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Bogalecka Magda

Kołowrocki Krzysztof
ORCID ID: 0000-0002-4836-4976

Maritime University, Gdynia, Poland

EU-CIRCLE: A pan-European framework for strengthening critical infrastructure resilience to climate change
Project taxonomy and methodology – Critical infrastructure accident consequences terminology and methodology

Keywords

critical infrastructure, critical infrastructure accident consequences modelling and prediction

Abstract
The paper presents critical infrastructure accident consequences terminology, used in the project titled "A pan-European framework for strengthening Critical Infrastructure resilience to climate change – EU-CIRCLE", realized under the European Union's Horizon 2020 research and innovation program. The methodology concerned with EU-CIRCLE project Case Study 2, investigating chemical spill due to extreme surges related to critical infrastructure accident consequences modelling in the scope of project issues is proposed as well.

1. Introduction

The papers covers all recognized, and collected by EU-CIRCLE project participants, terms and definitions concerned among the critical infrastructure accident consequences, used in other previous and current projects, and in available literature as well. Main parts of this paper present contents of the third section of the report – terminology existing in resilience field.
Moreover, the paper introduces methodology of critical infrastructure accident consequences modelling also proposed in the report [8], being the base for works undertaken in this field, covered by further EU-CIRCLE reports.

2. Critical infrastructure accident consequences terminology

In this chapter, the general terminology for critical infrastructure accident consequence that are analysed within the scope of the EU-CIRCLE project according to the report [8] are presented. Below terms and definitions, concerned with critical infrastructure accident consequence, are presented in alphabetical order.
Accident. An unplanned event that results in harm to people, damage to property or loss to process [10].
Aggregate impacts. Total impacts summed up across sectors and/or regions [5].
Barrier. The various "layers of protection" afforded facility and site personnel, the general public and the environment by the design and operational controls of each facility [25].
Carcinogen. A chemical, physical or biological agent that can cause cancer in humans or animals [10].
Cascade failure. A disruption of one infrastructure that causes a disruption in another infrastructure. [6].
Cascading effects. There are the dynamics present in disasters, in which the impact of a physical event or the development of an initial technological or human failure generates a sequence of events in human subsystems that result in physical, social or economic disruption. Thus, an initial impact can trigger other phenomena that lead to consequences with significant magnitudes. Cascading effects are complex and multi-dimensional and evolve constantly over time. They are associated more with the magnitude of vulnerability than with that of

hazards. Low-level hazards can generate broad chain effects if vulnerabilities are widespread in the system or not addressed properly in sub-systems. For these reasons, it is possible to isolate the elements of the chain and see them as individual (subsystem) disasters in their own right. In particular, cascading effects can interact with the secondary or intangible effects of disasters [16].

Cascading. It is a form of general dynamic that may multiply the effects of a combination of different hazards, such as an earthquake that produces a breakdown in infrastructure, whose failure contaminates water and causes disease to spread, which disrupts the local economy. The interdependent nature of many infrastructure systems significantly increases the potential for cascading effects that could spread from one kind of infrastructure to another [16].

Catastrophic disaster. The term implies an event or incident, which produces severe and widespread damages of such a magnitude as to result in the requirement for significant resources from outside the affected area to provide the necessary response. It results in large numbers of deaths and injuries; causes extensive damage or destruction of facilities that provide and sustain human needs; produces an overwhelming demand on state and local response resources and mechanisms; causes a severe long-term effect on general economic activity; and severely affects state, local, and private sector capabilities to begin and sustain response activities [25].

Chemical agent. A chemical substance that affects the body, a part of the body, or any of its functions. The effects may be beneficial or harmful [10].

Chemical spill. It is defined as the uncontrolled release of a hazardous or harmful chemical substance, either as a solid, liquid or a gas.

Chronic effect. A change that occurs in the body over a relatively long time (weeks, months, years) following repeated exposure or a single over-exposure to a substance [10].

Combustible. Capable of catching fire and burning, usually a material that has a flash point above 37.8°C [10].

Condition. Any as-found state, whether or not resulting from an event, that may have adverse safety, health, quality assurance, security, operational or environmental implications. A condition is usually programmatic in nature; for example, an error in analysis or calculation; an anomaly associated with design or performance; or an item indicating a weakness in the management process are all conditions [25].

Consequence. The effect of an event, incident, or occurrence, including the number of deaths, injuries, and other human health impacts along with economic impacts both direct and indirect and other negative outcomes to society [20]-[22].

Consequence assessment. The process used to evaluate the impacts of a release of radioactive or other hazardous materials. The assessment of consequences is the evaluation and interpretation of all available information concerning an actual or potential release of hazardous materials to the environment for the purpose of estimating personnel exposure/dose [25].

Consequence management. Planning, preparedness, and response activities for addressing the consequences of a terrorism incident. These activities include measures to: alleviate damage, loss, hardship, or suffering caused by the incident; protect public health and safety; restore essential Government services; and provide emergency assistance to those affected [25].

Contaminant. An unwanted material (for example, radioactive, biological or chemical) that is likely to harm the quality of the working environment. The most common workplace contaminants are chemicals that may be present in the form of dusts, fumes, gases or vapours [10].

Corrosive. A substance that will burn the skin or eyes on contact [10].

Critical infrastructure accident consequences mitigation. Efforts and actions to prevent and reduce effects of potential hazards coming from CI accident by their elimination or reduction of their consequences by changing decreasing their dangerous interactions with CI operating environment and making alerts.

Critical infrastructure accident consequences reduction. Efforts and actions to reduce negative effects of CI accident by changing and decreasing their dangerous interactions with CI operating environment.

Critical infrastructure accident. An event that causes changing the critical infrastructure safety state into the safety state worse than the critical safety state that is dangerous for the critical infrastructure and its operating environment.

Critical injury. The serious injury that is life-threatening or produces unconsciousness or results in a substantial loss of blood or involves the fracture of a leg or arm (but not a finger or toe) or involves the amputation of a leg, arm, hand or foot (but not a finger or toe) or consists of burns to a major portion of the body or causes the loss of sight in an eye [10].

Damage. An injury or harm impairing the function or condition of a person or thing [16].
Decomposition. The breakdown of a material or substance (by heat, chemical reaction, rotting or other process) into parts or elements [10].
Detection of impacts of climate change. For a natural, human, or managed system, identification of a change from a specified baseline. The baseline characterizes behaviour in the absence of climate change and may be stationary or non-stationary (e.g., due to land use change) [11].
Disaster management. Social processes for designing, implementing, and evaluating strategies, policies, and measures that promote and improve disaster preparedness, response, and recovery practices at different organizational and societal levels [12].
Disaster operations. Disaster Operations are activities undertaken by Local and State government agencies to provide direct assistance to and in the protection of the general public immediately before, during and an immediate aftermath of a disaster event [16].
Disaster preparedness. It measures, including early warning and the development of contingency or emergency plans, may be considered a component of, and a bridge between, disaster risk reduction and disaster management. Preparedness accepts the existence of residual, unmitigated risk, and attempts to aid society in eliminating certain of the adverse effects that could be experienced once a physical event(s) occurs (for example, by the evacuation of persons and livestock from exposed and vulnerable circumstances) [19].
Disaster. A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources [7], [14], [16].
Dust. Fine particles of a solid that can remain suspended in air. The particle size of a dust is larger than that of a fume. Dusts are produced by mechanical action, such as grinding. Some dusts may be harmful to an employee’s health [10].
Economic and environmental impacts. There are the sum of the costs of cure or healthcare, cost of immediate or longer-term emergency measures, costs of restoration of buildings, public transport systems and infrastructure, property, cultural heritage, etc., costs of environmental restoration and other environmental costs (or environmental damage), costs of disruption of economic activity, value of insurance pay-outs, indirect costs on the economy, indirect social costs, and other direct and indirect costs, as relevant [17].
Environmental impact assessment. Process by which the environmental consequences of a proposed project or programme are evaluated, undertaken as an integral part of planning and decision- making processes with a view to limiting or reducing the adverse impacts of the project or programme [24].
Evaporation. The process by which a liquid, without reaching its boiling point, changes into a vapour and mixes with the air [10].
Event. Any real-time occurrence or significant deviation from planned or expected behaviour that could endanger or adversely affect people, property, or the environment [25].
Explosive. A substance, mixture or compound that is capable of producing an explosion [10].
Exposure values. The concentrations of a biological, chemical, or physical agent to which it is believed nearly all workers may be exposed without experiencing any harmful effects [10].
Exposure. People, property, systems, or other elements present in hazard zones and subject to potential losses [7].
Flammable. Capable of easily catching fire and of burning, usually a material that has a flash point below 37.8°C [10].
Flash point. The lowest temperature at which a liquid will give off enough vapours to form a mixture that will burn if ignited. The lower the flash point, the higher the risk of fir [10].
Hazardous material. Any substance that may produce adverse health and/or safety effects to people or the environment [10].

– how that degree of damage or loss is likely to escalate with time following an incident

Human error. This term is used today to include not just workers’ errors, but engineering deficiencies and lack of adequate organizational controls which together account for the majority of accidents [10].
Human impacts. There are defined as the quantitative measurement of the following factors: number of deaths, number of severely injured or ill people, and number of permanently displaced people [17].
Ignition source. A source of energy, such as heat, flame, sparks or static electricity, that is capable of causing a fuel mixture to burn [10].
Impact analysis. The identification of critical business processes, and the potential damage or loss that may be caused to the organization resulting from a disruption to those processes. Business impact analysis identifies:
Impact assessment. The practice of identifying and evaluating, in monetary and/or non-monetary terms, the effects of climate change on natural and human systems [5].
Impact. The result of an unwanted incident [9].

Incident. An unwanted event which, in different circumstances, could have resulted in harm to people, damage to property or loss to a process [10].
Incompatible. A term used to describe materials that could cause dangerous reactions if they come in direct contact with one another [10].
Inhalation. The breathing in of an airborne gas, vapour, fume, mist or dust [10].
Initiating event. An unplanned occurrence caused by human or natural phenomena provided to the incident or accident.
Irritant. A substance which, in sufficient quantities, can inflame or irritate the eyes, skin or respiratory system (lungs, etc.). Symptoms include pain and reddening [10].
Market impacts. Impacts that are linked to market transactions and directly affect gross domestic product (GDP, a country's national accounts) [5].
Melting point. The temperature at which a solid changes to a liquid. For mixtures, a range of temperatures may be given [10].
Mutagen. An agent that causes sudden and permanent changes in one or more hereditary features, generally by modifying one or more genes (changes to genetic material). The changes may or may not be passed on to offspring [10].
Natural disaster. Violent, sudden and destructive change in the environment without cause from human activity, due to phenomena such as floods, earthquakes, fire and hurricanes [16].
Natural hazard. Natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage [24].
Non-market impacts. Impacts that affect ecosystems or human welfare, but that are not directly linked to market transactions — for example, an increased risk of premature death [5].
Oxidizing agent. A substance that gives up oxygen easily (this oxygen can fuel a fire) or reduces the hydrogen in other compounds. Some examples of oxidizing agents are peroxides, chlorates, perchlorates, nitrates and permanganates. Oxidation and reduction reactions always occur at the same time [10].
Physical impacts. Physical impacts of disasters include casualties (deaths and injuries), losses of structures, animals, and crops and property damage (households, infrastructure etc.). The physical impacts of a disaster are usually the most obvious, easily measured, and first reported by the news media.
Political/social impacts. The impacts usually rated on a semi-quantitative scale and may include categories such as public outrage and anxiety, encroachment of the territory, infringement of the international position, violation of the democratic system, and social psychological impact, impact on public order and safety, political implications, psychological implications, and damage to cultural assets, and other factors considered important which cannot be measured in single units, such as certain environmental damage [17].
Prevention. Actions taken to avoid an incident or to intervene to stop an incident from occurring. Prevention involves actions taken to protect lives and property. It involves applying intelligence and other information to a range of activities that may include such countermeasures as deterrence operations; heightened inspections; improved surveillance and security operations; investigations to determine the full nature and source of the threat; immunizations, isolation, or quarantine; public health and agricultural surveillance and testing processes; and, as appropriate, specific law enforcement operations aimed at deterring, preempting, interdicting, or disrupting illegal activity and apprehending potential perpetrators and bringing them to justice [16].
Priority. Sequence in which an incident or problem needs to be resolved, based on impact and urgency [9].
Procedure. A written description of a course of action to be taken to perform a given task [9].
Process. An organized set of activities which uses resources to transform inputs to outputs [9].
Protection. Protection includes such actions and measures needed to ensure protective reactions which do not unnecessarily interfere with citizen's freedoms and liberties [16].
Radiation. The energy transmitted by waves through space or some medium. There are two types of radiation: ionizing (for example, X-Rays or radiation from a radioactive device), and non-ionizing radiation (for example, IR radiation, UV radiation) [10].
Reactivity. The capability of a substance to undergo a chemical reaction with the release of energy. Unwanted effects include: pressure build-up, temperature increase, and formation of harmful by-products. These effects may occur because of the reactivity of a substance to heat, an ignition source, or direct contact with other chemicals in use or in storage [10].
Reducing agent. A substance that accepts oxygen or gives up hydrogen during a chemical reaction.

Oxidation and reduction always occur at the same time [10].
Rescue. The safe removal of persons or animals from actual or threatened danger of physical harm [23].
Sea environment degradation. Appearing and changing in time the sea environment state that is hazardous for the sea environment caused by the environment threats appearing and existing in this environment.
Sea environment threat. Appearing and changing in time phenomenon that is hazardous for the sea environment caused by the objects operating and interacting in this environment.
Sea pollution vulnerability. Sea environment feature that makes it easily influenced by various pollutions coming from different kinds of objects activity at this environment.
Sea pollution. Sea environment pollution caused by hazardous phenomena resulting from the activity of objects operating and interacting in this environment.
Sensitizer. A substance which on first exposure causes little or no reaction in humans or test animals. However, on repeated exposure, it may cause a marked response not necessarily limited to the contact site [10].
Social responsibility. Responsibility of an organization for the impacts of its decisions and activities on society and the environment, through transparent and ethical behaviour [13].
Socio-natural hazard. The phenomenon of increased occurrence of certain geophysical and hydro-meteorological hazard events, such as landslides, flooding, land subsidence and drought, that arise from the interaction of natural hazards with overexploited or degraded land and environmental resources [24].
Synergistic effects. The health effects of two or more substances or agents that are greater than the sum of their separate effects [10].
Teratogen. An agent that causes birth defects by harming the unborn child [10].

- the form the loss or damage will take
- the minimum staffing, facilities and services needed to enable business processes to continue to operate at a minimum acceptable level
- the time for full recovery of the business processes [9].

Threshold limit value. A threshold limit value refers to the airborne concentration of a substance to which it is believed that nearly all workers may be repeatedly exposed day after day (for 8 hours per day) without harmful effect. Because of individual susceptibility, however, a small percentage of workers may experience discomfort from substances in concentrations at or below the threshold limit. A smaller percentage may be affected more seriously by aggravation of a pre-existing condition or by the development of an occupational illness [10].
Toxic substance. Any substance that can cause acute or chronic effects to a person or is suspected to cause disease or injury under certain conditions [10].
Unstable. The tendency of a material to break down or to undergo other unwanted chemical changes during normal handling or storage [10].
Vapour. The form that a gas or liquid takes when it evaporates into the air [10].

3. Critical infrastructure accident consequences methodology

This chapter of the paper is introducing the taxonomy, specified in the report, in regard to methodology related to critical infrastructure accident consequences modelling [1] with accordance to the report [8].
General model of critical infrastructure accident consequences. The probabilistic joint general model of critical infrastructure accident consequences including models of the process of initiating events generated either by the critical infrastructure accident or by its loss of safety critical level, the process of environment threats and the process of environment degradation (*Figure 1*).

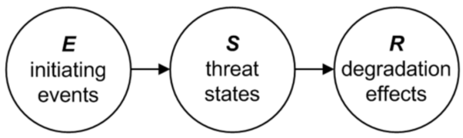

Figure 1. Interrelations of the critical infrastructure accident consequences general model

To construct this general model of critical infrastructure accident consequences and to apply it practically, the basic notions concerned with those three particular processes it is composed should be defined and the methods and procedures of estimating those processes unknown parameters should be developed. Under those all assumptions from the constructed model after its unknown parameters identification, the main characteristics of the process of environment degradation can be predicted. Finally, the proposed model can be applied to modelling, identification and prediction of the critical infrastructure accident consequences generated by real critical infrastructures [1].
The proposed approach and the methods will be applied to modelling, identification and prediction of the critical infrastructure accident consequences generated by the critical infrastructure defined as a ship operating in the Baltic Sea area (Project Case Study 2, Scenario 2).

3.1. Process of initiating events

Initiating event. An event initiating dangerous for the critical infrastructure operating environment after either the critical infrastructure accident or its loss of safety critical level.

Process of initiating events. Changing in time of initiating events' states in the critical infrastructure operating environment and interacting with that environment.

State of process of initiating events. The fixed set of initiating events that occurs after either the critical infrastructure accident or its loss of safety critical level.

Process of initiating events modelling. To model the process of initiating events, we distinguish n_1, $n_1 \in N$, events initiating the dangerous situation of the critical infrastructure operation environment after its accident and mark them by $E_1, E_2, ..., E_{n_1}$. Moreover, we introduce the set of vectors $E = \{e : e = [e_1, e_2, ..., e_{n_1}], e_i \in \{0,1\}\}$, where

$$e_i = \begin{cases} 1, \text{if the initiating event } E_i \text{ occurs,} \\ 0, \text{if the initiating event } E_i \text{ does not occur,} \end{cases}$$

for $i = 1,2,\dots,n_1$.

We number the vectors of the set E and we assume that there are ω, $\omega \in N$, different elements of the set $E = \{e^1, e^2, ..., e^{\omega}\}$, where $e^l = [e_1^l, e_2^l, ..., e_{n_1}^l]$, $l = 1,2,...,\omega$. Further, we define the process of initiating events $E(t)$ on the time interval $t \in <0,\infty)$, with its discrete states from the set $E = \{e^1, e^2, ..., e^{\omega}\}$.

Parameters of the process of initiating events. The process of initiating events may be described by:

– *number of states* ω, $\omega \in N$;
– *initial probabilities* $p^l(0) = P(E(0) = e^l)$, $l = 1,2,\dots,\omega$, of the process of initiating events $E(t)$ staying at the state e^l at the moment $t = 0$;
– *probabilities of transitions* p^{lj}, $l, j = 1,2,\dots,\omega$, $l \neq j$, of the process of initiating events $E(t)$ between the states e^l and e^j;
– *conditional distribution functions* $H^{lj}(t) = P(\theta^{lj} < t)$, $t \in <0,\infty)$, $l, j = 1,2,\dots,\omega$, $l \neq j$, of the process of initiating events $E(t)$ conditional sojourn times θ^{lj} at the state e^l while its next transition will be done to the state e^j, $l, j = 1,2,\dots,\omega$, $l \neq j$.

Process of initiating events identification. The statistical identification of the unknown parameters of the process of initiating events, i.e. estimating the probabilities of this process of staying at the states at the initial moment, the probabilities of this processes transitions between its states and the parameters and forms of the distributions fixed for the description of this process conditional sojourn times at their states can be performed according to the way presented in [2], [15].

Initiating events prediction. Finding the characteristics of the process of initiating events like ones listed below and other.

Characteristics of the process of initiating events. The process of initiating events may be characterized by:

– *unconditional distribution functions* $H^l(t) = P(\theta^l < t)$, $t \in <0,\infty)$, $l = 1,2,\dots,\omega$, of the sojourn times θ^l, $l = 1,2,\dots,\omega$, of the process of initiating events $E(t)$ at the state e^l, $l = 1,2,\dots,\omega$,
– *limit transient probabilities* p^l of the probabilities $p^l = P(E(t) = e^l)$, $t \in <0,\infty)$, $l = 1,2,\dots,\omega$, of the process of initiating events $E(t)$ staying at the state e^l, $l = 1,2,\dots,\omega$.

3.2. Process of environment threats

Process of environment threats. Appearing and changing in time phenomena that are hazardous for the critical infrastructure operating environment caused by the initiating events generated by critical infrastructure accident interacting with this environment.

Process of environment treats modelling. To construct the general model of the environment threats caused by the process of the initiating events generated by critical infrastructure loss of required safety critical level, we distinguish the set of n_2, $n_2 \in N$, kinds of threats as the consequences of initiating events that may cause the sea environment degradation and denote them by $H_1, H_2, ..., H_{n_2}$. We also distinguish n_3, $n_3 \in N$, environment sub-regions $D_1, D_2, ..., D_{n_3}$ of the considered critical infrastructure operating environment region $D = D_1 \cup D_2 \cup ... \cup D_{n_3}$, that may be degraded by the environment threats H_i, $i = 1,2,\dots,n_2$. The environment threats possibility of influence on the distinguished its operating environment sub-regions is presented in *Figure 2*.

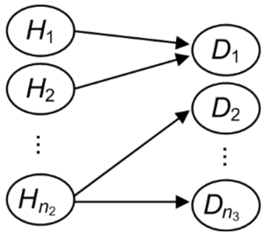

Figure 2. Hazardous accident consequences influence on the marine environment sub-regions degradation

We assume that the operating environment region D can be affected by some of threats H_i, $i = 1,2,\ldots,n_2$, and that a particular environment threat H_i, $i = 1,2,\ldots,n_2$, can be characterised by the parameter f^i, $i = 1,2,\ldots,n_2$. Moreover, we assume that the scale of the threat H_i, $i = 1,2,\ldots,n_2$, influence on region D depends on the range of its parameter value and for particular parameter f^i, $i = 1,2,\ldots,n_2$, we distinguish l_i ranges $f^{i1}, f^{i2}, \ldots, f^{il_i}$ of its values.

Sub-region environment threat state. A vector $s_{(k)} = [f^1_{(k)}, f^1_{(k)}, \ldots, f^{n_2}_{(k)}]$, $k = 1,2,\ldots,n_3$, where

$$f^i_{(k)} = \begin{cases} 0, & \text{if a threat } H_i \text{ does not appear at the sub-region } D_k, \\ f^{ij}_{(k)}, & \text{if a threat } H_i \text{ appears at the sub-region } D_k \text{ and its parameter is in the range } f^{ij}_{(k)},\ j = 1,2,\ldots,l_i, \end{cases}$$

for $i = 1,2,\ldots,n_2$, $k = 1,2,\ldots,n_3$, is called the environment threat state of the sub-region D_k. Further, we number the sub-region environment threat states and mark them by $s^{\upsilon}_{(k)}$ for $\upsilon = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, and form the set $S_{(k)} = \{s^{\upsilon}_{(k)},\ \upsilon = 1,2,\ldots,\upsilon_k\}$, $k = 1,2,\ldots,n_3$, where $s^i_{(k)} \neq s^j_{(k)}$ for $i \neq j$, $i,j \in \{1,2,\ldots,\upsilon_k\}$. The set $S_{(k)}$, $k = 1,2,\ldots,n_3$, is called the set of the environment threat states of the sub-region D_k, $k = 1,2,\ldots,n_3$, while a number υ_k is called the number of the environment threat states of this sub-region.

Sub-process of environment threats model. A function $S_{(k)}(t)$, $k = 1,2,\ldots,n_3$, defined on the time interval $t \in < 0,\infty)$, and having values in the environment threat states set $S_{(k)}$, $k = 1,2,\ldots,n_3$, is called the sub-process of the environment threats of the sub-region D_k, $k = 1,2,\ldots,n_3$.

Conditional sub-process of environment threats model. To involve the sub-process of environment threats of the sub-region with the process of initiating events, we introduced the function $S_{(k/l)}(t)$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$, defined on the time interval $t \in < 0,+\infty)$, depending on the states of the process of initiating events $E(t)$ and taking its values in the set of the environment threat states set $S_{(k)}$, $k = 1,2,\ldots,n_3$. This function is called the conditional sub-process of the environment threats in the sub-region D_k, $k = 1,2,\ldots,n_3$, while the process of initiating events $E(t)$ is at the state e^l, $l = 1,2,\ldots,\omega$.

Parameters of the conditional sub-process of environment threats. The conditional sub-process $S_{(k/l)}(t)$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$, of environment threats may be described by:

– *number of states* υ_k, $\upsilon_k \in N$;
– *initial probabilities* $p^i_{(k/l)}(0) = P(S_{(k/l)}(0) = s^i_{(k)})$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$, of the conditional sub-process of environment threats $S_{(k/l)}(t)$, staying at the state $s^i_{(k)}$ at the moment $t = 0$;
– *probabilities of transitions* $p^{ij}_{(k/l)}$, $i,j = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$, of the conditional sub-process of environment threats $S_{(k/l)}(t)$ between the states $s^i_{(k)}$ and $s^j_{(k)}$;
– *conditional distribution functions* $H^{ij}_{(k/l)}(t) = P(\eta^{ij}_{(k/l)} < t)$, $t \in < 0,+\infty)$, $i,j = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$, of the conditional sub-process of environment threats $S_{(k/l)}(t)$, conditional sojourn times $\eta^{ij}_{(k/l)}$ at the state $s^i_{(k)}$, while its next transition will be done to the state $s^j_{(k)}$, $i,j = 1,2,\ldots,\upsilon_k$, $i \neq j$.

Process of environment treats identification. The statistical identification of the unknown parameters of the process of environment threats i.e. estimating the probabilities of this process of staying at the states at the initial moment, the probabilities of this processes transitions between its states and the parameters and forms of the distributions fixed for the description of this process conditional sojourn times at their states can be performed in the similar way to that presented in [3], [15].

Environment treats prediction. Finding the characteristics of the process of environment threats like ones listed below and other.

Characteristics of conditional sub-process of environment threats. The conditional sub-process of environment threats may be characterized by:

– *unconditional distribution functions* $H^i_{(k/l)}(t) = P(\eta^i_{(k/l)} < t)$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$, of the sojourn times

$\eta^{i}_{(k/l)}$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$, of the conditional sub-process of environment threats $S_{(k/l)}(t)$ at the state $s^{i}_{(k)}$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$;

– *limit transient probabilities* $p^{i}_{(k/l)}(t) = P(S_{(k/l)}(t) = s^{i}_{(k/l)})$, $t \in <0,\infty)$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$, $l = 1,2,\ldots,\omega$, of the conditional sub-process of environment threats $S_{(k/l)}(t)$ staying at the state $s^{i}_{(k)}$, $i = 1,2,\ldots,\upsilon_k$, $k = 1,2,\ldots,n_3$.

3.3. Process of environment degradation

Process of environment degradation modelling. The particular states of the process of the environment threats $S_{(k)}(t)$ of the sub-region D_k, $k = 1,2,\ldots,n_3$, may lead to dangerous effects degrading the environment at this sub-region. Thus, we assume that there are m_k different dangerous degradation effects for the environment sub-region D_k, $k = 1,2,\ldots,n_3$, and we mark them by $R^{1}_{(k)}, R^{2}_{(k)},\ldots,R^{m_k}_{(k)}$. This way the set $R_{(k)} = \{R^{1}_{(k)}, R^{2}_{(k)},\ldots,R^{m_k}_{(k)}\}$, $k = 1,2,\ldots,n_3$, is the set of degradation effects for the environment of the sub-region D_k.

These degradation effects may attain different levels. Namely, the degradation effect $R^{m}_{(k)}$, $m = 1,2,\ldots,m_k$, may reach $\nu^{m}_{(k)}$ levels $R^{m1}_{(k)}, R^{m2}_{(k)},\ldots,R^{m\nu^{m}_{(k)}}_{(k)}$, $m = 1,2,\ldots,m_k$, that are called the states of this degradation effect. The set $R^{m}_{(k)} = \{R^{m1}_{(k)}, R^{m2}_{(k)},\ldots,R^{m\nu^{m}_{(k)}}_{(k)}\}$, $m = 1,2,\ldots,m_k$, is called the set of states of the degradation effect $R^{m}_{(k)}$, $m = 1,2,\ldots,m_k$, $k = 1,2,\ldots,n_3$, for the environment of the sub-region D_k, $k = 1,2,\ldots,n_3$.

Environment sub-region degradation process model. A vector $R_{(k)}(t) = [R^{1}_{(k)}(t), R^{2}_{(k)}(t),\ldots,R^{m_k}_{(k)}(t)]$, $t \in <0,+\infty)$, where $R^{m}_{(k)}(t)$, $t \in <0,+\infty)$, $m = 1,2,\ldots,m_k$, $k = 1,2,\ldots,n_3$, are the processes of degradation effects for the environment of the sub-region D_k, defined on the time interval $t \in <0,+\infty)$, and having their values in the degradation effect state sets $m = 1,2,\ldots,m_k$, $k = 1,2,\ldots,n_3$, is called the degradation process of the environment of the sub-region D_k.

Sub-region environment degradation state. The vector $r^{m}_{(k)} = [d^{1}_{(k)}, d^{2}_{(k)},\ldots,d^{m_k}_{(k)}]$, $k = 1,2,\ldots,n_3$, where

$$d^{m}_{(k)} = \begin{cases} 0, & \text{if a degradation effect } R^{m}_{(k)} \text{ does not appear at the sub-region } D_k, \\ R^{mj}_{(k)}, & \text{if a degradation effect } R^{m}_{(k)} \text{ appears at the sub-region } D_k \text{ and its level is equal to } R^{mj}_{(k)},\ j = 1,2,\ldots,\nu^{m}_{(k)}, \end{cases}$$

for $m = 1,2,\ldots,m_k$, $k = 1,2,\ldots,n_3$, is called the degradation state of the sub-region D_k. Further, we number the sub-region D_k, $k = 1,2,\ldots,n_3$, degradation states defined by (11) and (12) and mark them by $r^{\ell}_{(k)}$ for $\ell = 1,2,\ldots,\ell_k$, $k = 1,2,\ldots,n_3$, and form the set of degradation states $R_{(k)} = \{r^{\ell}_{(k)},\ \ell = 1,2,\ldots,\ell_k\}$, $k = 1,2,\ldots,n_3$, where $r^{i}_{(k)} \neq r^{j}_{(k)}$ for $i \neq j$, $i,j \in \{1,2,\ldots,\ell_k\}$.

The set $R_{(k)}$, $k = 1,2,\ldots,n_3$, is called the set of the environment degradation states of the sub-region D_k, $k = 1,2,\ldots,n_3$, while a number ℓ_k is called the number of the environment degradation states of this sub-region.

Environment degradation process. A function $R_{(k)}(t)$, $k = 1,2,\ldots,n_3$, defined on the time interval $t \in <0,+\infty)$, and having values in the environment degradation states set $R_{(k)}$, $k = 1,2,\ldots,n_3$, is called the sub-process of the environment degradation of the sub-region D_k, $k = 1,2,\ldots,n_3$.

Conditional environment sub-region degradation process model. To involve the environment sub-region D_k, $k = 1,2,\ldots,n_3$, degradation process with the process of the environment threats, we define the conditional environment sub-region degradation process, while the process of the environment threats $S_{(k)}(t)$ of the sub-region D_k, is at the state $s^{\upsilon}_{(k)}$, $\upsilon = 1,2,\ldots,\upsilon_k$, as a vector $R_{(k/\upsilon)}(t) = [R^{1}_{(k/\upsilon)}(t), R^{2}_{(k/\upsilon)}(t),\ldots,R^{m_k}_{(k/\upsilon)}(t)]$, $t \in <0,+\infty)$, where $R^{m}_{(k/\upsilon)}(t)$, $t \in <0,+\infty)$, $m = 1,2,\ldots,m_k$, $k = 1,2,\ldots,n_3$, $\upsilon = 1,2,\ldots,\upsilon_k$, defined on the time interval $t \in <0,+\infty)$, and having values in the degradation effect states set $R^{m}_{(k)}$, $m = 1,2,\ldots,m_k$, $k = 1,2,\ldots,n_3$.

Parameters of the conditional environment sub-region degradation process. The conditional environment sub-region degradation process $R_{(k/\upsilon)}(t)$, may be described by:

- *number of states* ℓ_k, $\ell_k \in N$;
- *initial probabilities* $q^i_{(k/\upsilon)}(0) = P(R_{(k/\upsilon)}(0) = r^i_{(k)})$, $i = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$, $\upsilon = 1,2,\ldots,\upsilon_k$, of the conditional sub-process of environment degradation $R_{(k/\upsilon)}(t)$, staying at the state $r^i_{(k)}$ at the moment $t = 0$;
- *probabilities of transitions* $q^{ij}_{(k/\upsilon)}$, $i,j = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$, $\upsilon = 1,2,\ldots,\upsilon_k$, of the conditional sub-process of environment degradation $R_{(k/\upsilon)}(t)$ between the states $r^i_{(k)}$ and $r^j_{(k)}$;
- *conditional distribution functions* $G^{ij}_{(k/\upsilon)}(t) = P(\zeta^{ij}_{(k/\upsilon)} < t)$, $t \in <0,+\infty)$, $i,j = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$, $\upsilon = 1,2,\ldots,\upsilon_k$. of the conditional sub-process of environment degradation $R_{(k/\upsilon)}(t)$, conditional sojourn times $\zeta^{ij}_{(k/\upsilon)}$ at the state $r^i_{(k)}$ while its next transition will be done to the state $r^j_{(k)}$, $i,j = 1,2,...,\ell_k$, $i \neq j$.

Environment sub-region degradation process identification. The statistical identification of the unknown parameters of the process of the environment degradation, i.e. estimating the probabilities of this process of staying at the states at the initial moment, the probabilities of this processes transitions between its states and the parameters and forms of the distributions fixed for the description of this process conditional sojourn times at their states can be performed in the similar way to that presented in [4], [15].

Environment sub-region degradation process prediction. Determining the characteristics of the process of the environment sub-region degradation like ones listed below and other.

Characteristics of the environment sub-region degradation process. The conditional sub-process of environment degradation be characterized by:

- *unconditional distribution functions* $G^i_{(k/\upsilon)}(t) = P(\zeta^i_{(k/\upsilon)} < t)$, $i = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$, $\upsilon = 1,2,\ldots,\upsilon_k$, of the conditional environment sub-region degradation process $R_{(k/\upsilon)}(t)$ uconditional sojourn times $\zeta^i_{(k/\upsilon)}$ at the state $r^i_{(k)}$, $i = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$;
- *limit transient probabilities* $q^i_{(k/\upsilon)}(t) = P(R_{(k/\upsilon)}(t) = r^i_{(k/\upsilon)})$, $t \in \langle 0,+\infty)$, $i = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$, $\upsilon = 1,2,\ldots,\upsilon_k$, of the environment sub-region degradation process $R_{(k/\upsilon)}(t)$, $t \in \langle 0,+\infty)$ staying at the state $r^i_{(k)}$, $i = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$;
- *mean value of sojourn total time* $\zeta^i_{(k)}$, $i = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$, of the environment sub-region degradation process $R_{(k)}(t)$, $t \in \langle 0,+\infty)$, $k = 1,2,\ldots,n_3$, in the time interval $\langle 0,\theta \rangle$, $\theta > 0$, at the state $r^i_{(k)}$ $i = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$, is given by $E[\zeta^i_{(k)}] \cong q^i_{(k)}\theta$, $i = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$.

3.3. Environment losses

Environment losses caused by the process of the environment sub-region degradation process modelling. We denote by $C^i_{(k)}(t)$, $i = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$, the losses associated with the process of the environment degradation $R_{(k)}(t)$, $t \in \langle 0,+\infty \rangle$, $k = 1,2,\ldots,n_3$, in the sub-region D_k, $k = 1,2,\ldots,n_3$, at the environment degradation state $r^i_{(k)}$, $i = 1,2,...,\ell_k$, $k = 1,2,\ldots,n_3$, in the time interval $\langle 0,t \rangle$.

Conditional mean value of environment sub-region losses. The approximate expected value of the environment losses in the time interval $\langle 0,\theta \rangle$, associated with the process of the environment degradation $R_{(k)}(t)$, of the sub-region D_k can be defined by

$$C_{(k)}(\theta) \cong \sum_{i=1}^{\ell_k} q^i_{(k)} \cdot C^i_{(k)}(\theta) \text{ for } k = 1,2,\ldots,n_3.$$

Total mean value of critical infrastructure operating environment region losses. The total expected value of the environment losses in the time interval $\langle 0,\theta \rangle$, associated with the process of the environment degradation $R(t)$, in all sub-regions of the considered critical infrastructure operating environment region D, can be evaluated by

$$C(\theta) \cong \sum_{k=1}^{n_3} C_{(k)}(\theta).$$

Optimization of critical infrastructure accident consequences. Application of the results coming from the general model of the process of environment degradation and the linear programming to the critical infrastructure accident consequences optimization. The application is related to the optimization of the critical infrastructures accident consequences by determining the optimal values of limit transient probabilities at the environment degradation states of the process of the environment region degradation that minimize the total mean value of critical infrastructure operating environment region losses for the fixed interval of time.

4. Conclusions

The paper is the improved modification of the part of the report [8] prepared in the scope of EU-CIRCLE project activity deliverable. It includes critical infrastructure accident consequences terminology and methodology.

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