed critical infrastructure general model to the evaluation and prediction of the safety characteristics of a port oil piping transportartion system and a maritime ferry technical system may be done. The considered piping transportation system could be the port oil piping transportation system operating at one of the Baltic oil terminals that is designated for the reception from ships, the storage and sending by carriages or cars the oil products. It is also designated for receiving from carriages or cars, the storage and loading the tankers with oil products such like petrol and oil. The considered maritime ferry could be a passenger Ro-Ro ship operating at the Baltic Sea between two ports on regular everyday line. Those applications will be based on the real operation and safety statistical data coming from the port oil piping transportation system and the ferry operators. The results obtained from the models practical application to the identification and prediction will also be apply to safety and risk optimization of the port oil piping transportation system and the maritime ferry technical system to justify the proposed solutions practical utility. The final results obtained from these models practical usage to the prediction and optimization of main safety characteristics of the port oil piping transportation system and the maritime ferry technical system will verify the validity of the proposed approach to the critical infrastructures safety modelling and prediction and allow to improve the quality and modify the models which were proposed in Section 3. Modifications of the final results coming from the general models of complex critical infrastructures included Section 3.1 based on the results of their practical applications and testing will be performed. The final modified models, procedures and algorithms that allow to find the main an practically important safety characteristics of the complex critical infrastructures at the variable operation condition will be elaborated. Modifications of the final results coming from the models of critical infrastructure accident consequences included in Section 4.2 based on the results of their practical applications and testing will be performed. The final modified models, procedures and algorithms that allow to find the main an practically important risk characteristics of the critical infrastructure accident consequence will be elaborated. The creation of new strategies assuring high safety of critical infrastructures and low critical infrastructure accidents consequences based on the results of practical application of critical infrastructures safety models will be proposed as well.

7.1. Safety of port transportation system

7.1.1. Port oil piping transportation system

The considered oil piping transportation system is operating at one of the Baltic Oil Terminals that is designated for the reception from ships, the storage and sending by carriages or cars the oil products. It is also designated for receiving from carriages or cars, the storage and loading the tankers with oil products such like petrol and oil. The considered terminal is composed of three parts *A*, *B* and *C*, linked by the piping transportation system with the pier. The scheme of this terminal is presented in *Figure 10*.

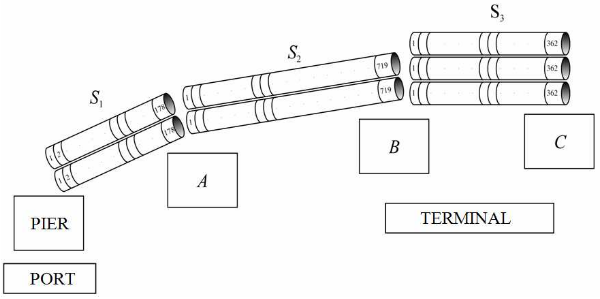


Figure 10. The scheme of the port oil transportation system

The unloading of tankers is performed at the pier placed in the port. The pier is connected with terminal part *A* through the transportation subsystem S_1 built of two piping lines composed of steel pipe segments with diameter of 600 mm. In the part *A* there is a supporting station fortifying tankers pumps and making possible further transport of oil by the subsystem S_2 to the terminal part *B*. The subsystem

S_2 is built of two piping lines composed of steel pipe segments of the diameter 600 mm. The terminal part *B* is connected with the terminal part *C* by the subsystem S_3. The subsystem S_3 is built of one piping line composed of steel pipe segments of the diameter 500 mm and two piping lines composed of steel pipe segments of diameter 350 mm. The terminal part *C* is designated for the loading the rail cisterns with oil products and for the wagon sending to the railway station of the port and further to the interior of the country.

Thus, the port oil pipeline transportation system consists of three subsystems:

- the subsystem S_1 composed of two pipelines, each composed of 178 pipe segments and 2 valves,
- the subsystem S_2 composed of two pipelines, each composed of 717 pipe segments and 2 valves,
- the subsystem S_3 composed of three pipelines, each composed of 360 pipe segments and 2 valves.

The subsystems S_1, S_2, S_3, indicated in *Figure 1* are forming a general series port oil pipeline system safety structure presented in *Figure 11*.

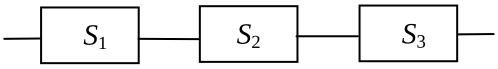


Figure 11. General scheme of the port oil pipeline system safety structure

The system is a series system composed of two series-parallel subsystems S_1, S_2, each containing two pipelines and one series-“2 out of 3” subsystem S_3.

7.1.2. Port oil piping transportation system operation process

The subsystems S_1, S_2 and S_3 are forming a general series port oil pipeline system safety structure presented in *Figure 2*. However, the pipeline system safety structure and its subsystems and components safety depend on its changing in time operation states [16].

Taking into account expert opinions on the varying in time operation process of the considered piping system, we distinguish the following as its eight operation states [16]:

- an operation state z_1 – transport of one kind of medium from the terminal part B to part C using two out of three pipelines of the subsystem S_3,
- an operation state z_2 – transport of one kind of medium from the terminal part C to part B using one out of three pipelines of the subsystem S_3,
- an operation state z_3 – transport of one kind of medium from the terminal part B through part A to pier using one out of two pipelines of the subsystem S_1 and one out of two pipelines of the subsystem S_2,
- an operation state z_4 – transport of one kind of medium from the pier through parts A and B to part C using one out of two pipelines of the subsystem S_1, one out of two pipelines in subsystem S_2 and two out of three pipelines of the subsystem S_3,
- an operation state z_5 – transport of one kind of medium from the pier through part A to B using one out of two pipelines of the subsystem S_1 and one out of two pipelines of the subsystem S_2,
- an operation state z_6 – transport of one kind of medium from the terminal part B to C using two out of three pipelines of the subsystem S_3, and simultaneously transport one kind of medium from the pier through part A to B using one out of two pipelines of the subsystem S_1 and one out of two pipelines of the subsystem S_2,
- an operation state z_7 – transport of one kind of medium from the terminal part B to C using one out of three pipelines of the subsystem S_3, and simultaneously transport second kind of medium from the terminal part C to B using one out of three pipelines of the subsystem S_3.

The influence of the above system operation states changing on the changes of the pipeline system safety structure is as follows.

At the system operation states z_1 and z_7, the system is composed of the subsystem S_3, that is a series-”2 out of 3” system containing three series subsystems with the scheme showed in *Figure 12*.

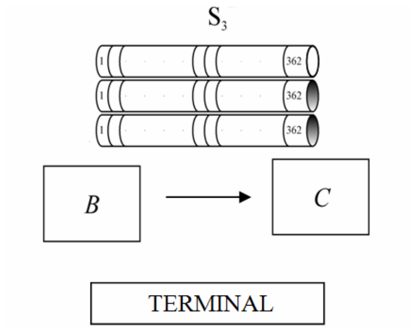


Figure 12. The scheme of the port oil piping transportation system at the operation states z_1 and z_7

At the system operation state z_2, the system is composed of a series-parallel subsystem S_3, which contains three pipelines with the scheme showed in *Figure 13*.

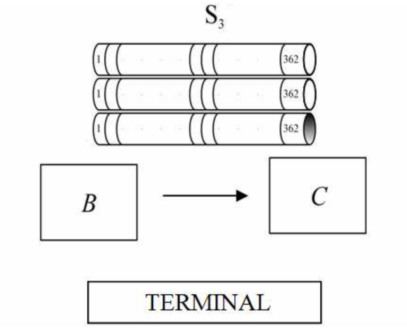


Figure 13. The scheme of the port oil piping transportation system at the operation state z_2

At the system operation states z_3 and z_5, the system is series and composed of two series-parallel subsystems S_1, S_2, each containing two pipelines with the scheme showed in *Figure 14*.

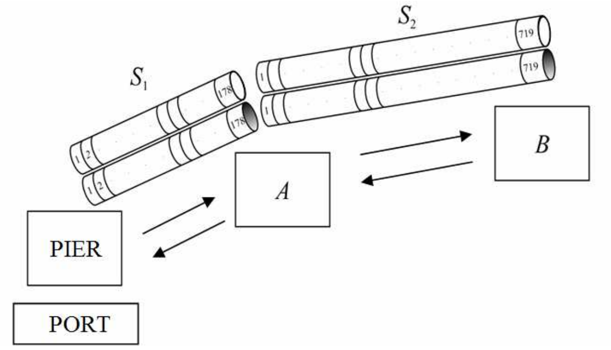


Figure 14. The scheme of port oil piping transportation system at the operation states z_3 and z_5

At the system operation states z_4 and z_6, the system is series and composed of two series-parallel subsystems S_1, S_2, each containing two pipelines and one series-“2 out of 3” subsystem S_3 with the scheme showed in *Figure 15*.

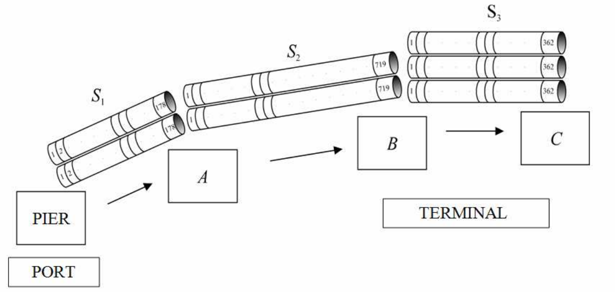


Figure 15. The scheme of the port oil piping transportation system at the operation states z_4 and z_6

7.1.2. Port oil piping transportation system safety identification, prediction and optimization

To identify the unknown parameters of the port oil piping transportation system operation process the suitable statistical data coming from its real realizations should be collected. The lack of sufficient statistical data about the port oil piping transportation system operation process causes that it is not possible to estimate exactly its operation parameters. However, even on the basis of the fragmentary statistical data coming from experts, the port oil piping transportation system operation process probabilities p_{bl} of transitions from the operation state z_b into the operation state z_l, $b,l = 1,2,...,7,$ $b \neq l,$ can be evaluated approximately.

After considering the comments and opinions coming from experts, taking into account the effectiveness and safety aspects of the operation of the oil pipeline transportation system, we distinguish the following three safety states $(z = 2)$ of the system and its components:

- a safety state 2 – piping operation is fully safe,
- a safety state 1 – piping operation is less safe and more dangerous because of the possibility of environment pollution,
- a safety state 0 – piping is destroyed.

Moreover, by the expert opinions, we assume that there are possible the transitions between the components safety states only from better to worse ones and we assume that the system and its components critical safety state is $r = 1$.

The port oil piping transportation system safety structure and its subsystems and components safety depend on its changing in time operation states. The influence of the system operation states changing on the changes of the system safety structure and its components safety functions is described in [9].

Finally, considering the results given in [9], we get the piping system unconditional safety function

$$\boldsymbol{S}(t,\cdot) = [1, \boldsymbol{S}(t,1), \boldsymbol{S}(t,2)] \text{]}, \ t \geq 0, \qquad (29)$$

where the coordinates $\boldsymbol{S}(t,1)$ and $\boldsymbol{S}(t,2)$ are given in [9], respectively by (90) and (91).

The coordinates of the piping system unconditional safety function are presented in *Figure 16*.

The expected values of the pipeline system unconditional lifetimes in the safety state subsets $\{1,2\}$, $\{2\}$, calculated from the results given by (89)-(91) in [9], according to (5) and using the results (45), (50), (67), (72), (77), (82), (92) given in [9], respectively are:

$$\mu(1) \cong 0.395\ 0.309 + 0.060\ 0.464 + 0.003\ 0.207 + 0.002\ 0.156 + 0.200\ 0.207 + 0.058\ 0.156 + 0.282\ 0.309 = 0.288 \text{ year},$$

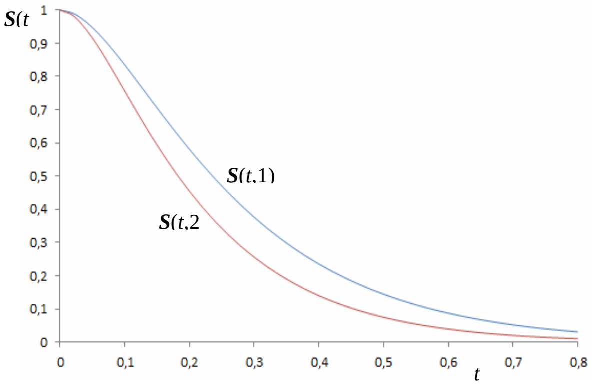


Figure 16. The graph of the piping system unconditional safety function

$$\mu(2) \cong 0.395\ 0.247 + 0.060\ 0.370 + 0.003\ 0.146 + 0.002\ 0.114 + 0.200\ 0.146 + 0.058\ 0.114 + 0.282\ 0.247 = 0.226 \text{ year}, \tag{30}$$

and further, using (9) and (92) from [9], the mean values of the unconditional lifetimes in the particular safety states 1, 2, respectively are:

$$\bar{\mu}(1) \cong 0.062,\ \bar{\mu}(2) \cong 0.226 \text{ year}. \tag{31}$$

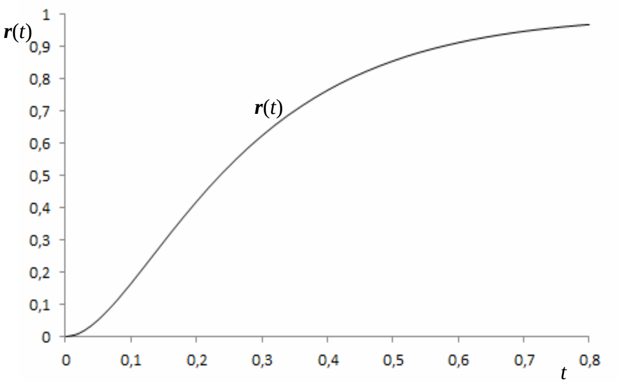


Figure 17. The graph of the piping system risk function

As the critical safety state is r =1, then the system risk function, according to (6), is given by

$$\boldsymbol{r}(t) = 1 - \boldsymbol{S}(t,1) \tag{32}$$

where $\boldsymbol{S}(t,1)$ is given by (90) in [9] and by (7), the moment when the system risk exceeds a permitted level δ = 0.05 is

$$\tau = \boldsymbol{r}^{-1}(0.05) = 0.049. \tag{33}$$

Further, the piping transportation system safety and operation optimization may be performed and practical suggestions and procedures improving its safety can be worked out.

7.2. Risk of chemical spills and pollutions at sea modelling, identification, prediction and optimization

Applications of the proposed general model of the process of environment degradation and the methods and procedures of its unknown parameters to the risk model of chemical spills and pollutions at sea, identification, prediction and optimization may be performed. This application will be based on the real statistical data coming from IMO Global Integrated Shipping Information System and Centre of Documentation, Research and Experimentation on Accidental Water Pollution. The final results obtained from these models practical usage to the prediction and optimization of main characteristics of the the process of sea environment degradation will verify the validity of the proposed approach to the critical infrastructures accident consequences modeling and prediction and allow to improve the quality and modify the models which will be performed.

7.3. New strategy assuring high safety of critical infrastructures

From the performed analysis of the results of the port oil piping transportation system and the maritime ferry technical system operation processes optimization it can be suggested to organize these systems operation processes in the way that causes the replacing (or the approaching/convergence to) the conditional mean sojourn times of the systems at the particular operation states before the optimization by their optimal values after the optimization. The possibility of fulfilling this suggestion of the operation process parameters changing is not easy and has to be checked in practice. It seems to be practically a bit easier way, changing the operation processes characteristics that results in replacing (or the approaching/convergence to) the unconditional mean sojourn times of the port oil piping transportation system and the maritime ferry technical system at the particular operation states before the optimization by their optimal values after the optimization. The easiest way of these system operation process reorganizing is that leading to the replacing (or the approaching/convergence to) the total sojourn times of the port oil piping transportation system and the maritime ferry technical system operation process at the particular operation states during the operation time before the optimization by their optimal values after the optimization. These coming directly from the practice suggestions on the way of improving considered systems safety will be the basis for creating the general procedures and strategies assuring the improvement of critical infrastructures safety.

7.4. New strategy assuring low critical infrastructure accidents consequences

From the performed analysis of the results of the chemical spills and pollutions at sea consequences optimization it can be suggested to modify the process of accident initiating events and the process of environment threats in the way that causes the replacing (approximately) the conditional mean sojourn times of the environment degradation process at its particular states before the optimization by their optimal values after the optimization. Instead of this practically difficult modification it seems to be easier to change the process of accident initiating events and the process of environment threats characteristics that results in replacing (approximately) the unconditional mean sojourn times of the environment degradation process at its particular states before the optimization by their optimal values after the optimization. The easiest way of these two processes modification is that leading to the replacing (approximately) the total sojourn times of the process of accident initiating events and the process of environment threats at their particular states during the fixed time before the optimization by their optimal values after the optimization. These coming directly from the practice suggestions on the way of minimizing the environment losses will be the basis for creating the general procedures and strategies assuring the critical infrastructures accident consequences decease the environment losses.

8. Integrated Critical Infrastructures Safety System – ICISS

The main practical goal of the proposed approach is creating practical tools improving safety of critical infrastructures safety in the form of a guide-book, training courses, procedures and regulations and illustration of their applications addressed to critical infrastructures users.

8.1. ICISS – Guidebook

The guide-book "Integrated Critical Infrastructure Safety System" – ICISS is composed of the following items:
Scheme of ICISS (presented in *Figure 18*)

- ICISS 1. Critical Infrastructure Analysis
- ICISS 2. Introduction to Safety of Critical Infrastructures
- ICISS 3. Critical Infrastructure Operation Process Modelling
- ICISS 4. Critical Infrastructure Operation Process Identification
- ICISS 5. Critical Infrastructure Operation Process Prediction
- ICISS 6. Critical Infrastructure Components Safety Modelling
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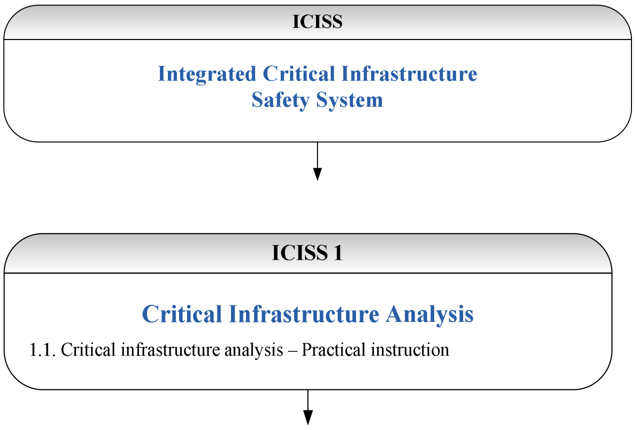
- ICISS 8. Critical Infrastructure Safety Prediction
- ICISS 9. Critical Infrastructure Accident Consequences Modelling
- ICISS 10. Critical Infrastructure Accident Consequences Model Identification
- ICISS 11. Critical Infrastructure Operation Process Optimization
- ICISS 12. Critical Infrastructure Safety Optimization
- ICISS 13. Critical Infrastructure Accident Consequences Optimization
- ICISS 14. Applications
- ICISS 15. Critical Infrastructure Operation and Safety New Strategy



ICISS 2

Introduction to Safety of Multistate Critical Infrastructre

Contents

2.1. Safety of multistate critical infrfstructur – Basic definitions and notions
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2.1.2. Safety analysis of multistate critical infrastructure

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ICISS 4

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4.1. Data collection for estimating unknown parameters of critical infrastructure operation process – Practical instruction
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4.2. Critical ifrastructure operation process identification – Theoretical backgrounds
4.2.1. Estimating basic parameters of critical infrastructure operation process
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6.2.1. Safety of multistate critical infrastructure component in variable operation conditions

ICISS 7

Critical Infrastructure Components Safety Identification

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ICISS 8

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ICISS 9

Critical Infrastructure Accident Consequences Modelling

Contents

9.1. Defining parameters of critical infrastructure accident consequences – Practical instruction
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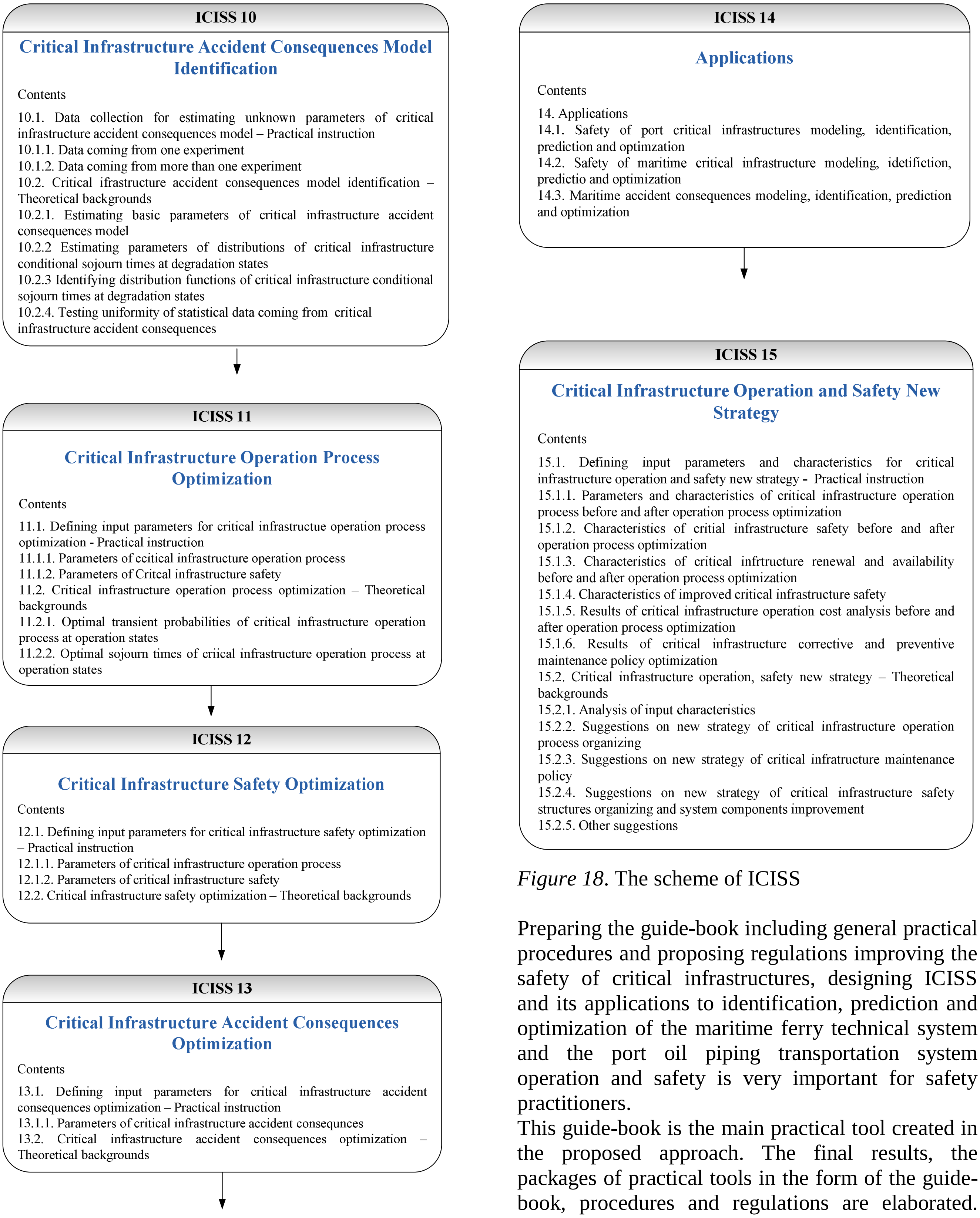

ICISS 10

Critical Infrastructure Accident Consequences Model Identification

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10.1. Data collection for estimating unknown parameters of critical infrastructure accident consequences model – Practical instruction
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ICISS 11

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11.1. Defining input parameters for critical infrastructue operation process optimization - Practical instruction
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11.1.2. Parameters of Critcal infrastructure safety
11.2. Critical infrastructure operation process optimization – Theoretical backgrounds
11.2.1. Optimal transient probabilities of critical infrastructure operation process at operation states
11.2.2. Optimal sojourn times of criical infrastructure operation process at operation states

ICISS 12

Critical Infrastructure Safety Optimization

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12.1. Defining input parameters for critical infrastructure safety optimization – Practical instruction
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ICISS 13

Critical Infrastructure Accident Consequences Optimization

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ICISS 14

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Contents

14. Applications
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Critical Infrastructure Operation and Safety New Strategy

Contents

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15.1.1. Parameters and characteristics of critical infrastructure operation process before and after operation process optimization
15.1.2. Characteristics of critial infrastructure safety before and after operation process optimization
15.1.3. Characteristics of critical infrtructure renewal and availability before and after operation process optimization
15.1.4. Characteristics of improved critical infrastructure safety
15.1.5. Results of critical infrastructure operation cost analysis before and after operation process optimization
15.1.6. Results of critical infrastructure corrective and preventive maintenance policy optimization
15.2. Critical infrastructure operation, safety new strategy – Theoretical backgrounds
15.2.1. Analysis of input characteristics
15.2.2. Suggestions on new strategy of critical infrastructure operation process organizing
15.2.3. Suggestions on new strategy of critical infratructure maintenance policy
15.2.4. Suggestions on new strategy of critical infrastructure safety structures organizing and system components improvement
15.2.5. Other suggestions

Figure 18. The scheme of ICISS

Preparing the guide-book including general practical procedures and proposing regulations improving the safety of critical infrastructures, designing ICISS and its applications to identification, prediction and optimization of the maritime ferry technical system and the port oil piping transportation system operation and safety is very important for safety practitioners.

This guide-book is the main practical tool created in the proposed approach. The final results, the packages of practical tools in the form of the guide-book, procedures and regulations are elaborated. Those tools can be applied and tested in the maritime and coastal transportation industry to provide practically validated individual safety and reliability decision support systems for individual maritime transport sectors as well as an overall Integrated Critical Infrastructure Safety System - ICISS. This created the integrated support system is general and may be applied not only in maritime industry sectors but in other industry sectors as well.

The ICISS is intended to be testified by applications in the operation, reliability, safety and operation cost modelling, identification, prediction and optimization of the port, shipyard and maritime technical transportation systems.

The ICISS is going to be supplemented by training courses directed to the industry.

The ICISS will mainly be based on the monographs [1], [16], [26], the significant results the proposed approach, including the main theoretical results of the approach, together with their practical applications and promoting the results internationally.

The procedure of the ICISS usage is presented in the form of detailed and clear scheme-algorithm placed at the guide-book. The procedure should start from the scheme-algorithm item ICISS 1, to study if it is necessary its introductory item ICISS 2 and to continue with the items ICISS 3-15. The user should follow the successive steps of the scheme using the support given in the forms of practical instructions and theoretical backgrounds placed at the further parts of the guide-book.

To make the use of the ICISS easy and fluent, it is suggested to study its practical application to the safety analysis of real critical infrastructure systems the guide-book appliqué item 14 and its wide and detailed practical applications to maritime and coastal transport industry and presented in the monographs [1], [16]. [26].

8.2. ICISS – Packages of training and educational courses

The following training and educational courses are intended to be prepared:

- TC 1. Identification of critical infrastructure operation processes;
- TC 2. Testing uniformity of statistical data from the critical infrastructure operation processes;
- TC 3. Identification of critical infrastructure components safety models;
- TC 4. Prediction of critical infrastructure operation processes;
- TC 5. Prediction of critical infrastructure safety;
- TC. 6. Modelling critical infrastructure accident consequences
- TC. 7. Identification of critical infrastructure accident consequences model
- TC 8. Optimization of critical infrastructure operation and safety.
- TC. 9. Optimization of critical infrastructure accident consequences

8.3. ICISS – Packages of procedures and regulations

Soma packages of procedures and regulations, based on the new strategies assuring high safety of critical infrastructures developed in Section 7.3 and new strategies assuring low critical infrastructure accidents consequences developed in Section 7.4, are intended to be prepared.

9. Conclusions

The potential of the contribution is in its ability to mobilize a critical mass of research and development resources and competence in the field of safety of critical infrastructures, which will improve current effectiveness and competitiveness in this field. It will have positive impact on the sustainable development of knowledge in safety of complex industrial infrastructures. The proposed approach brings together theoretical and applied research, which includes research in the natural, technical, social, economical sciences and industry practice with an inclination towards practical applications. Linking theoretical scientific activity with testing and practical applications is particularly important for increasing complex industrial systems and processes safety and operation procedures optimization. The development of new knowledge applications will result in safer, more reliable and more effective people engaging in current industrial activities.

Examples of potential impacts of the approach are as follows:

- The approach will contribute to increasing the international research potential with respect to the development of safety methods in investigating complex critical infrastructures through the dissemination activities such as conferences, workshops, schools and seminars;
- In the long term, the approach will contribute significantly towards increasing the safety level of various industrial critical infrastructures;
- The results of the approach will form an important input to activities for national and international organizations, standardization and certification bodies as well as other similar institutions that deals with the critical infrastructures safety;
- In maritime and port transportation, the results of the approach will have significant impact on improving the infrastructure and operation decisions resulting in making the whole sectors safer, economically-efficient and user-friendly.
- The approach is expected to lead to the development of high advanced research with serious impact on the development of the world

science and knowledge in the field of safety with the possibilities of industrial applications.

The approach main activities are concerned with the issue of safety of critical infrastructures research, education and training. The approach will also have a look into the definition of strategies and concepts for various critical infrastructures research as well as its implementation into the infrastructure policies which is convergent with the international safety organizations' objectives given in their regulations, directives and declarations. The approach, with such a foundation, will undoubtedly contribute to the national and international organizations dealing with safety.

The approach aims to deliver the followings effects:

- A general safety model of critical infrastructures relating to their inside and outside dependencies and hazards;
- A general model of risk assessment of critical infrastructures accidents consequences;
- A statistical study of current critical infrastructures to evaluate unknown parameters of these general models using empirical data mining techniques;
- A systematic study of methods for safety that includes an evaluation of current complex critical infrastructures and processes;
- A systematic study of maintenance strategies for critical infrastructures;
- General methodology of safety of critical infrastructures (monograph [16] published internationally);
- Modelling safety of complex technical systems (monograph [26] published internationally);
- Risk analysis of chemical spills at sea (monograph [1] published internationally);
- Integrated Critical Infrastructures Safety System (a guidebook [17]) – ICISS;
- User-friendly guidebooks for practitioners, which includes methods, procedures, descriptions, applications, etc.;
- Contributions to scientific seminars and conferences, organizing training courses and publishing the approach results at the internet website.

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